Modulation of Selected Species of Neutral Interstellar Gas and Their Derivative Populations in the Heliosphere Due to Solar Activity Cycle Effects

Justyna M. Sokół

Supervisor:
Dr. habil. Maciej Bzowski
Associate Professor in SRC PAS

A thesis submitted for the degree of Doctor of Philosophy in Physics

Space Research Centre
Polish Academy of Sciences

Warsaw 2016

This page is intentionally left blank.

Acknowledgments

I would like to thank my supervisor, Professor Maciej Bzowski, for the support and advice with the direction and quality of my research throughout the years.

I am indebted to the Director of the Space Research Centre, PAS, Professor Iwona Stanisławska, for approval of my work at home in the months of the most intense preparations for exams and during writing up the first sketch of the dissertation, and also for the scholarship for PhD candidates in the recent months.

The thesis research was supported by the grants of the Polish Ministry for Science and Higher Education NN-203-513-038 and NS-1260-11-09 and the grant from the National Science Center, Poland, 2012/06/M/ST9/00455.

This PhD thesis is a result of the work in the *Laboratory for Solar System Physics and Astrophysics* in SRC PAS from 2010 to 2016, I appreciate the time spent together with its staff in these years.

I acknowledge the IBEX Science Team for fruitful discussions during the team meetings in 2011, 2012, 2013, 2014. I also greatly appreciate participation in the International Space Science Institute (ISSI, Bern, Switzerland) Working Group *Cross-calibration of past FUV experiments (Fully ON-line Datacenter for Ultraviolet Emissions, FONDUE)* and International Team 223 *Spatial and temporal studies of the heliospheric interaction with the local interstellar medium from SOHO/SWAN UV, IBEX neutral atom, and ACE and STEREO pickup ion observations*. These meetings highly affected the results presented in the dissertation.

I would like to thank all inspiring and helpful people I have met during my heliospheric journey. It is impossible to thank all of you individually, but my special and grateful thanks are dedicated to Eberhard Möbius, Peter Bochsler, and Martin Snow.

Finally, I would like to thank two great people who extremely support me in the last months, without the encouragement from them, I would not found enough strength to go so far.
I would like to thank Professor Stanisław Grzędzielski for the enormous help he gave me, for patience, understanding, cheering, and for the inspiring talks we had.
I would like to thank my best friend, my husband Marcin Szpanko, for the limitless and borderless help and care he gives me every day.

This page is intentionally left blank.

Contents

Abbreviations and symbols

ACE	*Advanced Composition Explorer*
AMPTE	*Active Magnetospheric Particle Tracer Explorers*
AU	astronomical unit
aWTPM	analytic Warsaw Test Particle Model
CAT	computer-assisted tomography
CELIAS	*Charge, ELement, and Isotope Analysis System*
CEM	channel electron multiplier
CIR	corotating interaction region
CCF	cross-correlation function
CME	coronal mass ejection
CR	Carrington rotation
CR-map	Carrington (rotation) map, the solar map of the solar wind speed distribution as a function of longitude and latitude during one Carrigton rotation
ΔN_e	solar wind electron density fluctuation level
ENA	energetic neutral atom
ESA	electrostatic analyzer
EUV	extreme ultraviolet
EVE	*EUV Variability Experiment*
FOV	field of view
FUV	far ultraviolet
GOME	*Global Ozone Monitoring Experiment*
IBEX	*Interstellar Boundary Explorer*
IMAP	*Interstellar Mapping and Acceleration Probe*
IMF	interstellar magnetic field
IMP	*Interplanetary Monitoring Platform*
IPS	interplanetary scintillation
ISEE	*International Sun-Earth Explorer* `[spacecraft]`
ISEE	Institute for Space-Earth Environmental Research
ISM	interstellar medium
ISN	interstellar neutral
L1	libration point 1
LIC	Local Interstellar Cloud
LISM	Local Interstellar Medium
LOS	line of sight
MFPS	model fitting to power spectra
MUV	middle ultraviolet
NSW	neutral solar wind
PUI	pick-up ion
$\mathbf{R}_E$	radius of the Earth
$\mathbf{R}_\odot$	radius of the Sun
SC	solar cycle

SCIAMACHY	*Scanning Imaging Absorption Spectrometer for Atmospheric CHartographY*
SDO	*Solar Dynamics Observatory*
SEE	*Solar EUV Experiment*
SEM	*Solar Extreme Ultraviolet Monitor*
SOHO	*SOlar and Heliospheric Observatory*
SOLSTICE	*SOLar-STellar Irradiance Comparison Experiment*
SORCE	*SOLar Radiation and Climate Experiment*
STEREO	*Solar TErrestrial RElations Observatory*
SW	solar wind
SWAN	*Solar Wind ANisotropies*
SWE	*Solar Wind Experiment*
SWEPAM	*Solar Wind Electron, Proton, and Alpha Monitor*
SWOOPS	*Solar Wind Observations Over the Poles of the Sun*
TIMED	*Thermosphere Ionosphere Mesosphere Energetics Dynamics*
TOF	time-of-flight
TSI	total solar irradiance
UV	ultraviolet
VIS	visible (portion of the solar spectrum)
WTPM	Warsaw Test Particle Model
XUV	X-ray ultraviolet

Abstract

The subject of this PhD dissertation is the modulation of the interstellar neutral gas (ISN) and its derivative populations, like energetic neutral atoms (ENAs) and pick-up ions (PUIs), inside the heliosphere due to the solar activity cycle effects. The Sun emits into the space a supersonic flow of particles and a flux of extreme ultraviolet (EUV) radiation that both create the environment in the Solar System and in the Local Interstellar Cloud in which the Sun is embedded. As a result of interaction of the solar plasma with the interstellar plasma a cavity around the Sun, called the heliosphere, is created. The neutral component of the local interstellar medium (LISM) can enter freely the heliosphere and can be detected in the vicinity of the Sun, bringing information about the physical processes at the edges of the heliosphere. The ISN gas interacts with the solar wind particles and solar EUV radiation inside the heliosphere being finally ionized and thus creates new populations of heliospheric particles, like PUIs that are picked-up by the ambient magnetic field. Also ENAs that are created at the edges of the heliosphere and which enter the heliosphere are ionized by the solar factors. The ionization can be due to the charge exchange, photoionization, or electron impact ionization reactions. The solar wind and the solar EUV radiation varies in time with the cycle of solar activity. In this thesis we studied the modulation of the solar ionization factors in time and in heliolatitude and the effect of this modulation on the observations of the ISN gas, ENAs, and interstellar PUIs observed from the Earth's orbit. We developed a model to reconstruct the variation in time of the heliolatitudinal structure of the solar wind proton speed and density based on the available and carefully selected measurements in and out of the ecliptic plane. We constructed a composite photoionization rate model based on available measurements of the EUV flux and carefully selected series of the EUV proxies. We used these models to calculate the ionization rates for the H, He, Ne, and O species and to assess of their survival probabilities in the heliosphere. The models were next employed to study the density of the interstellar species as expected at the Earth's orbit, to determine the Ne/He, O/He, and Ne/O abundances, to simulate the PUI production rate and count rate time series, and to calculate the corrections for ionization losses for the full sky maps of H ENA flux observed by IBEX. We studied the evolution of He, Ne, and O PUI count rate along Earth's orbit during the solar cycle and found differences in their evolution among the species. We concluded that the solar cycle variation in the density of the parent ISN species and in the ionization rates may cause a systematic shift in the flow direction of the ISN gas in the heliosphere derived from the analysis PUI measurements. We extended an existing software to model hypothetical departures of the distribution function of ISN He gas in the LISM from thermal equilibrium in order to study resulting signatures of these departures in the ISN He flux observed by the IBEX mission. We compared the results with the observations and concluded that the signal simulated for two different populations with the Maxwellian distribution function reproduces the data better than the kappa distribution function. We identified regions in the sky where the signatures from the signal given by the kappa distribution should be visible. The results of the study show that the modulation of the ionization factors inside the heliosphere due to solar activity is significant for the modeling of the ISN gas and its heliospheric particle populations and for the correct interpretation of the observations.

This page is intentionally left blank.

Streszczenie

Heliosfera powstaje w wyniku oddziaływania materii pochodzącej ze Słońca z otaczającą Słońce lokalną materią międzygwiazdową. Oddziaływanie to kształtowane jest częściowo przez korpuskularne i elektromagnetyczne promieniowanie ze Słońca oraz jego pole grawitacyjne i magnetyczne. Przyjmuje się, że otaczająca heliosferę materia międzygwiazdowa jest jednorodna i stacjonarna co najmniej na przestrzeni rozmiaru heliosfery, podczas gdy materia pochodząca ze Słońca zmienia się w czasie i w przestrzeni. W fizyce heliosfery w skalach globalnych istotne są zmienności materii emitowanej ze Słońca w skalach czasowych rzędu długości cyklu aktywności słonecznej, jak również w skalach dłuższych i krótszych.

W wyniku oddziaływania plazmy słonecznej z plazmą międzygwiazdową powstają różne populacje cząstek zjonizowanych i neutralnych. Należą do nich atomy energetyczne (ENA, z ang. energetic neutral atom) oraz jony pochwycone (PUI, z ang. pick-up ion), które wraz z atomami międzygwiazdowymi kształtują heliosferę. Obserwacje tych trzech typów cząstek w heliosferze stanowią podstawowe narzędzie do badania heliosfery i jej granic. Powstawanie ENA i PUI oraz ich rozkład w heliosferze modulowane są poprzez jonizację przez wiatr słoneczny i promieniowanie ultrafioletowe ze Słońca. Główne czynniki modulujące to szybkość i gęstość wiatru słonecznego, strumień promieniowania w zakresie skrajnego ultrafioletu (EUV) w zakresie odpowiedzialnym za jonizację (długości fali poniżej $\sim$ 91 nm), linia Lyman-α (121.6 nm), oraz temperatura elektronów w wietrze słonecznym. Istotna jest zmienność materii pochodzącej ze Słońca wraz z cyklem słonecznym zarówno w skalach czasowych, jak i przestrzennych.

Jonizacja wewnątrz heliosfery powoduje powstawanie nowych populacji cząstek oraz modyfikacje populacji już istniejących. Jonizacja może być realizowana poprzez wymianę ładunku z cząstkami wiatru słonecznego, fotojonizację oraz zderzenia z elektronami wiatru słonecznego. Tworzenie populacji cząstek w heliosferze jest hierarchiczne. Pierwotne populacje to neutralny gaz międzygwiazdowy, który wniknął do wnętrza heliosfery oraz wiatr słoneczny. Jonizacja gazu międzygwiazdowego wewnątrz heliosfery prowadzi do powstania jonów pochwyconych, a w przypadku wymiany ładunku dodatkowo atomów energetycznych. Populacje te ulegają kolejnym stratom jonizacyjnym, tworząc kolejne populacje cząstek. Efektywność produkcji nowych populacji zależy od rozkładu szybkości cząstek oraz od intensywności czynników jonizacyjnych.

W dotychczasowych badaniach efekty modulacji populacji cząstek heliosferycznych poprzez jonizację pochodzącą od Słońca były uwzględniane w uproszczony sposób. Powodem stosowania uproszczeń był brak spójnego, jednorodnego modelu czynników słonecznych odpowiedzialnych za jonizację. Pierwsze wyniki pokazały, że dokładne śledzenie historii zmienności jonizacji na drodze cząstki w heliosferze może mieć istotne znaczenie dla uzyskiwanych wyników.

Początkowo brakowało wystarczającej liczby dostępnych danych pomiarowych czynników słonecznych. Następnie wykorzystywano pojedyncze pomiary do konstruowania bardzo przybliżonej zmienności w czasie, jednakże uniemożliwiała ona śledzenie zmienności na drobnych skalach czasowych (np. w skali obrotu Słońca) w długim przedziale czasu. Ponadto z uwagi na przekonanie, że największe starty jonizacyjne mają miejsce tuż przed detekcją, często pomijano śledzenie histo-

rii jonizacji atomów na ich trajektoriach w heliosferze, przyjmując że jest ona mało znacząca. Na przełomie XX i XXI wieku liczba dostępnych danych pomiarowych wzrosła, jednak pochodziły one z różnych źródeł i stworzenie jednolitego w czasie szeregu czynników jonizacyjnych wymagało ich skalibrowania i unormowania.

Wzrost dostępnych danych pomiarowych związanych z wiatrem słonecznym, bezpośrednich i pośrednich, oraz bezpośrednie pomiary widma promieniowania słonecznego w zakresie EUV wraz z powstaniem skalibrowanych serii kompozytowych wskaźników (ang. proxies) promieniowania EUV umożliwiły zbudowanie jednolitego w czasie zbioru czynników słonecznych modulujących gaz międzygwiazdowy w heliosferze na przestrzeni ostatnich cykli słonecznych. Spójny, jednorodny i wystarczająco długi w czasie szereg czynników jonizacyjnych mógł być następnie zaimplementowany do istniejących modeli rozkładu gazu międzygwiazdowego w heliosferze oraz zastosowany do interpretacji obserwacji z misji kosmicznych w tym w szczególności z sondy IBEX.

Przedmiotem prezentowanej rozprawy doktorskiej jest modulacja wybranych pierwiastków gazu międzygwiazdowego i jego populacji pochodnych w heliosferze w wyniku efektów związanych z cyklem aktywności słonecznej. W ramach przeprowadzonej analizy

– wypracowano jednorodny, spójny i oparty na obserwacjach model czynników jonizacyjnych w heliosferze

– zbadano wpływ jonizacji na gęstości międzygwiazdowych atomów He, Ne, O widziane z orbity Ziemi

– zbadano, czy efekty jonizacyjne mogą znacząco wpłynąć na wyznaczanie kierunku napływu gazu międzygwiazdowego z pomiarów PUIs

– oszacowano, na ile możliwe jest obserwacyjne poszukiwanie odstępstw neutralnej populacji międzygwiazdowej od stanu równowagi termodynamicznej poprzez obserwacje prowadzone z orbity Ziemi

– zbadano modyfikację strumieni H ENA wskutek zmienność jonizacji w czasie i szerokości heliograficznej.

Realizacja postawionego tematu i wynikające z niej wnioski przedstawione są w następujących dziewięciu artykułach opublikowanych w recenzowanych czasopismach naukowych. Kolejność artykułów, które stanowią rozprawę, odpowiada kolejności realizacji postawionych zadań:

Artykuł **S1** **Sokół, J. M.**, Bzowski, M., Tokumaru, M., Fujiki, K., McComas, D. J., 2013, *Heliolatitude and time variations of solar wind structure from in-situ measurements and interplanetary scintillation observations*, Solar Physics, vol. 285, pp. 167-200, DOI:10.1007/-s11207-012-9993-9; (Sokół et al. 2013b)

Artykuł **S2** **Sokół, J. M.**, Swaczyna, P., Bzowski, M., Tokumaru, M., 2015c, *Reconstruction of heliolatitudinal structure of the solar wind proton speed and density*, Solar Physics, vol. 290, pp. 2589-2615, DOI:10.1007/s11207-015-0800-2; (Sokół et al. 2015d)

Artykuł **B1** Bzowski, M., **Sokół, J. M.**, Tokumaru, M., Fujiki, K., Quèmerais, E., Lallement, R., Ferron, S., Bochsler, P., McComas, D. J., 2013b, *Solar parameters for modeling the interplanetary background*, Chapter 3 in "Cross-Calibration of Far UV Spectra of Solar System Objects and the Heliosphere", ISSI Scientific Report Series 13, ed. E. Quémerais, M. Snow, R.-M. Bonnet, Springer Science + Business Media, New York, pp. 67-138, DOI:10.1007/978-1-4614-6384-9_3; (Bzowski et al. 2013b)

Artykuł **B2** Bzowski, M., **Sokół, J. M.**, Kubiak, M. A., Kucharek, H., 2013a, *Modulation of neutral interstellar He, Ne, O in the heliosphere: survival probabilities and abundances at IBEX*, Astronomy & Astrophysics, vol. 557, A50, DOI:10.1051/0004-6361/201321700; (Bzowski et al. 2013a)

Artykuł **S3** **Sokół, J. M.**, Bzowski, M., Kubiak, M. A., Möbius, E., 2016, *Solar cycle variation of interstellar neutral He, Ne, O density and pick-up ions along the Earth's orbit*, Monthly Notices of the Royal Astronomical Society, vol. 458, Issue 4, pp. 3691-3704, DOI:10.1093/-mnras/stw515; (Sokół et al. 2016)

Artykuł **S4** **Sokół, J. M.**, Kubiak, M. A., Bzowski, M., Swaczyna, P., 2015b, *Interstellar neutral helium in the heliosphere from Interstellar Boundary Explorer observations. II. The Warsaw Test Particle Model (WTPM)*, Astrophysical Journal Supplement Series, vol. 220:27 (24pp), DOI:10.1088/0067-0049/220/2/27; (Sokół et al. 2015c)

Artykuł **S5** **Sokół, J. M.**, Bzowski, M., Kubiak, M. A., Swaczyna, P., Galli, A., Wurz, P., Möbius, E., Kucharek, H., Fuselier, S. A., McComas, D. J., 2015a, *The interstellar neutral He haze in the heliosphere: what can we learn?*, Astrophysical Journal Supplement Series, vol. 220:29 (12pp), DOI:10.1088/0067-0049/220/2/29; (Sokół et al. 2015b)

Artykuł **M1** McComas, D. J., Dayeh, M. A., Allegrini, F., Bzowski, M., DeMajistre, R., Fujiki, K., Funsten, H. O., Fuselier, S. A., Gruntman, M., Janzen, P. H., Kubiak, M. A., Kucharek, H., Livadiotis, G., Möbius, E., Reisenfeld, D. B., Reno, M., Schwadron, N. A., **Sokół, J. M.**, Tokumaru, M., 2012, *The first three years of IBEX observations and our evolving heliosphere*, Astrophysical Journal Supplement Series, vol. 203:1 (36pp), DOI:10.1088/-0067-0049/203/1/1; (McComas et al. 2012)

Artykuł **M2** McComas, D. J., Allegrini, F., Bzowski, M., Dayeh, M. A., DeMajistre, R., Funsten, H. O., Fuselier, S. A., Gruntman, M., Janzen, P. H., Kubiak, M. A., Kucharek, Möbius, E., Reisenfeld, D. B., Schwadron, N. A., **Sokół, J. M.**, Tokumaru, M., 2014, *IBEX: The First Five Years (2009–2013)*, Astrophysical Journal Supplement Series, vol. 213:20 (28pp), DOI:10.1088/0067-0049/213/2/20; (McComas et al. 2014a).

Artykuł S1 przedstawia wypracowany fenomenologiczny model ewolucji czasowej i przestrzennej wiatru słonecznego. Do jego konstrukcji wykorzystano dane zgromadzone w bazie OMNI, zebrane z bezpośrednich pomiarów wykonywanych w płaszczyźnie ekliptyki, oraz jedyne dostępne bezpośrednie dane o wietrze słoneczny spoza płaszczyzny ekliptyki, zebrane przez sondę Ulysses. Zbiór danych uzupełniono o dane z szybkością wiatru słonecznego, uzyskane z obserwacji scyntylacji międzyplanetarnych, przygotowywane i udostępnione przez ISEE[1]. Model ten został rozwinięty w Artykule S2. Opracowany model ewolucji struktury wiatru słonecznego posłużył następnie m.in. do szacowania temp wymiany ładunku między populacjami cząstek w heliosferze oraz jonizacji poprzez zderzenia z elektronami w wietrze słonecznym.

Aby oszacować tempo jonizacji poprzez promieniowanie ultrafioletowe ze Słońca, przeanalizowano dostępne pomiary widma EUV Słońca oraz jego wskaźników. Odpowiednio dobrano dane kierując się ich odpowiedniością, jednolitością oraz zakresem dostępności czasowej. Skonstruowano kompozytowy model fotojonizacji pierwiastków helu, neonu, tlenu i wodoru w heliosferze. Wyniki przedstawione są w Artykule B2 oraz, dla wodoru, w Artykule B1.

Obydwa opracowane modele posłużyły do oszacowania całkowitego tempa jonizacji neutralnej składowej gazu międzygwiazdowego w heliosferze, jak również populacji jonów pochwyconych oraz atomów energetycznych wodoru z wykorzystaniem modeli rozkładu gazu rozwijanych w *Zakładzie Fizyki Układu Słonecznego i Astrofizyki* (ZFUSiA) od lat 1990-tych. Artykuł B2 oraz Artykuł S3 prezentują modulację gęstości, strumieni, obfitości oraz jonów pochwyconych He, Ne i O w heliosferze wskutek strat jonizacyjnych wewnątrz heliosfery. Wyniki pokazują, że zmiany tempa jonizacji związane z cyklem aktywności słonecznej mogą znacząco modyfikować rozkłady gęstości atomów międzygwiazdowych. Śledzenie zmian czasowych jonizacji wzdłuż trajektorii cząstki w heliosferze jest konieczne do precyzyjnego badania pierwiastków neonu i tlenu oraz wodoru. Modulacja He jest najmniejsza spośród badanych pierwiastków, najbardziej tłumiony w heliosferze jest tlen i wodor. Rozkład wodoru jest dodatkowo modulowany przez zmienne w czasie efektywne działanie ciśnienia promieniowania w wodorowej linii Lyman-α, jednakże efekty te znane są w literaturze i nie były przedmiotem badań, choć uwzględniono je w wykonywanych rachunkach. Efekty zmienności temp jonizacji z szerokością heliograficzną są istotne w badaniu tlenu i mogą prowadzić do systematycznych przesunięć w położeniu ekstremów gęstości wzdłuż orbity Ziemi.

Zmienności gęstości atomów międzygwiazdowych w płaszczyźnie orbity Ziemi są istotne m.in. do badania temp produkcji jonów pochwyconych, powstających w procesie jonizacji atomów miedzygwiazdowych, oraz do szacowania obfitości pierwiastków wewnątrz heliosfery i w jej warstwach zewnęrznych. W Artykule S3 prezentowane są tempa lokalnej produkcji oraz przewidywane tempa zliczeń jonów pochwyconych He, Ne i O. Wyniki wskazują, że zmienność rozkładu międzygwiazdowego gazu neutralnego w pobliżu orbity Ziemi, wskutek zmienności temp jonizacji w czasie i szerokości heliograficznej, może znacząco modyfikować rejestrowany strumień jonów pochwyconych. Modyfikacja ta prowadzi do przesunięcia położenia maksimów w rozkładach obserwowanych bezpośrednio wzdłuż orbity Ziemi, które używane są do wyznaczenia kierunku napływu gazu międzygwiazdowego na heliosferę. W efekcie dochodzi do złudzenia, że gaz międzygwiazdowy napływa z kierunku przesuniętego o kilka stopni. Czynniki odpowiedzialne za modulację modelowanych wielkości badane były ze szczególną uwagą poświęconą ich modyfikacji wskutek jonizacji w

[1]Institute for Space-Earth Environmental Research, Nagoya University, Japonia

pobliżu Słońca. Odkryto, że głównym powodem systematycznego przesunięcia kierunku napływu gazu międzygwiazdowego, otrzymywanego z jonów pochwyconych, jest modulacja rozkładu macierzystego gazu międzygwiazdowego wzdłuż orbity Ziemi w trakcie cyklu słonecznego. Krótkotrwałe zmienności w tempie produkcji jonów pochwyconych są odpowiedzialne za dodatkowy roczny rozrzut i powiększają obserwowane różnice. Kierunek różnic między wartościami oczekiwanymi a otrzymanymi zgadza się w obrębie wszystkich trzech badanych pierwiastków (He, Ne, O), i jest w stronę większych długości dla tzw. półksiężyca (ang. crescent, wzrost obserwowanych wartości po stronie napływu gazu względem Słońca), natomiast dla tzw. stożka (ang. cone, wzrost obserwowanych wartości po stronie spływu gazu względem Słońca wskutek grawitacyjnego zakrzywienia trajektorii cząstek) kierunek różnic jest w kierunku przeciwnym. Wyniki te wskazują, że najbardziej prawdopodobnym wyjaśnieniem systematycznych różnic w wyznaczonym kierunku napływu gazu międzygwiazdowego do heliosfery z obserwacji jonów pochwyconych jest zaniedbanie w oryginalnej analizie danych modulacji gazu międzygwiazdowego wewnątrz heliosfery spowodowanej aktywnością słoneczną.

Znając prawdopodobieństwa przeżycia atomów międzygwiazdowych w heliosferze można wypracować czynniki określające zmianę względnych stosunków He, Ne i O wskutek jonizacji wywołanej promieniowaniem korpuskularnym i elektromagnetycznym ze Słońca. Zastosowanie ich do strumieni tych pierwiastków zmierzonych z okoli orbity Ziemi umożliwia oszacowanie obfitości na szoku końcowym, a po uwzględnieniu filtracji w otoku heliosferycznym, również obfitości w lokalnym ośodku międzygwiazdowym. Wpływ zmiennej w czasie jonizacji na takie oszacowania przedstawiony jest w Artykule B2. Dyskutowana jest w nim również zależność obfitości Ne/He, O/He i Ne/O, od parametrów gazu międzygwiazdowego napływającego do heliosfery. Wyniki pokazują, że najbardziej zmienne w cyklu słonecznym są stosunki prawdopodobieństw przeżycia Ne/He i O/He, natomiast Ne/O wykazuje zmienność zdominowaną przez kilkuletnie zmiany w strumieniu wiatru słonecznego w płaszczyźnie ekliptyki. Stosunki prawdopodobieństw przeżycia dla badanych pierwiastków zmieniają się również z parametrami gazu międzygwiazdowego napływającego do heliosfery. Dla stosunków Ne/He i O/He maleją ze wzrostem wartości długości kierunku napływu i spadkiem szybkości gazu, natomiast dla stosunku Ne/O rosną ze wzrostem zarówno wartości długości kierunku napływu, jak i szybkości gazu.

W sytuacji, gdy czynniki jonizacyjne pochodzące ze Słońca wewnątrz heliosfery są już dobrze poznane i kontrolowane oraz dane są w postaci kompletnego, jednorodnego i ciągłego w czasie modelu, można zastosować je do modelowania gazu międzygwiazdowego w zakresie wykraczającym poza dotychczas przyjmowane standardowe założenia. Artykuł S5 przedstawia analizę helowej składowej neutralnego gazu międzygwiazdowego w heliosferze przy różnych założeniach o funkcji rozkładu gazu przed heliosferą. Skonstruowane zostały mapy pełnego nieba sygnału pochodzącego od gazu z rozkładem zadanym przez funkcję kappa, pojedynczą funkcję Maxwella-Boltzmanna oraz sumę dwóch rozkładów Maxwella-Boltzmanna osobno dla populacji pierwotnej i Ciepłej Bryzy, czyli niedawno odkrytej populacji gazu międzygwiazdowego w heliosferze, która prawdopodobnie jest tzw. wtórną populacją neutralnego gazu międzygwiazdowego w heliosferze, powstającą w zewnętrznym otoku. Następnie porównano je jakościowo z danymi. Celem była identyfikacja obszarów na niebie, w których efekty pochodzące od niestandardowych założeń byłyby najbardziej widoczne. Wnioski wskazują, że spodziewane sygnatury byłyby możliwe do detekcji, jednakże wymagana jest większa czułość energetyczna detektora niż ta, którą dysponuje IBEX-Lo. Ponadto interesujące obszary na niebie znajdują się w tych częściach orbity IBEXa, które są przysłonięte przez magnetosferę Ziemi. Na potrzeby tych oszacowań rozwinięto analityczną wersję oprogramowania do badania rozkładu gazu międzygwiazdowego w heliosferze używanego w ZFUSiA, tzw. Warsaw Test Particle Model (WTPM), szczegóły przedstawione są w Artykule S4. Analityczna odmiana WTPM przeznaczona jest do używania na komputerach osobistych i doskonale sprawdza się w jakościowych oszacowaniach, gdyż nie wymaga zaawansowanych zasobów obliczeniowych.

Opracowane tempa jonizacji gazu międzygwiazdowego wewnątrz heliosfery posłużyły również do oszacowania strat jonizacyjnych strumieni atomów energetycznych wodoru (H ENA) obserwowanych przez instrument IBEX-Hi na pokładzie sondy IBEX. Jonizacja wewnątrz heliosfery jest różnicowa co doprowadza do istotnej modyfikacji funkcji rozkładu obserwowanych strumieni. Prawdopodobieństwa przeżycia są różne dla cząstek o różnych energiach, a zatem znacząco modyfikują widma energetyczne rejestrowanych strumieni. Dodatkowo materia jonizująca wewnątrz heliosfery (wiatr słoneczny) wykazuje anizotropię w szerokości heliograficznej, tym samym jonizacja również jest anizotropowa. Prowadzi to do odmiennej modyfikacji strumieni H ENA w heliosferze w zależności od kierunku obserwacji. Prawdopodobieństwa przeżycia H ENA posłużyły do wyznaczenia strumieni tych populacji w miejscu ich pochodzenia, czyli w powłoce heliosferycznej. W obszarze tym dochodzi do oddziaływania materii pochodzącej ze Słońca z materią lokalnego ośrodka międzygwiazdowego, która opływając heliosferę staje się anizotropowa. ENA są wskaźnikami stanu fizycznego plazmy oraz procesów i przepływów zachodzących w tych zewnętrznych obszarach heliosfery. Prawdopodobieństwa przeżycia poprawnie uwzględniające anizotropię środowiska jonizacyjnego wewnątrz heliosfery są niezbędne do odfiltrowania tych efektów w obserwacjach i wiarygodnego oszacowania anizotropii materii w zewnętrznych obszarach heliosfery. Dokładna analiza prawdopodobieństw przeżycia użytych do korekcji zmierzonych strumieni H ENA opisana jest w Artykułach M1 i M2.

Globalny obraz heliosfery i procesów zachodzących w jej zewnętrznych warstwach badany jest na podstawie obserwacji prowadzonych z okolic orbity Ziemi. Warunki jonizacyjne panujące wewnątrz heliosfery mają istotny wpływ na analizę tych obserwacji i poprawną ich interpretację. W przedstawianej rozprawie doktorskiej wykazano, że uwzględnienie jonizacji oszacowanej ze starannie zestawionych dostępnych danych obserwacyjnych i tworzącej spójny system ma znaczący wpływ na analizę obserwacji populacji cząstek międzygwiazdowych wewnątrz heliosfery. Przedstawione wnioski dotyczą zarówno składowej neutralnej, jak i zjonizowanej gazu międzygwiazdowego, jak również mogą mieć również wpływ na interpretację obserwacji heliosferycznej poświaty wodorowej i helowej.

1 Thesis

Heliosphere is created as a result of interaction between the plasma emitted by the Sun and the local interstellar medium (LISM) surrounding the Sun. The interaction is partially governed by the corpuscular and electromagnetic radiation from the Sun as well as the solar gravity and magnetic field. It is commonly accepted that LISM is uniform and stable on a scale of the order of the size of the heliosphere, whereas the solar medium varies in time and space. In the study of the global heliosphere significant are variations of the solar-born medium on time scales of the solar activity cycle as well as variations on finer and longer time scales.

As a result of the interaction between the solar and the interstellar matter new populations of neutral and ionized particles are created. They are the energetic neutral atoms (ENAs) and the pick-up ions (PUIs). Together with the interstellar neutral (ISN) gas which entered inside the heliosphere and the solar wind they determine the populations of heliospheric particles. Observations of these particles inside the heliosphere constitute a basic tool for investigation of the global structure of the heliosphere and its boundaries. Production of ENAs and PUIs and their distributions inside the heliosphere are modulated by the solar wind and the solar ultraviolet (UV) radiation. The most important solar factors are the solar wind proton speed and density, solar extreme ultraviolet (EUV) radiation in the wave-range responsible for ionization (wavelengths smaller than $\sim$ 91 nm), solar Lyman-α line (121.6 nm) responsible for the resonant radiation pressure acting on neutral H, and the density and temperature of the solar wind electrons. Their temporal and spatial variation during the solar cycle is important for the study of heliospheric particles.

Ionization inside the heliosphere modulates the existing populations and produces new populations of particles. The ionization is due to the reactions of charge exchange with the solar wind particles, photoionization, and collisions with the solar wind electrons. Production of the new populations of particles in the heliosphere is hierarchical. The primary populations are the neutral interstellar gas that entered the heliosphere and the solar wind. Ionization of the neutral interstellar gas inside the heliosphere produces PUIs and, in the case of charge exchange, ENAs. These populations are subsequently ionized and create next populations of particles. The efficiency of the production depends on the distribution of the parent particles and the intensity of the ionization.

The modulation of the populations of interstellar gas particles inside the heliosphere has been considered in a simplified and approximate way for many years. The simplifications were made because of the lack of homogeneous and continuous model of the solar ionization factors. Early studies showed that the detailed tracking of the history of the variation of ionization rates along the particle trajectory in the heliosphere can be important for the results, but there was not enough observations of the solar factors to construct a proper model. Single measurements were used to approximate the variation in time on the solar cycle scale, but the variation on finer time scales (e.g. Carrington rotation, CR) for a long time period was missing. Additionally, it was commonly accepted that detailed tracking of the ionization along the particle trajectory inside the heliosphere was not needed because the ionization predominantly happens just before the detection. At the turn of the 20th and 21th century the number of available observational data increased, but they have come from various sources and required cross-calibration and cross-normalization to create a homogeneous and continuous time series.

The increase of availability of observational data of solar wind (both direct and indirect) and direct measurements of the solar EUV radiation, together with time series of the solar EUV proxies, enables to create a homogeneous, continuous, and sufficiently long time series of the solar factors that modulate the ISN gas inside the heliosphere over a few last solar cycles. Such time series can subsequently be implemented in the existing models of the distribution of the ISN gas in the heliosphere and used to analysis of observations of various heliospheric measurements, including the observations made by the *Interstellar Boundary Explorer* (IBEX) mission.

The subject of this dissertation is the modulation of selected species of the ISN gas and their derivative populations inside the heliosphere during the solar cycle. As a part of the research the following objectives were realized:

– a model of homogeneous, continuous, and observation based solar ionization factors inside the heliosphere was created

– an impact of the varying ionization rates on the densities of ISN He, Ne, and O in the Earth's orbit was investigated

– an assessment of the effects related with ionization on the derivation of the flow direction of the ISN gas from the PUIs measurements was performed

– an assessment of the possibilities to search for the departures from equilibrium of the parent interstellar He population in the observations performed from the Earth's orbit

– a modulation of the heliospheric H ENA flux due to variations of the ionization rates as a function of time and heliolatitude was investigated.

The realization of these objectives and the results are presented in the following nine articles, published in scientific peer-reviewed journals. The order of the articles, which construct the dissertation, is organized by the objectives to fulfill:

Paper **S1** **Sokół, J. M.**, Bzowski, M., Tokumaru, M., Fujiki, K., McComas, D. J., 2013, *Heliolatitude and time variations of solar wind structure from in-situ measurements and interplanetary scintillation observations*, Solar Physics, vol. 285, pp. 167-200, DOI:10.1007/s11207-012-9993-9; (Sokół et al. 2013b)

Paper **S2** **Sokół, J. M.**, Swaczyna, P., Bzowski, M., Tokumaru, M., 2015c, *Reconstruction of heliolatitudinal structure of the solar wind proton speed and density*, Solar Physics, vol. 290, pp. 2589-2615, DOI:10.1007/s11207-015-0800-2; (Sokół et al. 2015d)

Paper **B1** Bzowski, M., **Sokół, J. M.**, Tokumaru, M., Fujiki, K., Quèmerais, E., Lallement, R., Ferron, S., Bochsler, P., McComas, D. J., 2013b, *Solar parameters for modeling the interplanetary* *background*, Chapter 3 in "Cross-Calibration of Far UV Spectra of Solar System Objects and the Heliosphere", ISSI Scientific Report Series 13, ed. E. Quémerais, M. Snow, R.-M. Bonnet, Springer Science + Business Media, New York, pp. 67-138, DOI:10.1007/978-1-4614-6384-9_3; (Bzowski et al. 2013b)

Paper **B2** Bzowski, M., **Sokół, J. M.**, Kubiak, M. A., Kucharek, H., 2013a, *Modulation of neutral interstellar He, Ne, O in the heliosphere: survival probabilities and abundances at IBEX*, Astronomy & Astrophysics, vol. 557, A50, DOI:10.1051/0004-6361/201321700; (Bzowski et al. 2013a)

Paper **S3** **Sokół, J. M.**, Bzowski, M., Kubiak, M. A., Möbius, E., 2016, *Solar cycle variation of interstellar neutral He, Ne, O density and pick-up ions along the Earth's orbit*, Monthly Notices of the Royal Astronomical Society, vol. 458, Issue 4, pp. 3691-3704, DOI:10.1093/mnras/-stw515; (Sokół et al. 2016)

Paper **S4** **Sokół, J. M.**, Kubiak, M. A., Bzowski, M., Swaczyna, P., 2015b, *Interstellar neutral helium in the heliosphere from Interstellar Boundary Explorer observations. II. The Warsaw Test Particle Model (WTPM)*, Astrophysical Journal Supplement Series, vol. 220:27 (24pp), DOI:10.1088/0067-0049/220/2/27; (Sokół et al. 2015c)

Paper **S5** **Sokół, J. M.**, Bzowski, M., Kubiak, M. A., Swaczyna, P., Galli, A., Wurz, P., Möbius, E., Kucharek, H., Fuselier, S. A., McComas, D. J., 2015a, *The interstellar neutral He haze in the heliosphere: what can we learn?*, Astrophysical Journal Supplement Series, vol. 220:29 (12pp), DOI:10.1088/0067-0049/220/2/29; (Sokół et al. 2015b)

Paper **M1** McComas, D. J., Dayeh, M. A., Allegrini, F., Bzowski, M., DeMajistre, R., Fujiki, K., Funsten, H. O., Fuselier, S. A., Gruntman, M., Janzen, P. H., Kubiak, M. A., Kucharek, H., Livadiotis, G., Möbius, E., Reisenfeld, D. B., Reno, M., Schwadron, N. A., **Sokół, J. M.**, Tokumaru, M., 2012, *The first three years of IBEX observations and our evolving heliosphere*, Astrophysical Journal Supplement Series, vol. 203:1 (36pp), DOI:10.1088/-0067-0049/203/1/1; (McComas et al. 2012)

Paper **M2** McComas, D. J., Allegrini, F., Bzowski, M., Dayeh, M. A., DeMajistre, R., Funsten, H. O., Fuselier, S. A., Gruntman, M., Janzen, P. H., Kubiak, M. A., Kucharek, Möbius, E., Reisenfeld, D. B., Schwadron, N. A., **Sokół, J. M.**, Tokumaru, M., 2014, *IBEX: The First Five Years (2009–2013)*, Astrophysical Journal Supplement Series, vol. 213:20 (28pp), DOI:-10.1088/0067-0049/213/2/20; (McComas et al. 2014a).

The following sections present a brief description of the realization of these objectives. A detailed presentation is presented in the papers. In Section 2 a short introduction about the Sun and the solar activity cycle, the solar wind, and the heliosphere is given. Section 3 presents the developed models of the solar ionization factors inside the heliosphere, i.e., the model of evolution of the solar wind as a function of time and heliolatitude (Section 3.2), and the composite model of the photoionization rates (Section 3.3). Section 4 shortly presents results of the study of the modulation of the ISN gas density and interstellar PUIs in the Earth's orbit. In Section 5 an assessment of the possibilities to study hypothetical signatures of departures of ISN He gas distribution from the thermal equilibrium is presented. Section 6 concisely discusses the modulation of H ENA flux due to variation of ionization losses in time and heliolatitude. Section 7 summarizes the study and presents the conclusions. This section completes the description part of the dissertation. The main part of the dissertation is the aforementioned homogeneous set of scientific articles. These articles, in the order given above, are attached at the end of the dissertation (Section ***Articles of the thesis***) together with the statements of all co-authors about their individual contribution to these papers (Section ***Statements of co-authors***).

2 Introduction

2.1 The Sun and the solar cycle

The Sun is located in the Orion arm of our host galaxy, Milky Way. It is a main sequence star of a spectral type $G2V$, which indicates a yellow dwarf with spectral lines from heavy elements and with a surface temperature being $\sim$ 5778 K. The average luminance of the Sun is about 1.88 Gcd/m^2, however, it is not constant across the disk, featuring a darkening at the limb. The Sun comprises $\sim$ 99% of the mass of the Solar System and is its gravitational center. Its absolute magnitude is $M = 4.83$, and the apparent brightness equals $m = -26.74$. The Sun formed about 4.6 billion years ago from the gravitational collapse of the matter of a molecular cloud, triggered by shock-waves from supernovae explosions. In consequence, it is rich in heavy elements and thus is a Population I star. The chemical composition of the Sun consists of hydrogen, helium, and the heavy elements. They account for $\sim$ 74.9%, $\sim$ 23.8%, and less than 2% of the mass in the photosphere, respectively, with oxygen, carbon, neon, and iron being the most abundant among the heavy species. The Sun is presently in a half of its age and will remain stable for the coming five billion years. When the hydrogen fusion in its core stops, the Sun will undergo a series of changes to become a red giant.

The Sun does not have a well defined boundary as a solid body, as its atmosphere extends far away in the form of the solar wind. However, the Sun's radius ($R_\odot \simeq$ 695 700 km) is considered to be the distance from its center to the photosphere, the visible surface of the Sun. The Sun has a layered structure. The dense ($\sim$ 150 g/cm^3) and hot (15.7×10^6 K) core extends from the center to about 20 – 25% of $R_\odot$. The Sun's energy is produced by the nuclear fusion through the $p - p$ process (proton-proton chain reaction) that converts H into He. The thermal energy produced in the core heats the upper parts of the solar interior and is emitted into the interplanetary space as electromagnetic radiation and kinetic energy of the solar particles.

The radiative zone is a layer in which the energy is transported by the thermal radiation. This zone extends from the core to about $0.7R_\odot$. In this part of the Sun the temperature decreases from 7×10^6 K to 2×10^6 K and density of the matter decreases from 20 g/cm^3 to 0.2 g/cm^3 from the bottom to the top of the zone. The radiation comes from H and He electron emission.

The next layer is the tachocline, which separates the radiation and convective zones. It is the region where the rotation of the solar interior changes from the solid body rotation to the differential rotation of the outer parts of the Sun.

The next layer outward is the convection zone, which ranges from $\sim 0.7R_\odot$ to the photosphere. In this region the temperature still decreases and the heat is transported by outward convective motion. This convective motion in the presence of magnetic field results in differential rotation and the effect of solar dynamo. Additionally, the low density of the matter in the convective zone enables development of convective currents and the matter is organized into groups known as a solar granulation.

The photosphere, the next zone, is the visible surface of the Sun, because the Sun interior is opaque to the visible light below it. It is due to a decreasing amount of H ions, which absorb the visible light. The upper part of the photosphere is cooler than the lower part and, in consequence, the Sun appears brighter in the center than on the edge (limb) of the solar disk. The spectrum of sunlight in the ultraviolet, visible, and infrared domain has approximately the spectrum of a black-body radiation at about 5800 K, interspersed with atomic absorption lines from the tenuous layers above. The photosphere is a region where the sunspots are present. They are dark spots of lower temperature with a concentration of the magnetic flux. This makes them visible as darker from the surroundings. Sunspots appears in groups with a bipolar structure which consists of a leading group with a strongly concentrated magnetic polarity and a trailing group with opposite polarity which follows the leading group. The number of sunspots on the solar surface is one of the indicators of the phase of the solar activity cycle.

Above the photosphere begins the regions called the solar atmosphere. It is composed of the chromosphere, the transition region, and the corona, which extends outward. The density of the chromosphere is lower than the density in the photosphere and decreases outward. The temperature in this zone initially decreases to about about 4000 K, and subsequently starts to increase again to about 20 000 K in the upper parts. The chromosphere can be visible from Earth during the total eclipse. Its spectrum is dominated by the emission lines with the strongest one from being the Hα at 656.3 nm. The solar corona is separated from the chromosphere by a thin and irregular layer of the transition region, where the temperature rapidly increases from about 20 000 K to about 10^6 K. The transition region is visible from space in ultraviolet wavelengths due to the presence of emission lines of heavy species ions.

The solar corona is the outer region of the Sun. The temperature of the solar corona of $\sim 10^6$ K is hotter than the temperature of the solar surface. The process of the heating is not fully understood, but the most probable explanation is deposition of the energy of the Alfvén waves, propagating in the solar atmosphere. Due to the high temperature the corona shines brightly in X-rays. The matter in the solar corona is of a very low density and is of the order of 10^{-12} of the density of the photosphere. Additionally, it is not in the thermodynamic equilibrium. The corona is visible from the Earth during solar eclipses or can be observed with the use of special telescopes designed to block out the direct light from the solar disk, a coronograph. There are three sources of the emission in the corona, which enable to distinguish the so-called K, F, and E corona. The K-corona is created by the free electron scattering and appears as a spectral continuum without absorption lines. The F-corona spectrum contains the Fraunhofer absorption lines coming from the scattering of the sunlight on dust particles. The E-corona is created by the emission lines produced by the corona plasma ions. The corona is so hot that the gravity force cannot hold the plasma inside, which is emitted trough the open magnetic field lines far away from the Sun in the form of the solar wind (Section 2.2), which creates a cavity in the interstellar medium called the heliosphere (Section 2.4).

The outer regions of the Sun rotate faster at the equatorial region ($\sim$ 25.6 days) and slower at the regions close to the poles ($\sim$ 33.5 days). This differential rotation is a result of the conservation of angular momentum in the accretion phase of the star formation and the convection in the star interior. Convection is a motion of the mass caused by temperature gradients from the core outwards. Differential rotation depends on temperature differences in adjacent layers of the star. The whole radiative interior rotates as solid body at a constant speed and starts to vary with radius and latitude within the convective parts. Carrington (1858, 1863) determined the solar rotation rate from observations of the low-latitude sunspots. He defined a fixed solar coordinate system that makes full rotation during 25.38 days in a sidereal frame (with respect to the stars). The Carrington coordinates are heliographic, Sun-centered, and measure latitude and longitude in the rotating frame. The Carrington time is defined by the rotation number and the longitude of the point on the Sun that is at the sub-terrestrial point. Carrington rotation No 1 was set arbitrarily to November 9, 1853, and the subsequent rotations are counted from this epoch. The central meridian longitude decreases from 360° to 0° during each rotation as the central meridian point rotates under the Earth.

In this thesis we use the Carrington rotation period as a time unit. It is an average over the mean synodic rotation period of the Sun (it is visible from the Earth which moves in the same direction as the solar rotation) and equals 27.2753 days (Meeus 1998; Fränz & Harper 2002). Please note that the definition of the Carrington rotation in Paper S2 is misleading, with wrongly given period for the sidereal rotation. In all our papers we use the synodic rotation period of 27.2753 days.

The solar cycle, also referred to as the solar (magnetic) activity cycle or the solar sunspot cycle, is a quasi-periodic change of the solar magnetic field configuration, accompanied by changes in the solar surface and atmosphere, manifested in radiation and appearance. There are four phases of the activity cycle. The minimum occurs when the activity is low and the Sun then is called quiet. It takes about 3-4 years, there is a very small number of sunspots, the solar magnetic field configuration is poloidal, and the magnetic field in the corona has a closed streamer-like shape in a wide equatorial band and open field lines over the poles. The next phase during the solar cycle is the increasing phase, when the global solar magnetic field configuration starts to change towards a toroidal field configuration, and more sunspots appears. It progresses to the maximum, when the activity is high and the Sun is called active. This phase lasts about 4 years. The solar maximum has two peaks observed through the activity indices, separated by a 1-2 year gap and known as the Gnevyshev gap (Gnevyshev 1963). There are several suggestions for the reason of this double-peak phenomenon, like, e.g., two waves of activity, two separate surges of solar activity, the north/south asymmetry in solar activity due to a slight shift in phase in e.g., sunspot number and sunspot area between the two hemispheres. However, Norton & Gallagher (2010) concluded that the Gnevyshev gap is a phenomena that occurs in both hemispheres and is not due to the superposition of two hemispheres out of phase with each other (some discussion can be found in (Svalgaard & Kamide 2013) and also in a comprehensive review by (Hathaway 2015)). During the solar maximum the solar corona streamers and open lines intersperse at all latitudes, the number of sunspots is the biggest, and the ultraviolet radiation is the highest. The last phase of the solar cycle is the decreasing phase, when the magnetic field changes toward the initial poloidal field configuration and the sunspots gradually disappear. The decreasing phase lasts almost two times longer than the increasing phase.

The solar activity features are present in the photosphere, chromosphere, and the corona. The apparent period of the solar cycle variations is about 11 years and was determined by S.H. Schwabe in 1843 from observations of sunspots. During the activity cycle, sunspots migrate from high latitudes ($\sim 40°$) at the beginning of the increasing phase of solar activity towards lower latitudes ($\sim 10°$) at the end of the phase of high activity. This migration with latitude, when plotted as a function of time, leads to the so-called butterfly diagrams of sunspots. The variation of sunspot latitudes during the solar cycle can be predicted with the use of the Spörer's law. The cyclic evolution of sunspots is the most common indicator of the phase of solar activity. Sunspots together with a variety of other features on the solar surface and in the solar atmosphere, like prominences, faculae, flares, bursts, and many others, compose active regions. Their concentration and frequency of appearance varies significantly with the solar cycle.

The solar activity cycle is governed by the changes of the solar magnetic field and the complete change of the solar magnetic field lasts about 22 years (a composition of two 11-year cycles). It was deduced by G.E. Hale at the beginning of the 20th century. Babcock (1961) proposed that the cyclic changes of the global solar magnetic field are due to the differential rotation of the Sun. In this hypothesis, the solar cycle is due to a dynamo-like process which is governed by the internal magnetic field in the tachocline at the bottom of the convection zone. A strong magnetic field is periodically strengthened and weakened in this region, from which magnetic flux tubes arise and emerge at the photosphere, creating bipolar sunspot pairs. The differential rotation of the solar interior shears the new emerging fields gradually into a more toroidal field, until surface diffusion by granular convection breaks up the field and the meridional flows transport the fragments towards the poles. The surface diffusion neutralizes the toroidal field component increasingly during the decay of the cycle, so that a weak poloidal global field is left at the cycle minimum. When the internal dynamo strengthens the tachocline field again, the rate of the buyoant flux tubes increases and the cycle starts over (Aschwanden 2005).

The Sun varies on many time scales (from seconds to epochs) and the variability manifests also as a function of the observed wavelength of the solar emission. The solar irradiance is the power per unit area received from the Sun in the form of electromagnetic radiation in the wavelength range of the measuring instrument. Irradiance may be measured in space or at the Earth's surface after accounting for atmospheric absorption and scattering. It is measured perpendicular to the incoming sunlight and is a function of distance from the Sun and the solar cycle. Total solar irradiance (TSI) is a measure of the solar power integrated over a full-disk and over all wavelengths per unit area measured at the Earth's upper atmosphere. The so-called solar constant includes all types of solar radiation and is a conventional measure of mean TSI at a distance of 1 AU[2]. It is measured as being 1.361 kW/m^2 at solar minimum and approximately 0.1% greater at solar maximum.

The intrinsic solar cycle variability of TSI is of the order of one-tenth of a percent in the visible portion of the spectrum (VIS, $400-700$ nm). The amount of radiation decreases in the middle ultraviolet spectrum (MUV, $200-300$ nm) while the variability increases by an order of magnitude to a few percent of TSI. In the far ultraviolet (FUV, $120-200$ nm) and extreme ultraviolet (EUV, $30-120$ nm) ranges, the amount of radiation decreases further, while the solar cycle variability continues to increase, with the magnitude of the variation approaching a factor of two (e.g. for the hydrogen Lyman-α emission at 121.6 nm), and an order of magnitude for the high-temperature coronal lines. Solar radiation shortward of 200 nm has a spectrum consisting of emission lines superimposed on a rapidly declining continuum. The emission lines arise in higher temperature layers of the outer solar

[2]The astronomical unit (AU), a length unit equal to the mean distance from the Sun to the Earth, approximately 1.5×10^9 km.

atmosphere under non-local thermal equilibrium conditions and are strongly related to the magnetic activity of the Sun. The X-ray ultraviolet (XUV, 1 – 30 nm) region is dominated completely by emission lines of primarily coronal origin that may vary by an order of magnitude during an 11-year solar cycle. Short-term irradiance variations, lasting from minutes to hours, occur during eruptive events on the Sun. Intermediate term variations, modulated by the 27-day rotation period of the Sun, are related to the appearance and disappearance of active regions on the solar disk. Solar UV measurements are only possible above the atmosphere and the long-term variations in the XUV and EUV ranges had been poorly determined before 2002 due to the lack of adequate long-term measurements (Woods et al. 2005). As will be presented further in Section 3.3.1 the solar UV radiation sources are used as proxies for the composite model of photoionization rates inside the heliosphere and its variation with the solar cycle.

2.2 The solar wind

The solar wind is a stream of plasma from the solar corona, continuously blowing out into interplanetary space. This solar plasma flow interacts with the bodies of the solar system (planets, moons, comets). In the case when the bodies are magnetized, like the Earth, the interaction results in the formation of a magnetosphere with a discontinuous boundary, a magnetopause, which separates the solar wind plasma and the region dominated by the planetary magnetic field. In the case of comets, the solar wind is the factor that forms the cometary tails. The solar wind is also partially responsible for the creation of the heliosphere in the LISM (see Section 2.4). The solar wind is composed of charged particles, mainly protons (ionized hydrogen), electrons, fully ionized helium (i.e., alpha particles, $\sim 4\%$), and trace amounts of highly charged ions of heavy atoms like C, N, O, Ne, Mg, Si, S, and Fe (e.g. von Steiger et al. 2000; Kasper et al. 2012).

The solar corona is so hot that the matter inside it cannot be held by the solar gravity force nor confined by the pressure of the interstellar medium and, in consequence, it flows outward. There are two commonly known descriptions of the solar wind outflow, the fluid model and the kinetic model. The first one was postulated by Parker (1958) (see also Section 2.3) and next developed by, e.g., Weber & Davis (1967, 1970) and Grzędzielski (1968, 1969b,a). The kinetic model was developed by Chamberlain (1960), and next explored by, e.g., Lemaire & Scherer (1971), who also give a brief summarize of the kinetic models. In the fluid theory, the solar wind is assumed to be a flow of plasma. This description requires that the medium is close to the local thermodynamic equilibrium to assume the heat transport, however it is not the case in the outer solar atmosphere. Parker assumed a uniform temperature and infinite heat conductivity, however this requires an additional energy for the fast solar wind. In contrast, the kinetic theory considers particles instead of fluids and the heat flux is calculated without approximations, as it is done in the fluid model. In the kinetic model, the solar wind is described as an evaporation of a hot atmosphere in the near vacuum of the interstellar medium. Due to different thermal speeds of electrons and protons, a separation of charges is created, which produces an outward electric force acting on the protons. This force outweighs the gravitation force and produces a supersonic wind (Meyer-Vernet 2007). Although the kinetic description has an advantage of enabling to calculate the heat flux and to address non-equilibrium plasmas, it was disregarded due to too small value of the electric field, which produces only a slow breeze. Currently, the description of the solar wind origin requires a complex study to correctly account for the still not fully resolved questions about the solar corona heating and the solar wind acceleration.

The solar wind originates from a quiescent region of the solar atmosphere and is accelerated to supersonic speeds in the solar corona. Most of the dynamics of the solar wind is determined by the magnetic field in the solar corona. The solar atmosphere is trapped in the closed magnetic field lines, but when the lines are open and stretch out into the space, like in the coronal holes, the plasma from the solar atmosphere flows out. These regions together with several other phenomena are the sources of the solar wind (Baumjohann & Treumann 1996). In general, the solar wind is a mixture of the ubiquitous slow streams, fast streams from coronal holes, plasma flows in the stream-stream interaction regions, corotating interaction regions (CIRs), interplanetary coronal mass ejections (CMEs), magnetic clouds, rariefied regions, etc (e.g., Yermolaev et al. 2009).

The source of the so-called slow wind ($\sim 450\ \mathrm{km\,s^{-1}}$, $\sim 10\ \mathrm{cm^{-3}}$ at 1 AU) is still under investigation. The slow streams are associated with the heliospheric current sheet and with streamers at low latitudes during solar minimum. They may also arise from the boundary of the coronal holes (e.g., Wang & Sheeley 1990; Panasenco & Velli 2013; Owens et al. 2014; Zhao et al. 2014). In contrast, the so-called fast solar wind ($\geq 750\ \mathrm{km\,s^{-1}}$, $\leq 5\ \mathrm{cm^{-3}}$ at 1 AU) is commonly accepted to come from the coronal holes. However, the streams at high latitudes from polar coronal holes are faster than the streams from the coronal holes at the lower latitudes (e.g., McComas et al. 2002; Elliott et al. 2012; Rotter et al. 2012; Zhao & Landi 2014). The study of the composition, abundances, and charge state ratios of heavy ions in the solar corona (like, e.g., Mg/O, Fe/O, O^{7+}/O^{6+}, C^{6+}/C^{5+}) is a useful tool to study the properties, evolution, and source of the solar wind (e.g., von Steiger & Geiss 1993; von Steiger et al. 2000; Wimmer-Schweingruber 2002; Kasper et al. 2012).

The distribution of the solar wind slow and fast streams at the solar surface is a function of heliolatitude and evolves with the cycle of solar activity. The evolution of the solar wind structure with the solar cycle will be further discussed in Sections 2.3, 3.1, and 3.2.

2.3 A short history of investigation of the solar wind

The beginning of the humankind interest in the solar wind and its effect on the Earth's atmosphere, known today as space weather, can be placed in the 19th century, when R. Carrington connected the observed solar flare and an aurora that came in a few days afterward (Meyer-Vernet 2007). The first years of the 20th century brought studies of A. Eddington, who hypothesized that the material ejected from comets consists of charged particles, and of K. Birkeland and F. Lindemann, who reported that the Sun emits two kinds of charged particles. The 1930-ties observations of the solar corona during eclipse precipitated to a presumption that the solar corona has a temperature of a million degree Celsius. In 1951 L. Biermann, based on observation of comets, noticed that their tails always point away from the Sun, and in 1955 S. Chapman postulated that if the solar corona is so hot, it has to extend away from the Sun. In the first years of 1950-ties A. Hewish reported about the scintillations in the radio waves (1951) and next about the irregularities in the outer regions of the solar corona (1955). In the next years, P. Morrison, among others, postulated a need of a cavity around the Sun in the interstellar medium to explain the observations of cosmic rays (the postulated cavity was subsequently recognized as the heliosphere). Finally, in 1958 E. Parker, in a paper regarded as the solar wind theoretical discovery paper, joined Chapman's and Biermann's theories with the cosmic ray observations and predicted theoretically the existence of the solar wind as the outward flux of the expanding solar corona (Parker 1958). In January 1959 a Soviet spacecraft Luna 1 registered the corpuscular radiation of the solar origin, which next was confirmed by two other spacecraft, launched in September (Luna 2) and October (Luna 3) of the same year (Gringauz et al. 1960). In 1961, the next Soviet space probe to Venus, Venera 1, registered the signal from the solar wind, and finally with the measurements of the US Mariner 2 mission, the solar wind was believed to exist (Neugebauer & Snyder 1962).

After the in-situ confirmation of the existence of the solar wind its exploration, both theoretical and experimental, speeded up. In the meantime, A. Hewish developed a study of radio observations and in 1964 reported the discovery of the interplanetary scintillation phenomenon (Hewish et al. 1964), and just in 1967, together with P. A. Dennison, announced that IPS from compact radio sources can give an estimate of the solar wind speed outside the plane of the ecliptic (Dennison & Hewish 1967). The era of remote-sensing investigation of the heliolatitudinal structure of the solar wind has began. In the 1970-ties and 1980-ties the ground-based observations of the solar wind through the IPS were highly developed and advanced. In consequence, the fast solar wind from the polar regions was discovered together with its solar cycle related changes (e.g. Kakinuma 1977; Coles et al. 1980). On 6 October 1990 the Ulysses mission (e.g., Wenzel et al. 1989) was launched to study the Sun's atmosphere outflow as a function of solar latitude, which begun in June 1994 and lasted to June 2009. Up to now, Ulysses is the sole mission in the humankind on the solar polar orbit.

Currently, with almost 60 years of solar wind direct and indirect investigation, we know that the solar wind structure in latitude varies in time with the cycle of solar activity. It is almost uniform during the solar maximum, with ubiquitous slow and dense streams, with intermittent flow of very fast wind emerging from abrupt phenomena at solar surface. During the solar minimum, the slow and dense solar wind is shrunk to a narrow band around the solar equator and the fast and rare streams dominate the mid and high latitudes. During the ascending and descending phases of the solar cycle the slow wind band expands and contracts, respectively. Additionally, during the last 20 years the solar wind flux showed a secular drop. The discussion of the evolution of the heliolatitudinal solar wind structure with the solar activity over almost the three last solar cycles is presented in Paper S2, with a comprehensive illustration in Figures 7 and 11 therein. The discussion of the secular decrease of the solar wind flux in the in-ecliptic measurements is presented in Paper S1 and is illustrated in Figures 1, 2, and 3 there; a similar discussion is also present in Paper B1.

The beginning of 1970-ties also brought the first sky maps of the background Lyman-α flux (Thomas & Krassa 1971; Bertaux & Blamont 1971) caused by the solar hydrogen Lyman-α line at 121.6 nm (Blamont & Vidal-Madjar 1971) and the observations of the sky glow in the solar He 58.4 nm line (Paresce et al. 1974; Weller & Meier 1974). As a source of both of them was suggested the ISN gas which enter inside the heliosphere and which resonantly scatters the photons of solar origin and produces the observed glow (Fahr 1968; Blum & Fahr 1969, 1970; Fahr 1974). The observations revealed an anisotropic distribution in the sky, which connected with the mechanism of glow production due to the solar radiation flux brought in the coming years to conclusion about the latitudinal asymmetries in the solar wind flux, as theoretically postulated by Suess & Nerney (1973); Nerney & Suess (1975). A new tool for indirect investigation of the solar wind and its latitudinal structure was established and successfully used (e.g. Joselyn & Holzer 1975; Lallement et al. 1985). In 1996 a *SOlar and Heliospheric Observatory* (SOHO) mission was launched in L1 point[3] (e.g. Lo Galbo & Bouffard 1992), with the *Solar Wind ANisotropies* (SWAN) instrument onboard to study the anisotropies in the latitudinal distribution of the solar wind with the use of the Lyman-α backscatter glow (Bertaux et al. 1995). More about the ISN H helioglow is presented in Sections 3.1.3 and the history of the study of the heliospheric glow and its use to investigate the solar wind can be found in Section *Historical Perspective: Insight from Heliospheric Backscatter Glow* in Paper B1.

In addition to the remote methods for solar wind investigation, i.e., the observations of interplanetary scintillation (Section 3.1.4) and the observations of the Lyman-α helioglow (Section 3.1.3), there are also attempts to retrieve the information about the solar wind from the white light solar corona images, Thomson scattering, the observations of the cometary tails, and interpretation of the EUV images of the Sun (especially to study the fine scale phenomena like CMEs, CIRs, etc.), but they are out of our interest for the needs of the study. Firstly, this is because we were interested in a long time series of data (on the time scale of the order of solar cycle) and in the global solar wind properties. Secondly, because we have tried to select those indirect data sources from which the retrieved solar wind data were as little model dependent as possible. We also do not discuss the retrieval of solar wind information from the investigation of cometary tails because comets are too intermittent and their distribution around the Sun is too sparse to continuously and completely study the solar wind structure.

2.4 The heliosphere

The interstellar medium (ISM) in the Milky Way consists of 99% gas, neutral and ionized, and of 1% dust. It is composed of $\sim$ 70% hydrogen, $\sim$ 28% helium, and $\sim$ 2% other elements by mass and is permeated by the magnetic field. It is filled with remnants of explosions of stars like novae or supernovae. Some of the stars that were born in this medium are surrounded by cavities, the astrospheres, created by interaction of the stellar wind that expands away from the parent star, with the surrounding interstellar matter. The Sun's astrosphere is called the heliosphere (after *helios*, which in the ancient Greek means Sun). The heliosphere is inflated by the supersonic solar wind and embedded interplanetary magnetic field. The Sun moves with respect to the local ISM at $\sim 25\ \mathrm{km\,s^{-1}}$and the interaction of the magnetized solar wind with the magnetized interstellar matter produces an asymmetric structure of the heliosphere, with the compressed front part (the "nose") and a stretched out long "heliotail" at

[3]The Lagrangian point or libration point; a position in an orbital configuration of two bodies where a small object affected only by gravity can maintain a stable position relative to the two bodies.

the opposite side.

The interaction of the interstellar and solar wind plasmas leads to the creation of three distinct interstellar boundaries at the edge of the heliosphere. The first boundary on the inside is the termination shock which forms at about 90 AU, where the supersonic solar wind slows to subsonic speed, heats, and begins to divert away from the inflowing LISM. The heliopause, located at about 120 AU, is the next boundary. It separates the slowed solar wind plasma from the ionized LISM material. The region between the termination shock and the heliopause is called the inner heliosheath. It is a region where the solar plasma finally turns the flow direction. In the inner heliosheath the slowed and heated solar wind and the imbedded hydrogen PUIs react by charge exchange with local interstellar atoms and produce ENAs. Significant portion of these ENAs move inward and can be detected by detectors in the close vicinity of the Sun. The last boundary of the heliosphere is the bow shock or bow wave (depending on the not fully resolved plasma state there), which separates the region of the unperturbed LISM plasma from the region where the interstellar plasma begins to divert around the heliosphere. The region between the heliopause and the bow shock/wave, known as the outer heliosheath, is a region where the secondary component of the ISN gas is expect to be created.

The interstellar plasma is rare and the magnetic field strength is the dominant source of force acting on the ions. Thus the motion of the ionized component of ISM is governed by the magnetic and electric fields. The neutral component of the ISM is insensitive to the magnetic field and can freely enter the heliosphere. The sampling of the ISN gas at close distances to the Sun brings information about the physical properties of the interstellar matter surrounding the Sun. The neutral atoms also resonantly scatter the solar radiation, producing a sky background radiation in the hydrogen 121.6 nm and helium 58.4 nm lines which enables to study the distribution of H and He in the heliosphere, respectively. The distribution of ISN H has the dominant role in the solar wind interaction with the LISM, because it is the most abundant species. The ISN H however, may experience some filtration at the heliospheric boundaries, being decelerated and heated when passing from the LISM into the heliosphere. For the remaining species, like He and heavy species, this interaction in almost negligible, and thus they can provide information about the conditions in the pristine LISM.

The distribution of the ISN gas from the LISM inside the heliosphere can be calculated with the use of the Boltzmann equation (e.g., Equation 3.1 in Paper B1) for the particle distribution function dependent on position, velocity, and time. The force acting on particle is the gravity and, in the case of hydrogen, the radiation pressure. The loss term on the right-hand side of the equation is due to ionization along the particle trajectory. Typically, the distribution function for the ISN gas in LISM is the Maxwell-Boltzmann distribution with the assumed bulk velocity vector and temperature of the gas "at infinity". In the case when the thermal speed of the atom is assumed to be much less than its bulk flow speed relative to the Sun, the gas distribution is called a cold model of gas distribution, which fundamentals were given by Fahr (1968); Blum & Fahr (1970); Holzer (1970); Holzer & Axford (1970, 1971); Axford (1972). Under the assumption of a spherically symmetric and steady solar wind and solar radiation field the ISN H population is strongly depleted within $\sim 6-10$ AU producing a region called the ionization cavity.

The model of a cold ISN gas distribution provides considerable insight in the gas distribution inside the heliosphere, however it is not completely adequate, because the thermal and bulk flow speeds of atoms in the LISM are comparable. Additionally, the LISM temperature is needed for the interpretation of the heliospheric observations. In consequence, the cold model was extended by, e.g, Fahr (1971); Thomas & Krassa (1971); Fahr (1979); Wu & Judge (1979); Thomas (1978). In the model of hot distribution the source distribution function is assumed to be a Maxwellian. The particle trajectories are obtained by solving the Kepler's equation. The number density, velocity, and temperature for the hot distribution can be obtained by taking appropriate moments of the distribution function with the term for the losses taken into account (e.g., Equation 3 in Paper S4). The hot model for the ISN H gas distribution in the heliosphere leads to the following conclusions (after Zank 1999): the calculated neutral radial velocity distribution at 1 AU is very well fitted by a Maxwellian distribution for a variety of directions; an asymmetry in the heliospheric neutral temperature gradient is predicted (for upwind directions, the H temperature decreases with decreasing heliocentric distance, whereas the opposite is true for the downwind direction), the ionization cavity is evident within $6 - 10$ AU in the density distribution and the cavity is elongated in the downstream direction.

Both classical cold and hot models of the ISN gas distribution in the heliosphere assume that the radiation pressure and ionization losses are constant in time. For large distance from the Sun the time variations are negligible, as the gravity force and the solar radiation flux decrease with the squared distance, however at small distances ($\sim 10\ AU$ upstream and $\sim 40 - 50$ AU downstream) the time variation of radiation pressure and ionization rates can significantly affect the distribution of the ISN gas and the ionization cavity, which extends during solar minimum and shrinks during solar maximum. The model of the gas distribution which takes into account the solar cycle variability was developed by Ruciński (1985); Fahr et al. (1987); Ruciński & Bzowski (1995). The description of the model of gas distribution that we use in our studies is presented in Section 2 in Paper S4 and in Section *Brief Description of the Physics of the Neutral Interstellar Gas in the Inner Heliosphere* in Paper B1.

The interplanetary medium is filled with the supersonic solar wind plasma and solar EUV radiation. These two significantly affect the distribution of the particles. There are three ionization processes that are the most important in the study of the losses for the ISN gas and ENAs inside the heliosphere: (1) charge exchange with the solar wind particles, mostly protons and alpha particles; (2) ionization by solar EUV radiation; and (3) ionization by impact of solar wind electrons. Their intensities are species-dependent and all three vary with solar cycle. We discuss them briefly in Section 3.3. As a result of ionization of the particles inside the heliosphere new populations of charged particles are created, which respond almost instantaneously to the electromagnetic fields of the solar wind. They gyrate about the interplanetary magnetic field (IMF) in the solar wind frame of reference and they experience scattering and isotropization by either ambient or self-generated low-frequency electromagnetic fluctuations in the solar wind plasma. Since the newly born ions are eventually isotropized, their bulk velocity is that of the solar wind, i.e., they convect with the solar wind flow, and are said to be picked-up by the solar wind. The isotropized PUIs, which originate from the ISM, form a distinct population of energetic ions (~ 1 keV energies) in the solar wind (Zank 1999). The newly created PUIs can drive a host of plasma instabilities in the heliosphere. The evolution of PUI distribution is determined by a number of processes, like primarily pitch angle scattering and energy diffusion in the wave field, convection and adiabatic deceleration in the expanding solar wind, and the injection of newly ionized particles. The evolution of PUI distribution was first developed by Vasyliunas & Siscoe (1976), but in the absence of energy diffusion, which was next included by Isenberg (1987).

The neutral component of heliospheric particles can be ionized by the heated and slowed down solar wind plasma in the inner heliosheath or by charge exchange with the ionized matter in the outer heliosheath and the product of ionization are the energetic neutral atoms, ENAs. If such a newly created ENA has a velocity vector pointed towards the Sun, it can be detected in the vicinity of the Sun. The two populations of particles, ENAs and PUIs, can enter subsequent ionization reaction inside the heliosphere, creating next populations of particles. The effectiveness of the creation reaction depends on the velocity distribution of the particle population and the intensity of the ionization. Direct observation of outer-heliosphere ENAs in the vicinity of Earth has been carried out by IBEX since 2009 McComas et al. (2009a, more in the next Section 2.5).

The study of ISN gas and ENAs as well as PUIs from the Earth's orbit enables to remotely investigate the processes at the edge of the heliosphere and its interaction with the surrounding interstellar medium. A review by Zank (1999) gives an insight into the solar wind interaction with the LISM. A comprehensive reviews by Gruntman (1997) and Fahr et al. (2007) present the significance of ENAs for the heliosphere and interstellar medium study. Möbius et al. (2004) and Bzowski et al. (2009) give a review about the investigation of the ISN He and H gas inside the heliosphere, respectively, and Möbius (1986, 1996) about the possibilities of PUI investigation for the study of the ISN gas.

2.5 IBEX

The *Interstellar Boundary Explorer* (IBEX) is a NASA mission of the Small Explorers series (McComas et al. 2009b). Its main scientific goal is to explore the global interaction between the solar wind and the interstellar medium. IBEX was launched on 19 October 2008 and started to collect scientific data at the end of December 2008. IBEX is a spin-stabilized spacecraft, with a rotation rate of ~ 4 rpm. Its spin axis is maintained towards the Sun within few degrees. It was launched in a highly elliptical Earth orbit with the apogee at ~ 50 R_E (R_E is the Earth radius). For the first two and a half years of operation the orbital period of IBEX was ~ 7.5 days, with the spin axis repointed once each orbit around the perigee. In June 2011 the spacecraft was maneuvered to a long-term stable lunar synchronous orbit with the apogee still ~ 50 R_E but with the perigee raised from ~ 2.5 to ~ 8 R_E, which put IBEX above the outer radiation belts (McComas et al. 2011). On the new orbit, the orbital period is ~ 9.1 days, and the spin axis is repointed twice per orbit, near the perigee and the apogee, which divides the orbit into two arcs. The heliospheric observations are conducted when the spacecraft is above 15 R_E to avoid the significant foreground to the signal from the magnetosphere (Funsten et al. 2009).

IBEX has two highly sensitive ENA cameras: IBEX-Lo (Fuselier et al. 2009) and IBEX-Hi (Funsten et al. 2009), which measure ENAs in the ranges of ~ 10 – 2000 eV and ~ 300 – 6000 eV, respectively. IBEX-Lo has eight and IBEX-Hi six partially overlapping energy channels from ~ 300 eV to

2000 eV. The energy range of the IBEX detectors is optimized to globally image ENAs from the outer heliosphere and thus to investigate the interaction of the solar wind with the LISM. The detectors view in the plane perpendicular to the spacecraft spin axis, and during each spin of the spacecraft data are collected from a fixed circle in the sky with an angular resolution of $\sim 6.5^\circ \times 6.5^\circ$. During one full orbit, and after the orbit change during one orbital arc, a one $\sim 6.5^\circ$ swath in the sky is completed, so that in 6 months the full sky is covered. The resulting six-months all-sky map consists of two hemispheres, the so-called ram hemisphere, created from the part of the swaths where the detector points toward the direction of the velocity vector of the spacecraft, and the so-called anti-ram hemisphere, created from the part of the swaths where the detector looks in the opposite direction than the velocity vector of the spacecraft. To obtain the full-sky ram or anti-ram map, data collected over a complete Earth's orbit around the Sun are needed. In addition to H ENAs, IBEX-Lo also measures interstellar neutral atoms of He, H, Ne, O, and D (e.g. Möbius et al. 2009; Bochsler et al. 2012; Rodríguez Moreno et al. 2013) and the secondary population of the ISN He, the Warm Breeze (Kubiak et al. 2014; Kubiak et al. 2016).

The detailed description of the IBEX-Hi and IBEX-Lo sensors is given in Funsten et al. (2009) and Fuselier et al. (2009), respectively, and here we present only a brief outline of these instruments. The IBEX-Hi and IBEX-Lo sensors have almost identical collimators which define the instantaneous field of view (FOV) of the sensors and are maintained at a high positive voltage of 10 kV to keep energetic positive ions (up to 10 keV) out of the sensor. The annular diameter of the IBEX-Lo collimator is smaller and has two separate parts, one with a high angular resolution FOV ($\sim 3.5^\circ \times 3.5^\circ$), which takes one 90° azimuthal quadrant, and the other one with low angular resolution FOV ($\sim 7^\circ \times 7^\circ$) which is constructed of three 90° azimuthal quadrants. The high resolution FOV was planned to be used to measure ISN O in the springtime. The full sensor (combined high and low resolution FOVs) is used for H ENA measurements throughout the year and for measurements of ISN O in the fall (Fuselier et al. 2009).

The IBEX-Lo sensor has four subsystems. The entrance subsystem includes the annular collimator that collimates neutrals to the angular resolution sectors. The ISN gas atoms and ENAs that pass through the collimator are converted to negative ions in the conversion subsystem. The conversion subsystem includes a diamond-like carbon high yield conversion surface which is inclined at 15° to the sensor boresight. Subsequently, the negative ions are accelerated into an electrostatic analyzer (ESA), where the energy range is defined. The ions outside the energy range of a given pre-set energy channel are excluded. Finally, the negative ions exit the ESA and are post-accelerated to 16 kV (after mid 2012 to 7 kV), and then are further accelerated into a multiple carbon foil, triple-coincidence time-of-flight (TOF) mass spectrometer that measures the ion mass/charge ratio. The TOF subsystem effectively rejects random background while maintaining a high detection efficiency for negative ions. Mass analysis distinguishes the heliospheric-origin signal from interstellar-origin signal.

The triple coincidence TOF spectrometer determines the mass of the incoming neutral atoms directly for species that are turned into negative ions at the conversion surface, e.g., H, D, and O. Whereas noble gases, e.g. He and Ne, do not produce stable negative ions for detection (Smirnov 1982), they are detectable through negative ions of H, C, and O sputtered from the conversion surface

(Wurz et al. 2008). The IBEX-Lo sensor was designed and calibrated for the response to He and Ne flux which is inferred from the observed ratios of sputtered H, C, and O (Möbius et al. 2009; Bochsler et al. 2012; Möbius et al. 2012; Rodríguez Moreno et al. 2013; Park et al. 2014). The sputtered H and O atoms come from the conversion surface, which is permanently covered with a thin layer of terrestrial water, originating from the outgassing of the sensor.

The IBEX-Hi sensor is dedicated to measurements of H ENA and has a FOV of $\sim 6.5^\circ \times 6.5^\circ$ FWHM[4]. It utilizes an ultrathin carbon foil to ionize ENAs in order to measure their energy by subsequent electrostatic analysis. A multiple coincidence detection scheme using channel electron multiplier (CEM) detectors enables reliable detection of ENAs in the presence of substantial noise. In the IBEX-Hi sensor, ENAs are ionized by transmission through an ultrathin charge-stripping foil which provides a high ionization probability. In the IBEX-Lo sensor, which measures the low energy range of ENAs, the higher ionization probability is enabled by atomic reflection from the diamond-like carbon surface (Funsten et al. 2009). The IBEX-Hi sensor was designed and developed to maximize the sensitivity to ENAs and minimize the noise and backgrounds. The sensor is divided into four subsystems that are sequentially traversed by the ENAs. After going through the collimator, the ENA then encounters the charge conversion subsystem that positively ionizes a fraction of the ENAs that transit a foil. The ionized ENAs then enter the electrostatic energy analysis subsystem, which consists of nested toroidal analyzer plates, each with arrays of collinear hexagonal, photoetched apertures, that project the large entrance aperture onto a small detector subsystem. The bias of the inner electrostatic energy analyzer plate sets the energy passband for the ionized ENAs to enter the detector subsystem. ENAs entering the detector subsystem are accelerated by a bias of -6 kV for increased detection efficiency. The detector subsystem consists of three stacked cylindrical chambers, with each chamber separated by an ultrathin carbon foil. Each chamber has a CEM detector that detects secondary electrons generated by the interaction of the ENA with a foil or an interior wall of a chamber. An ionized ENA can transit all three chambers and register a pulse in multiple detectors, generating a double or triple coincidence event. The valid measurements are determined by the analysis of the coincidence combinations.

The measuring technique used in both sensors results in the energy width of the energy channels $\Delta E/E \simeq 0.7$. Thus, the flux measured includes the ENAs with substantially different energies. The collimator selects the incoming atoms directly, but still the directions of the incoming atoms within a given pixel in the sky may differ up to 15° (from end to end). These facts must be appropriately taken into account when calculating the effective survival probability for a given pixel and energy channel.

[4] full width at half maximum

3 Model of solar ionization factors

In the presented study we are interested in the neutral LISM component that entered unperturbed into the heliosphere and its derivative populations, like ENAs and PUIs. We pay a special attention to the modulation of the ISN gas, ENA, and PUIs inside the heliosphere due to the solar cycle variability. The solar wind and the solar EUV radiation are the most interesting components of the solar output from our point of view. These two significantly modify the flux of the ISN gas and ENAs from the outer heliosphere on the way from the heliospheric boundaries to the vicinity of the Sun. The modification manifests as losses due to ionization by solar wind particles or solar radiation. The magnitude of modification depends on the species and the kinematic parameters of the flow and vary with the phase of the solar activity because the solar corpuscular and electromagnetic radiation varies with the solar cycle. The topic of the ionization processes inside the heliosphere is discussed mainly in two papers that construct PhD thesis: Paper B1 and Paper B2. In the first one, a review on the ionization losses for ISN H is presented, in the second one, the ionization processes relevant for ISN He, Ne, and O are discussed, with additional results presented in Bochsler et al. (2014) and Sokół & Bzowski (2014).

3.1 In-situ and remote-sensing sampling of the solar wind

The solar wind can be investigated directly by detectors launched into the interplanetary space and by indirect methods, which are very helpful in a case when continuous in-situ information about the out-of-ecliptic structure of the solar wind is missing. There are two kinds of remote observations which can provide information on the global structure of the solar wind. The first (and probably the oldest one) is the observation of interplanetary scintillations, which has been used for extensive studies of the solar wind since the 1970-ties. The second method is the investigation of the heliospheric Lyman-α glow. Unfortunately, despite the advantage of sampling the solar wind out of the ecliptic plane, observations from both methods are line-of-sight (LOS) integrated, and an appropriate deconvolution of the signal is required.

3.1.1 OMNI database

The in-ecliptic solar wind has been monitored almost continuously at a $\sim$ 1 AU distance from the Sun since the beginning of the space age. The observations have been conducted by various missions from different orbits, using various instruments, various techniques, and over varying time ranges. For our study, the most relevant would be a long, homogeneous, and continuous time series with all the data sources commonly cross-calibrated and adjusted. Such a data collection is maintained and released for the public by Space Physics Data Facility in Goddard Space Flight Center. It is known as the OMNI database (King & Papitashvili 2005). A brief summary of the OMNI database is presented in Section *Evolution of Solar Wind in the Ecliptic Plane* in Paper B1 and Section 2.1 in Paper S1.

Since 1960-ties there have been numerous missions that were either dedicated to or supported the solar wind measurements. The OMNI database collects solar wind measurements performed from 1963 and is available through `http://omniweb.gsfc.nasa.gov/`. The data come from multiple spacecraft (about 11 various missions are used) and before publication are extensively cross-compared and cross-normalized to a common calibration. The data sources are prioritized, with data from the Wind and *Advanced Composition Explorer* (ACE) spacecraft being the primary source since mid 1990-ties. The process of creation of this database is extensively described by King & Papitashvili (2005) and at the OMNI database website. Some of the spacecraft have been operating from the geocentric orbit (like, e.g., the *Interplanetary Monitoring Platform*; IMP) and some from an orbit around the L1 point (e.g., ACE). The OMNI collection is intended to gather only the solar wind data, thus extraction of an appropriate portion of the orbits, when the detectors are free from non-solar wind contamination (e.g., magnetosphere), is carefully performed. The collection includes a high time resolution data adjusted at the front of the Earth's bow shock, therefore, prior to taking hourly averages, the time-shifts of higher resolution data (it is of about minute) to the expected magnetosphere-arrival times are done for data from the spacecraft in L1 orbits, like the *International Sun-Earth Explorer* (ISEE 3), Wind, ACE. The shift in time is performed with the assumption that the solar wind variation phase fronts are planar on arbitrarily large extent normal to the Sun-Earth line and normal to the ecliptic, and that they merely convect outward with the solar wind flow, assumed to be radial.

Because the collection is a compilation of data from various missions, there are random and systematic differences between high resolution data obtained by different spacecraft, which have to be inter-compared and normalized. The random differences may be due to many reasons, for example, the measurements may have differently distributed gaps in time or there may be time shifts due to different locations in space. Among these reasons for systematic differences are also the different processing approaches (e.g., derivation of the flow parameters from fits either to measured ion distribution functions or to their moments) and the calibration factors not accounted for in the initial data processing. Before release of the OMNI collection, an in-depth compensation for the differences between pairs of sources is performed in order to make the OMNI data a reliable representation of the near Earth solar wind.

There are typically two kinds of techniques to measure the solar wind parameters. One uses the Faraday Cup ion detector, as in the case of the Massachusetts Institute of Technology (MIT) *Solar Wind Experiment* (SWE) instrument onboard Wind, which provides measurements of the solar wind protons and alpha particles at energy/charge range from 150 V up to 8 kV (Ogilvie et al. 1995). The other uses the electrostatic analyzer similarly as for the Los Alamos National Laboratory (LANL) *Solar Wind Electron, Proton, and Alpha Monitor* (SWEPAM) onboard ACE (McComas et al. 1998), which provide measurements of electron and ion fluxes in the low-energy solar wind range (electrons: 1 to 1240 eV; ions: 0.26 to 35 keV). ACE/SWE is a modified version of the spare instrument of the BAM-E and BAM-I detectors that construct the *Solar Wind Observations Over the Poles of the Sun* (SWOOPS) experiment onboard Ulysses, which handle observations at the energy/charge from 1 to 900 eV for electrons and from 257 eV to 35 keV for solar wind ions (Bame et al. 1992).

The solar wind parameters included in the OMNI database are determined by taking moments over the measured distribution functions (e.g., ACE/SWEPAM, McComas et al. 1998) or are determined by making nonlinear fits of the convecting Maxwellian distribution functions (anisotropic bi-Maxwellians) to the observed distributions (Wind/SWE Kasper 2002; Kasper et al. 2006). OMNI involves the interspersion of moments-based parameters with fits-based parameters, for which the differences are subsequently partly compensated for by the cross-normalization of the multi-source data. The cross-normalization between the multi-source data was performed with the use of the scatter plot and regression fit interface and was done for several runs to minimize the sums of squares of perpendicular distances between data points and the best fit line (the least-square method). The linear and logarithmic[5] regressions were used, depending on the parameters.

It is important to note that among all highly advanced corrections and data cleaning made in the data sets that construct the OMNI database, one is left out. The solar wind densities are expected to decrease with the squared heliocentric distance on average. The L1 libration point at ~ 200 Earth's radii from Earth is close to 0.99 AU from the Sun. This means that the density of a plasma element measured at L1 should be decreased by ~ 2% when it reaches the Earth's magnetosphere at ~ 1.00 AU. The OMNI data do not account for this correction, because it was found that the density differences in comparing sources are typically greater than 2% (King & Papitashvili 2005, also `http://omniweb.gsfc.nasa.gov/html/ow_data.html`, `http://omniweb.gsfc.nasa.gov/-html/omni2_doc_old.html`). The accuracy of solar wind parameters available in the OMNI data collection varies with the priority data source and depends on the accuracy of the measurement, and thus it can vary from few to tens of percent. As an example, the uncertainty in the SWE proton density was estimated as 2%, whereas at low speed, the SWE and SWEPAM densities are virtually the same, while at high speed, the density from Wind is only ~ 82% of the density from ACE. And the SWE densities are less than IMP densities by varying extent, up to 15 − 20%, except for the slow flows ($< 350\ \mathrm{km\,s^{-1}}$), for which the SWE densities exceed the IMP densities by ~ 10%. However, as already mentioned, these systematic differences are eliminated in the process of cross-calibration of the input data sets from individual instruments.

In consequence, we chose the OMNI database of in-ecliptic measurements as the most relevant for the needs of our study of the modulation of ionization factors inside the heliosphere.

3.1.2 Ulysses

The solar wind out of the ecliptic plane from high and polar latitudes was measured in-situ only by Ulysses. The mission operated from 1990 to 2009 (e.g., Bame et al. 1992; McComas et al. 2000b,a). In addition, there were also sparse measurements within ~ ±30° off the ecliptic plane by Voyager 2 and Pioneer 10/11, but they are short time series and are not enough to sample the global structure of the solar wind over a long time period. Ulysses data are point measurements, and they involve a convolution of time, distance, and latitude variability. The polar orbit of Ulysses had two phases, so-called fast and slow scans. In the fast scans, the spacecraft moved from the south to the north pole through perihelion (~ 1.4 − 2.2 AU), which took about 1 year. In the slow scans, the spacecraft moved away from the Sun to aphelion at ~ 5.2 AU, sampling the north hemisphere, and subsequently returning close to the Sun, sampling the south hemisphere; the whole slow scan lasted about 5 years. Two of the fast scans (the first, in 1995, and third, in 2007/2008) were during very low solar activity

[5]linear regressions of logarithms of parameters

and one (in 2001) was during the solar maximum. Figure 4 in Paper S1 (also Figure 3.16 in Paper B1) illustrates the orbit of Ulysses as a function of time, heliolatitude, and phase of the solar activity. Ulysses ultimately confirmed the existence of the fast solar wind flow from the polar regions which was initially noticed through the IPS observations. Figure 8 in Paper S1 (the same also in Figure 3.18 in Paper B1) illustrates the latitudinal profiles of the solar wind speed measured by Ulysses during the fast scans compared with the solar wind speed retrieved from the IPS observations. Additionally, during the Ulysses mission a secular drop of the solar wind flux occurred mainly due to the global decrease of the solar wind density. The decrease in solar wind flux began in 1995, as evident in the in-ecliptic measurements presented in Figure 3 in Paper S1. The decrease stopped in 2008 at the level of $2 \times 10^{-8}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, which is on average a half less than before the change. Due to the fortunate circumstances, Ulysses did one solar minimum fast scan before, and one after these changes, thus it is possible to investigate how the change has affected the out-of-ecliptic structure of solar wind speed and density. Figure 6 in Paper S1 (the same in Figure 3.17 in Paper B1) presents the profiles of speed, density, and flux as a function of heliolatitude for all three fast scans, the secular change with a lower density and broader range of the slow solar wind around equator is clearly visible.

3.1.3 The ISN H helioglow

The hydrogen component of the ISN gas in the heliosphere is affected by solar gravity and Lyman-α radiation pressure force. It interacts with the medium of solar origin, which leads to modification of its distribution function. The solar Lyman-α photons are resonantly scattered on the ISN atoms and produce the heliospheric Lyman-α glow. This glow has been continuously observed by the SWAN instrument onboard SOHO spacecraft since 1996 (Bertaux et al. 1995, 1997). The SWAN experiment has been dedicated to study the latitudinal anisotropies in the solar wind flux and the boundaries of the heliosphere through the observations of the ISN H gas. The observations provide a full sky maps of the heliospheric Lyman-α backscatter radiation, and to interpret the data a deconvolution of the factors the form the signal is required. Thus, the study of the solar wind anisotropies via analysis of the Lyman-α back-scatter glow is a complex task. It requires a sophisticated model of the global heliosphere and of the distribution of the ISN H in front of and inside the heliosphere, as discussed by, e.g., Izmodenov et al. (2013), as well as advanced model of radiation transfer in the heliosphere (e.g., Quémerais & Bertaux 1993; Quémerais & Izmodenov 2002; Quémerais et al. 2008). Some attempts were performed in the past (Kyrölä et al. 1998; Bzowski et al. 2002, 2003), but they needed simplifying assumptions about the solar wind and ionization rates. The first results of the analysis of the SWAN observations were promising, but they also revealed many unexpected and unwanted features present in the data, like, e.g., non-solar background sources. Additionally, after the interruption of the communication with the spacecraft in 1998, a decrease in the sensors sensitivity was noticed.

Furthermore, the analysis of the full sky maps data is sensitive to the location of spacecraft on the Earth's orbit with respect to the gas flow, which leads to annual effects in the results, if only the ISN gas model and the radiation transfer model are not perfect. Thus the data analysis should be performed together with a careful modeling of both the distribution of ISN H gas in the heliosphere and the variation in time and latitude of the solar factors, like, e.g., the solar Lyman-α line. In consequence, the data interpretation requires an advance modeling similar to that developed by Izmodenov et al. (2013), Katushkina & Izmodenov (2011); Katushkina et al. (2015) and Fayock (2013); Fayock et al. (2013). The approach also requires an advanced computation facilities for calculations.

Additionally, the published analysis of SWAN data brings many unanswered questions. An example is the two peak structure of the ISN H ionization rates retrieved from the SWAN data, which is still unexplained and seems to not be physically justified (Figure 2 in Lallement et al. 2010), since such structure is not confirmed by the Ulysses in-situ observations (Figure 6 in Katushkina et al. 2013). The SWAN data are also publicly available in a form not straightforward to use and a development of the proper software is required to data analysis and a model to data interpretation. Thus, after a thorough consideration, we decided to not use the SWAN data in the development of our model. Nonetheless, in Paper B1, Section *Latitudinal Structure of the Solar Wind and Its Evolution During the Solar Cycle* a brief review of the methods to study the solar wind structure out-of-ecliptic with the use of SWAN data is presented.

3.1.4 Interplanetary scintillation observations

The observations of interplanetary scintillations have been used for extensive studies of the solar wind since 1970-ties. The main data source in Paper S1 and Paper S2 was the solar wind speed derived from the IPS observations conducted by the Solar Wind Group of Institute for Space-Earth Environmental Research (ISEE), formerly: Solar-Terrestrial Environment Laboratory (STEL), at Nagoya University in Japan (Tokumaru et al. 2010). IPS is a phenomenon of intensity fluctuation of the flux from compact radio sources (same as optical twinkling, but scaled to radio waves), discovered by A. Hewish in early 1960-ties, as mentioned in Section 2.3. Its connection with the solar wind parameters was quickly realized and has been explored ever since (e.g., Hewish et al. 1964; Houminer 1971; Coles & Maagoe 1972; Kakinuma 1977; Coles & Kaufman 1978; Coles et al. 1980; Kojima & Kakinuma 1990; Manoharan & Ananthakrishnan 1990; Jackson et al. 1997; Jackson et al. 1998; Jackson et al. 2003; Bisi et al. 2010; Tokumaru et al. 2010, 2012; Yu et al. 2015). IPS observations are ground-based measurements, which, however, limits the availability of the data in the case of adverse weather conditions or insufficient elevation of the Sun above the horizon at the receiving antenna location.

The fluctuations are in a form of diffraction patterns on observer's plane, produced by interference of radio waves coming from a remote compact radio source (e.g., quasar) with angular width $\leq$ 1 arcsec, scattered by small-scale (10-1000 km) electron density irregularities in the solar wind in the interplanetary space. The signal appears at Earth as an intensity pattern in the radio wavelengths that moves along with the solar wind. The registered signal is linearly related with the scintillation of the turbulent medium if only the scintillation is weak, it is the wave scatters only on the unscattered medium (Coles 1978; Coles & Harmon 1978). In a weak scintillation regime the Born approximation can be used and the diffraction pattern can be considered as a sum of contributions scattered from every part of the medium that is decomposed into thin slabs perpendicular to the LOS. Most of the scattering along the LOS comes from the region of the closest approach to the Sun. The center of this region is called the "P-point" and is located at a heliocentric distance $\sin\epsilon$ in AU, where ϵ is the elongation angle formed by the Sun-Earth line and the LOS to the source. The direction of the LOS outside the ecliptic plane allows to place "P-point" at different heliocentric latitudes and thus to probe the heliolatitudinal structure. The scintillations observed at Earth are modulated by the Fresnel filter function $\sin^2\left(q^2\lambda z/(4\pi)\right)$, where q is the wave number of the irregularities, z is the distance from Earth to "P-point", and λ is the wavelength of observations. The Fresnel filter enables to probe solar wind electron density fluctuations of scale sizes $\leq$ 1000 km by IPS observations at 327 MHz over a wide range of heliolatitudes and heliocentric distances (e.g., Bisoi et al. 2014). The IPS is observed at frequencies from a few tens to a few thousands MHz, with 327 MHz as the one most frequently used currently. This radio frequency enables observations of the solar wind at distances to the Sun down to 0.1 AU, and which is expected to be mostly free of the ionospheric scintillations.

The solar wind speeds are probed by IPS by applying either of two generalized data-analysis techniques: model fitting to power spectra (MFPS) from a single station, or cross-correlation functions (CCF) produced by cross-correlating of simultaneous IPS time series from at least two separate stations. The MFPS method to determine the solar wind speed from single-station observations was suggested by M. Bleiweiss, W. A. Coles, and S. Maagoe at the Astronomical Society of the Pacific Meeting in 1974, investigated by, e.g., Tyler et al. (1981); Scott et al. (1983), and employed with success by, e.g., Manoharan & Ananthakrishnan (1990); Mejia-Ambriz et al. (2015). The MFPS technique is applied to IPS flux fluctuations and an equation for spatial spectrum of intensity for a wave propagating through a thin dispersive layer of plasma in the weak scattering region is solved. The contributions of layers along the LOS are integrated and expressed as a theoretical power spectrum that depends on such parameters as the frequency of observed wave, the solar wind velocity, and the apparent size of the radio source.

The second technique, multi-station, was developed by Hewish et al. (1966). It requires two or more observing sites that are located sufficiently far apart to measure the difference in time of the scintillation pattern from one site to another. The distances between stations are typically about 100 km. The delay in the pattern of radio intensity between the stations is estimated from the time lag for the maximum of the CCF of the observed intensity fluctuations, which allows to derive a drift speed of the radiation pattern (e.g., Vitkevich & Vlasov 1970; Kakinuma et al. 1973; Coles & Kaufman 1978; Kojima 1979). Despite the fact that the multi-station observations of the IPS were highly developed in 1970-ties and 1980-ties, currently only one research institute in the world conducts such observations, it is the ISEE in Japan. In several other world spread observatories single-station observations are carried out: in India (Ooty Radio Astronomical Observatory, 326.5 MHz), Russia (Pushchino Radio Astronomical Observatory, 110 MHz), Mexico (MEXican Array Radio Telescope (MEXART), 140 MHz), China (Miyun Synthesis Radio Telescope (MSRT), 232 MHz), South Korea (Korean Space Weather Center, 327 MHz). There are also many other stations where IPS observations are collected, with the most known European systems, the *European Incoherent Scatter Scientific Association* (EISCAT) and the *Low-Frequency Array* (LOFAR), however, they are not directly dedicated to the monitoring of the global solar wind.

Retrieval of the solar wind speed from the IPS observations is possible owing to a relation between the electron density fluctuation level (ΔN_e) and the solar wind speed as a function of heliocentric distance as $\Delta N_e(r) \propto r^{-2} V^{-\gamma(r)}$, where r is the heliocentric distance, N_e is the electron density, V is the solar wind speed, and index $\gamma(r)$ varies with solar distance and must be determined experimentally (e.g., Asai et al. 1998; Coles et al. 1995; Manoharan 1993; Hick & Jackson 2004; Jackson et al. 2010; Tokumaru et al. 2012). The solar wind speeds are estimated with the use of the CCF method of the IPS data analysis. The computer-assisted tomography (CAT) method is used to deconvolve the LOS integrated signal and project the measured values on the solar surface (e.g., Asai et al. 1998; Jackson et al. 1998; Kojima et al. 1998; Fujiki et al. 2003; Kojima et al. 2007). The CAT method used by ISEE is a time sequence tomography. It uses a large synoptic grid of latitude versus Carrington longitude which spans multiple solar rotations. The LOSs to many sources observed on consecutive days are projected on the source surface, assumed at $2.5R_\odot$ (Kojima et al. 2007). This method allows to obtain a smooth connection at the boundary longitude between adjacent rotations and enables to retrieve a solar wind structure that persists for a few weeks and very slowly evolves from rotation to rotation. Although the source surface is inside the region of solar wind acceleration in the solar corona, the final data product is the fully accelerated solar wind. The CAT analysis provides 11 solar maps[6] (e.g., Thompson 2006; Ulrich & Boyden 2006) of the solar wind speed each year with a $1° \times 1°$ resolution in latitude and longitude, however, the resolution of the time-dependent 3D reconstruction can be smaller (see comments in Yu et al. 2015). The accuracy of the CAT analysis has been examined by comparison with Ulysses in-situ measurements out-of-ecliptic and the OMNI data collection in the ecliptic plane, and it has been shown that the IPS CAT method has a sufficient reliability and sensitivity for determining the solar wind structure (more in Fujiki et al. 2003; Kojima et al. 2004, 2007; Tokumaru et al. 2010).

ISEE has been carrying out multi-station observations at 327 MHz frequency almost continuously from 1983. Before 1994 it was a three-station system with antennas in Toyokawa, Fuji, and Sugadaira. In 1994 an antenna in Kiso was added, and a four-station system was constructed. From 1997 the disturbance g-factor (see next paragraph) has been determined regularly at one of the stations (i.e. in Kiso until 2009 and in Toyokawa after 2010). The system in Toyokawa was upgraded from 2005 to 2008 to be more sensitive and it operates now as a part of the Solar Wind Imaging Facility (SWIFT; Tokumaru et al. 2011). Next, in 2010, antennas in Fuji and Kiso were upgraded to collect data simultaneously with SWIFT and enable highly sensitive three-station cross-correlation analysis. It is the year when the solar wind speed data are missing, because not enough scientific observations could be done. The highly developed and advanced IPS observations collected by ISEE very often serve as a reference system to calibrate solar wind observations from other IPS stations. Before the system upgrade, the ISEE IPS data were collected on a daily basis from April to December for about 30 – 40 selected radio sources. The IPS data are not available during winter months to avoid the interruption of observations due to possible damage of the antenna operated in snow and ice.

The relation between ΔN_e and V was used to analyze the IPS data by ISEE before 1997 using the

[6]We further call them Carrington maps (CR-maps) because one map presents the solar surface during one complete Carrington rotation.

CAT method. After 1997, the quantity known as the disturbance *g*-factor[7] (Gapper et al. 1982), which represents an integral of ΔN_e along the LOS, was introduced to the IPS analysis performed by ISEE (Tokumaru et al. 2000). The *g*-factor represents the relative variation of the scintillation strength with respect to the mean level: $g = \Delta I/\overline{\Delta I\,(R)}$, where ΔI and $\overline{\Delta I\,(R)}$ are the observed instantaneous and average scintillation levels, respectively, and ΔI is computed from the observed power spectrum of the fluctuations (more details, e.g., in Tokumaru et al. 2012).

Since 1997, therefore, two alternative CAT analysis are used in ISEE to reconstruct the global distribution of the solar wind speed. One of two CAT analysis methods assumes an empirical relation between the solar wind speed and ΔN_e, and only uses speed estimates derived from multi-station IPS observations. The other method does not assume such a model and uses *g*-value data derived from single-station measurements and speed estimates from multi-station measurements. Thus the IPS speed estimate is a convolution integral of the actual speed and ΔN_e along the LOS. As shown in Asai et al. (1998) and Tokumaru et al. (2012), the solar wind speed derived from the relation $\Delta N_e \sim V^{-0.5}$ compares well with the results obtained from the analysis supported by the *g*-value data, except for the years of solar maximum. Therefore, the results from the CAT analysis using only the ΔN_e data can be used to discuss long-term changes in the solar wind over solar cycles.

The description about the IPS method of solar wind speed investigation is also presented in Section 2.3 in Paper S1, Section 2 in Paper S2, and Sections *Historical Perspective: Insight from Interplanetary Scintillation* and *Latitude Profiles of Solar Wind Velocity from Interplanetary Scintillation Observations* in Paper B1.

[7]It is called *g*-factor/value/index after *"a good proxy"* for the density (Hewish et al. 1985; Bisoi et al. 2014).

3.2 Heliolatitudinal structure of the solar wind speed and density

The model of the solar wind proton speed and density structure as a function of heliolatitude and time is discussed in the following articles that compose this PhD thesis: Paper S1, Paper S2, Paper B1, and Paper M2. Paper B1 presents the motivation to develop a model of solar wind for the needs of the global study of the heliosphere. The core model is presented in detail in Paper S1. In Paper S2, an extension and development of the model presented in Paper S1 is discussed. Appendix B in Paper M2 presents an approach to modify the way the solar wind density is reconstructed from the heliolatitudinal profiles of the solar wind speed and solar wind quasi-invariants in latitude, which finally is discussed in Paper S2. In these papers we focused only on the supersonic solar wind, assuming the radial expansion, solar wind density decrease with squared distance to the Sun, with the mass-loading effects neglected (e.g., Lee et al. 2009), and we assumed that the solar wind speed is constant with the increasing distance to the Sun.

3.2.1 Solar wind speed

Paper S1 presents the reconstruction of the evolution of the heliolatitudinal structure of the solar wind speed and density based on data selected from available in-situ measurements and remote observations. The Ulysses data were selected as a reference for the solar wind speed and density out of the ecliptic plane. The OMNI data set with the collection of in-ecliptic measurements was used as a reference for the latitudes close to the solar equator. The aim was to obtain information about the solar wind speed and density out-of-ecliptic as a long, continuous, and homogeneous time series, thus the data solely from Ulysses were not sufficient. As discussed earlier, there are two sources that can be used as a solar wind proxy in a large scale: the IPS observations and the heliospheric ISN H backscatter glow. In the initial phase of the construction of the model both of them were considered to utilize, but finally only the solar wind speed retrieved from the IPS was selected to further study. Nevertheless, a sketch of the method to reconstruct the solar wind flux and density from IPS and Lyman-α helioglow observations is discussed in the Section *Outlook: Latitudinal Structure of Solar Wind Flux and Density from IPS and Lyman-α Helioglow observations (A sketch of the Method)* in Paper B1.

Thank to the collaboration with Munethosi Tokumaru and Kenichi Fujiki from ISEE, we were provided with the solar wind speed retrieved from the IPS observations. In Paper S1 we used data from 1990 to 2011 with a one-year gap in 2010 (see also Section 3.1.4). This data set was next extended to the set which begun in 1985 and ended in 2013, with the gaps filled using the procedures described in Paper S2. Sections 2.3 and 3 in Paper S1 and Sections 2 and 3 in Paper S2 present in detail the IPS-based data product used in the respective models.

The solar wind speed data retrieved from the IPS observations contain spatial and temporal breaks, as illustrated in Figure 2 in Paper S2. The spatial gaps are present because of the limitation in the sky coverage of the sources which is due to the location of the observation facilities at the North hemisphere. The breaks in time are due to the so-called winter break in the antenna operation. Furthermore, the estimation of the solar wind speed for the Carrington maps with a low data coverage tends to underestimate the speed. In consequence, for further studies, we limited the original data set to those Carrington rotations for which the spatial coverage was high enough. An example Carrington map of the solar wind speed estimated from the IPS observations is presented in Figure 1 in Paper S2. The solar wind speed retrieved from IPS observations does not exceed 800 $\mathrm{km\,s^{-1}}$, because the solar wind model used in the CAT analysis has an upper bound at 800 $\mathrm{km\,s^{-1}}$, established based on the Ulysses measurements of the fast solar wind.

The model presented in Paper S1 has a low resolution because, due to the spatial and temporal gaps in the data, a coarse-grained averaging was introduced (the advanced gap-filling methods were developed later in Paper S2). In the first step of the model construction, each CR-map was averaged into latitudinal profiles with nineteen 10° bins in latitude, with each latitudinal bin averaged over 360° in longitude. These latitudinal profiles were next averaged over all available Carrington rotations for a given calendar year to get the yearly averages. Data processed this way are presented by dots in Figure 14 in Paper S1. This method of data preparation enabled to obtain a general information about the solar wind variation with heliolatitude over the year and thus it fits to our needs for the calculation of ionization rates. In the assessment of the ionization losses we were interested only in the general variation of the solar ionization factors, and not in small-scale changes.

Furthermore, we wanted to have an easy to use, analytic formula to describe the solar wind. Therefore we approximated the yearly profiles of the solar wind speed by an analytic piecewise function that is composed of 4 parabolae at mid- and low latitudes and 2 linear functions for the polar regions, with a requirement that they connect smoothly. This smooth function is illustrated in Figure 12 and defined in Equations 1,2, and 3, with the coefficients given in Tables 1, 2, and 3 in Paper S1. As illustrated with solid lines in Figure 14 therein, the resulting smooth profiles approximate the data well. In the next step of the construction of the model of the solar wind proton speed, we calculate the values for each CR in the interval of interest using a linear interpolation between the yearly averages. Finally, in the last step, we replaced the equatorial band by the in-ecliptic measurements collected in the OMNI database, with the ±10° bins replaced by the values interpolated from the adjacent bins (0°, ±20°; more in Section 3.3 in Paper S1). It is because we constructed the model in the heliographic frame, where the 0° bin means the solar equator, whereas the OMNI data sets are in the ecliptic frame and during the year they vary inside ±7° in heliographic frame. The interpolation between the in-situ in-ecliptic data placed at 0° and the IPS-retrieved data at ±10°-bin smooth the information inside the equatorial band during the year. This simplification is justified because the solar wind is almost homogeneous in this latitudinal range. Additionally, to get a smooth transition over the pole, we replaced the polar bin with a value obtained from a parabola fit to the set built with the 70° and 80° bins and their mirror reflection, for each pole separately.

In the model described in Paper S2 we increased the resolution of the model in time and in heliolatitude. Our main aim was to fill the spatial gaps and temporal breaks in the original solar wind speed data received from the IPS observations using as much of the available information as possible. Additionally, we wanted to get rid of the assumption on the shapes of the latitudinal profiles used in Paper S1. To realize the aims we followed the methods commonly used in the analysis of, e.g., geophysical, solar, in-ecliptic, and on-the-sphere data sets, it is the decomposition into spherical harmonics and singular spectrum analysis. The solar wind speed data from ISEE are organized in Carrington maps and thus represent the spherical surface of the Sun. This encouraged us to decompose the data into a set of spherical harmonics and reconstruct the spatial gaps for every map by approximation with the use of the spherical harmonic coefficients, obtained from analysis of the original and adjacent maps. The procedure is described in detail in Section 3.1 and Appendix A in Paper S2. Figure 3 therein illustrates how the procedure of decomposition on spherical harmonics reconstructs various types of spatial gaps in the data.

In the next step, we reconstructed the temporal breaks in the data with the use of the singular spectrum analysis of the time series of the spherical harmonics coefficients obtained from filling the spatial gaps in the previous step. The breaks in time are nearly periodically distributed. Figure 5 in Paper S2 presents the time series of the selected spherical harmonics coefficients. The blue dots represent the valid data, and the red dots the reconstructed values. We restricted the analysis only to the rank which allows for the reconstruction of the latitudinal profiles, with the longitudinal information averaged out. We did so because for the needs of the ionization rates of ISN atoms and ENAs a resolution of one Carrington rotation is sufficient and we did not want to bias the results by short-lived longitudinal variations of the solar wind speed, and we do not need to track the ionization rates on time scales smaller than one solar rotation. The details of the filling of the temporal breaks in the data are described in Section 3.2 and Appendix B in Paper S2. Figure 6 therein presents the final heliolatitudinal profiles of the solar wind speed for selected CRs after the filling of the mentioned two types of gaps.

Top panel of Figure 20 in Paper S1 and Figure 7 in Paper S2 illustrate the evolution of the solar wind speed as a function of time and heliolatitude obtained using the methods described in the respective papers. Comments on the solar wind evolution, including the phase shift between the north and south hemispheres, the secular offsets, etc., are also presented in these papers.

3.2.2 Solar wind density

The heliosphere is shaped by the solar wind ram pressure, which is proportional to the product of the solar wind density and squared speed. The solar wind proton density in the ecliptic plane has been measured for a long and most of the data are compiled in the OMNI database. The out-of-ecliptic measurements are solely available from Ulysses. However, the solar wind density out-of-ecliptic can be obtained from the indirect observations of the heliospheric ISN H glow and also from the IPS observations (e.g., Houminer & Hewish 1972, 1974; Tappin 1986; Hick & Jackson 2004; Jackson & Hick 2004). There exists a nonlinear relationship between the bulk density and the IPS scintillation level that has been widely and successfully used to study the corotating structures and CMEs as described in the review by Jackson et al. (2011) (see also, e.g., Jackson et al. 1998; Tokumaru et al. 2007; Bisi et al. 2009, 2010; Fujiki et al. 2014). However, in our study we used from the IPS observations only the solar wind speed estimation, because the assessments for the density were not available in the time of model development. We also did not evolve the model of the density retrieval from the IPS data and instead we developed a supplementary technique to calculate the solar wind density with the use of the solar wind speed.

In general, the solar wind density does not directly correlate with the speed, especially in the ecliptic plane, where different streams of solar wind flow mix. Figure 8 in Paper S2 presents the relation between the in-ecliptic solar wind proton density and speed at 1 AU based on the OMNI data set. The relation is crescent-like in shape, with a broad range in speed for low densities. This property impedes an unambiguous derivation of the density based solely on the speed. But Ulysses measurements revealed some approximate relations between these two parameters. The top and middle panels of Figure 6 in Paper S1 illustrate the solar wind speed and density measured by Ulysses during the fast latitudinal scans. Those fast scans show that the solar wind is fast with low density at the higher latitudes during minimum of solar activity, and slow with greater density around the ecliptic plane. A similar trend was also present in the data during the solar maximum, but with slow and dense flows spread over all latitudes. This slow-dense and fast-rare feature encouraged us to derive an approximate analytic formula to calculate the solar wind density based on the solar wind speed.

We took the data from Ulysses fast scans for the solar minimum and fit a linear relation to each of the two sets. The relation for the scan during the maximum of solar activity was derived as an average of the coefficients obtained from the fit to the previous two. At the end we arbitrarily set the time ranges for application of the respective formulae. The derived formulae can be used only to retrieve the solar wind density on a time scale not finer than CR average. The procedure is described in Section 3.2 in Paper S1. Figure 17 and Figure 18 present the data with the fitted relations and the goodness of reconstruction of the density for the second fast scan during solar maximum, respectively. Having the linear relation to calculate the density as a function of speed and the heliolatitudinal profiles of the solar wind speed for each year we were able to calculate the heliolatitudinal profiles of the solar wind proton number density, which are presented in Figure 19 in Paper S1. In the last step of the model construction, we replaced the equatorial band by the OMNI measurements and replaced the $\pm 10^\circ$ and $\pm 90^\circ$ bins by proper interpolation the same as in the case of speed. As will be discussed later on, such a simple and phenomenological method gives results that compare with the observations surprisingly well.

The method to retrieve the solar wind density presented in Paper S1 works well for the time ranges used to derive the density-speed relations on CR time scale. Unfortunately, the Ulysses mission ended in 2009 and since then the modeling of the solar wind density as a function of latitude has been challenging. In Appendix B in Paper M2 we discuss a new method of solar wind calculation with the use of solar wind quasi-invariants in latitude. There are two alternative quantities that approximately do not vary with latitude and track only the changes in time. They are the solar wind dynamic pressure and the solar wind thermal advection energy flux. They are defined in Equations 3 and 4 in Paper S2, respectively. Both were inferred from Ulysses measurements by McComas et al. (2008) and Le Chat et al. (2012), respectively. A comparison of the two quantities, calculated for the ecliptic plane at 1 AU, is presented in Figure 9 in Paper S2. The latitudinal invariant of the solar wind, which depends on the speed and density of the flow and is known from in-ecliptic measurements together with the profiles of the solar wind speed in latitude, enables to calculate the solar wind density as a function of heliolatitude, as defined in Equation B2 in Paper M2. In Paper M2 we chose the solar wind thermal advection energy flux to calculate the solar wind density from 2012.5, keeping the method developed in Paper S1 for the previous years. In Paper S2, we used the new method based on the solar wind latitudinal invariants to calculate the solar wind density for the whole studied period. Details are described in Section 5, and the resulting profiles for selected years are presented in Figure 10 therein. The bottom panel of Figure 20 in Paper S1 and Figure 11 in Paper S2, illustrate the variation of the solar wind density adjusted to 1 AU as a function of time and heliolatitude calculated with the use of both proposed methods.

3.2.3 Comparison with in-situ measurements

Section 5 and Figure 22 in Paper S1 and Section 6 and Figures 12 and 13 in Paper S2 present a comparison of the respective models with the in-situ measurements from the Ulysses measurements out of the ecliptic plane and the data collected in the OMNI database in the ecliptic plane. Both models reconstruct the solar wind speed measured by Ulysses very well, especially during the low solar activity. The good result of the comparison confirms that the data processing we introduced does not bias the data. The coarse-grained yearly averaging fits as well to the Ulysses data as the high resolution model with the reconstructed gaps in the solar wind speed data from IPS. The main differences between these two models of the solar wind speed is the scale of variations present in the final time series. The series presented in Paper S1 are, due to the used averaging, more smooth and trace only the general trend of the solar wind evolution. The series in Paper S2 at the scale of CR follow the solar wind variations with higher precision.

Both models are less precise for the times of higher solar activity. This can be caused by the difference in the technique of solar wind sampling between the in-situ and remote observations. While Ulysses made point measurements, the IPS observations are the LOS integrated observations and collect data from a much broader region. During solar maximum various types of quickly varying solar wind sources are spread all over the solar surface, and the fast and slow streams are present at all latitudes. Thus point measurements, like those from Ulysses, give information specific only for a given location, whereas IPS samples along the LOS and averages out the signal. The latter technique is better suited fore more regular shapes of solar wind profiles. Therefore, as mentioned in Tokumaru et al. (2010), the IPS reconstruction of the solar wind speed is slightly better for the solar minimum than the solar maximum conditions. The uncertainty of reconstruction of the solar wind speed in the two presented models, based on the comparison with Ulysses data, is up to 30% during solar maximum and less than 10% for the remaining phases of the solar activity.

The reconstruction of the solar wind density based on the solar wind latitudinal quasi-invariants is better than that from the phenomenological formula derived from Ulysses fast scans, as presented in Figure 13 in Paper S2. The new method traces the variations in the Ulysses measurements with a higher accuracy, especially after the activity maximum in 2000. Again, the result of the comparison for solar maximum is worse than for solar minimum, and this is due to the same reasons as for the speed. Additionally, the method of calculating the density from the speed transmits the discrepancies in the speed reconstruction to the reconstruction of the density.

In the model presented in Paper S1, the equatorial band of speed and density were replaced with the CR averaged series of solar wind speeds and densities from the OMNI database. This replacement was introduced to increase the accuracy of the model for the ecliptic plane, where most of heliospheric measurements are carried out. In particular, IBEX observes the ISN gas from the ecliptic plane, and the atoms are exposed to the most intense ionization shortly before the detection, i.e., mainly by the low latitudes solar wind streams. In the Paper S2 model we do not adjust the final time series to the OMNI data set, because our main goal was to fill the gaps in the solar wind speed data from IPS observations.

As the comparison with the OMNI time series in Figure 12 in Paper S2 shows that the agreement between the in-ecliptic series start to diverge about 2010. The reason for this difference is not resolved yet, but it may be either IPS or OMNI related. It can be either due to the empirical relation between the solar wind speed and the density fluctuations, which had been retrieved before the onset of the secular changes in the solar wind flux, or because the solar wind is not fully accelerated at the distances sampled by the LOSs, or the other, still undetermined reasons. Resolving these discrepancies is beyond the scope of this thesis.

3.3 Ionization processes inside the heliosphere

There are three main ionization processes for the ISN species inside the heliosphere that account for the total ionization rate: (1) ionization by the solar EUV radiation (photoionization), (2) ionization by charge exchange with solar wind particles, and (3) ionization by impact of solar wind electrons. In addition to the ionization factors for the ISN species, the effective acceleration by solar gravity and radiation pressure forces have to be added as another modulating factor. The solar radiation pressure is effective only for H and D and can be neglected for He, Ne, and O (e.g. Fahr 1979; Wu & Judge 1979; Ruciński 1985; Bzowski et al. 2013b). Figure 3.17 in Paper B1 and Figure 1 in Paper B2 present the times series of the rates for ionization processes at 1 AU and their contribution to the total ionization rate for H and He, Ne, O, respectively. Additionally, the bottom right panel in Figure 1 in Paper B2 illustrates a comparison of the total ionization rates for the four discussed species for almost two solar cycles.

In our studies we restrict the reconstruction of the ionization rates to CR averages. The argumentation for selecting this resolution in time is given at the end of Section 3.1 in Paper B2. In brief, the solar wind output varies on time scales from minutes to ∼ 11 years. The ISN gas atoms and ENAs travel from the source region located at approximately 100 AU from the Sun from months (the fastest ENAs) to dozens of years (the slowest ISN atoms). The rate of ionization depends on the distance from the Sun and decreases like r^{-2} with solar distance r for charge exchange and photoionization, and faster than r^{-2} for electron impact. Thus, the ISN atoms and ENAs are exposed to the most effective ionization at the distances to the Sun of the order of a few AU before detection. An example is presented in Figure 3 in Paper B2 for the discussion of the electron impact ionization. The integrand function for the ionization losses increase rapidly at small distances to the Sun for a few months before detection. Thus, the information about the ionizing conditions at a few CRs before the detection is the most important. The averaging over the CR means in practice smoothing over the short-scale variations in the solar output. In a result of this procedure the real conditions for the most important part of the orbit can be taken into account without a proper caution. But without continuous monitoring of the solar wind short-scale output along the atom trajectory, it is impossible to account the short-scale ionization effects properly, and the averaging seems to be a reasonable solution.

The distribution of ISN gas in the heliosphere has been extensively studied in the *Laboratory of Solar System Physics and Astrophysics* since late 1980-ties (e.g. Ruciński & Bzowski 1995; Ruciński et al. 1996; Fahr & Ruciński 1999; Bzowski 2001; Ruciński et al. 2003). In the software developed to model the distribution of the ISN gas and its population inside the heliosphere the model of photoionization had been simplified. It was due to the lack of a sufficiently long set of homogeneous and continuous data. In this dissertation we construct a composite model of the photoionization rates in the heliosphere using the available direct and indirect measurements.

3.3.1 Ionization by solar EUV radiation

Ionization by the solar EUV photons is the most effective source of losses for the ISN He and Ne and is of second importance for H and O. It is caused by the solar EUV radiation of wavelenghts shorten than 91.2 nm for H, 50.4 nm for He, 57.5 nm for Ne, and 91.1 nm for O, which corresponds to photon with energies greater than 13.6 eV, 24.6 eV, 21.6 eV, 13.6 eV, respectively. As a result of the photoionization process, which is an interaction between a neutral atom and a EUV photon, a singly ionized ion (PUI) and a free electron are created. The intensity of photoionization varies in time during the solar cycle because the distribution of the EUV radiation sources on the solar surface changes with the solar activity. Studies by Auchère et al. (2005a,b) of the He II 30.4 nm solar flux suggested that the photoionization is expected to vary with heliolatitude, with a ~ 0.8 pole-to-equator ratio and that some north-south anisotropy can exist, but this result needs further investigation.

The photoionization rate is calculated from integration of the solar spectral flux multiplied by the cross section for ionization over an interval from 0 up to the ionization threshold wavelength (Equation A.1 in Paper B2 and also Equation 3.21 in Paper B1). Among the cross sections for photoionization available in the literature (e.g., Samson et al. 1994; Verner et al. 1996; Samson & Stolte 2002), we selected the cross sections for non-relativistic objects given by an analytic formula in Verner et al. (1996), which are interpolated and smoothed over resonances. Figure A.2 in Appendix A in Paper B2 illustrates the cross sections for photoionization for the species we studied as a function of energy and wavelength.

In our study we were interested in reconstruction of a long, continuous, and homogeneous time series of the photoionization rates for He, Ne, O, and H. The regular measurements of the solar spectrum in EUV are available from 2002 from *Thermosphere Ionosphere Mesosphere Energetics Dynamics* (TIMED) mission (Woods et al. 2005). This time range was not enough for the study of survival probability of ISN gas in the heliosphere, especially for the study of He, which bulk atoms travel from the source region to the Sun for a few years. To study the ISN He observations made by IBEX-Lo (Bzowski et al. 2012; Bzowski et al. 2015), as well as the Warm Breeze (Kubiak et al. 2014; Kubiak et al. 2016), the reanalysis of the Ulysses/GAS measurements (Bzowski et al. 2014; Wood et al. 2015), and the review study of the historical and present ISN He sampling (Frisch et al. 2013, 2015), a time series as long as possible was needed. We developed such series based on the direct measurements of the EUV spectrum and a series of solar EUV proxies. The EUV proxies are usually single UV lines (like lines of ionized Mg, C, O, Fe or Lyman-α) that trace the solar cycle variations typical for a wider range of the EUV spectrum. Also an integral of a short interval of the EUV spectrum, if constantly observed, can be used as a proxy, like the measurements from the *Solar Extreme Ultraviolet Monitor* (SEM) on the *Charge, ELement, and Isotope Analysis System* (CELIAS) of the *Solar and Heliospheric Observatory* (SOHO) spacecraft (SOHO/CELIAS/SEM). Sometimes the sunspot number series are used as a EUV proxy, but due to doubts on the reconstruction of the long time series (e.g., Clette et al. 2014) we do not use them in our study. The set of EUV proxies used to the reconstruction of photoionization rates was selected after a careful investigation of the literature (e.g., Floyd et al. 2002; Dudok de Wit et al. 2005; Floyd et al. 2005; Dudok de Wit et al. 2008; Tobiska et al. 2008; Dudok de Wit et al. 2009) and available data sets. In our analysis we do not use proxies that were developed based on other available EUV proxies, like S10.7 or M10.7 (e.g., Tobiska et al. 2008), because, firstly, they are based on the correlations with other, more fundamental proxies, and secondly, they were developed before the issues with the SOHO/CELIAS/SEM and composite

$MgII_{c/w}$ were identified (Wieman et al. 2014; Snow et al. 2014).

The set of EUV proxies we selected to the reconstruction of the historical photoionization times series for He, Ne, O, and H contains: solar 10.7 cm radio flux, F10.7 (Covington 1969; Tapping 1987, 2013), ionized magnesium line core-to-wing ratio index, $MgII_{c/w}$(Heath & Schlesinger 1986; Viereck & Puga 1999; Snow et al. 2014), and solar Lyman-α line flux (Woods et al. 2000). As direct measurements of the solar EUV flux we used the first order and central order flux from SOHO/CELIAS/SEM (Hovestadt et al. 1995; Wieman et al. 2014) and the Level 3 data set from the *Solar EUV Experiment* (SEE) instrument onboard TIMED. Details of the data selection and the process of reconstruction of the photoionization rates for ISN gas are presented in Appendix A in Paper B2 and Section *Photoionization* in Paper B1, and also in Sokół & Bzowski (2014). Here, we restrict ourselves only to a brief summary.

3.3.1.1 F10.7

F10.7 is the longest data set among the EUV proxies after the sunspot number. It is a ground-base radio observations which has been almost continuously collected from 1947. The long time series, collected using well calibrated instruments, makes them a good proxy to reconstruct the past photoionization rates. The F10.7 index is an indicator of the solar emission at the wavelength of 10.7 cm from sources present on the solar disk. The measurements at this wavelength is sensitive to the conditions in the upper chromosphere and at the base of the solar corona, i.e., the parts of the Sun where the EUV emission is released, and thus is a good index of the level of solar activity. F10.7 is a measure of the solar flux density in a 100 MHz-wide band centered at 2.8 GHz and is expressed in solar flux units (1 sfu = 10^{-22} W m^{-2} Hz^{-1}).

The flux is a sum of three components, categorized on the basis of their characteristic scale of variation in time: a rapidly-varying component contains emissions that vary over timescales from the second-minute range to an hour (R component), a slowly-varying (S component), and a quiet, base level (Q component). These components come up due to different processes, which may be differently distributed over the solar surface, and which vary with time independently. The principal emission mechanisms are the thermal free-free emission from the chromosphere and corona, the emission from concentrations of plasma supported in the chromosphere and corona by active region magnetic fields, and emission from the thermal gyroresonance over sunspots. Also some nonthermal emission is expected. The R component typically comes from bursts, and the Q component from the overall background emission. The total emission from the whole solar disc may thus vary in intensity from seconds to years. It features transient emissions from flares that last milliseconds, bursts with typical timescale of minutes, active regions, and decay of the nonthermal emission from electrons accelerated by flares and trapped in coronal loops, which both can evolve on timescales of hours, days or months. They also change in intensity on timescale of years, with an increase and the following decrease of activity over the solar cycle.

The observations of the total emission in 10.7 cm are performed by ground base radio telescope a few times per day during specific 1-hour intervals and the data product is daily observations for a given hours in a day, not daily averages. According to Tapping (2013), the accuracy of F10.7 values is

1 sfu or 1% of the flux value, whichever is the larger. For the needs of the construction of the model of photoionization rates we use the F10.7 time series released by the National Oceanic and Atmospheric Administration (NOAA), which are the measurements from the stations in Penticton (before 1990 also from a station near Ottawa, more in Tapping (2013)), conducted by the Dominion Radio Astrophysical Observatory (DRAO). This data set is a homogeneous series of observations since 1947, with the series adjusted due to a change of the observing antenna (more about the calibration of the F10.7 measurements can be found in Tanaka et al. (1973) and in the case of NOAA time series in `dataset-description_penticton.pdf`[8]). We use the data set with the noon observations each day adjusted to 1 AU.

The F10.7 flux correlates well with the photoionization rates and other EUV proxies on the CR time scales, however the correlating function is a power function of the F10.7 flux with the power ranging from 0.5 to 0.7. The nonlinear correlation between F10.7 and the solar EUV flux rose questions about the applicability of this proxy for the reconstruction of the EUV flux, especially for the SC 23 and SC 24 and the reality of the lower level of the solar minimum in that time (e.g. Chen et al. 2011; Dudok de Wit et al. 2014; Svalgaard & Hudson 2010). The changes in the correlation between the F10.7 flux and the EUV flux may be due to changes in the solar radiation output or due to calibration adverse effects (e.g. not corrected degradation of the sensitivity) in the instruments that provide the EUV radiation data.

3.3.1.2 $\mathrm{MgII}_{c/w}$

The Magnesium II core-to-wing ratio (known as the $\mathrm{MgII}_{c/w}$ index) is commonly considered as a useful proxy for the solar EUV irradiance. It is calculated as a ratio of the brightness of the solar spectrum at 280 nm to the average of the solar spectrum at either side of 280 nm (Heath & Schlesinger 1986). It can be considered as a ratio of the chromospheric contribution to the photospheric contribution. The Mg II emission is a doublet, with the *h* and *k* lines at 279.56 and 280.27 nm, that lies at the bottom of a broad absorption feature. The ratio of the peak of the fully resolved *h* and *k* lines to the background near the lines varies over the solar cycle.

The $\mathrm{MgII}_{c/w}$ intensity ratio shows a strong correlation with the solar UV irradiance in the range from 150 to 450 nm and can serve as a proxy for photoionization rates. It is a space-borne measurement, collected by various instruments almost constantly from 1978. The $\mathrm{MgII}_{c/w}$ index is a ratio of two absolute measurements made using the same detector and, in consequence, it is almost insensitive to the degradation of the instrument. The *Laboratory for Atmospheric and Space Physics* (LASP, University of Colorado at Boulder) collects data from various measurements and creates a composite time series of $\mathrm{MgII}_{c/w}$ after a careful cross-normalization (see, e.g., the review by Snow et al. 2014). We used the composite time series prepared by LASP in the construction of the model of photoionization rates described in Paper B2 and Paper B1. However, when the model had already been completed, we noticed that the correlation between the $\mathrm{MgII}_{c/w}$ index and other EUV proxies start to diverge after the solar minimum in 2008 and, furthermore, the divergence was increasing in

[8] This document is available at `ftp://ftp.ngdc.noaa.gov/STP/space-weather/solar-data/solar-features/-solar-radio/noontime-flux/penticton/documentation/`.

time. In the result of a private communication with Martin Snow from LASP, we were informed that the measurements from one of the *SOLar-STellar Irradiance Comparison Experiment* (SOLSTICE) detectors onboard the *SOLar Radiation and Climate Experiment* (SORCE) mission (Rottman 2005) required correction for the instrumental effects (Snow et al. 2014). However, the data from SORCE stopped to be updated in 2013 after the breakdown of SOLSTICE instrument.

In consequence, we change the source of the $MgII_{c/w}$ composite time series and start to use the composite $MgII_{c/w}$ series conducted by the University of Bremen (Weber et al. 1998; Weber 1999; Skupin et al. 2005, (`http://www.iup.uni-bremen.de/gome/gomemgii.html`)). In this series, the data for SC 23 and SC 24 come from the *Global Ozone Monitoring Experiment* (GOME) and the *Scanning Imaging Absorption Spectrometer for Atmospheric CHartographY* (SCIAMACHY) missions. The Bremen $MgII_{c/w}$ composite series are complementary to the composite LASP series. The composite series has gaps due to the lack of measurements, which are filled with other EUV proxies, like e.g, F10.7 data. There are also other series of the $MgII_{c/w}$ data, like the composite series published by NOAA, however they contain data only to 2009, and thus does not fit to our needs, as for the composite photoionization rate model we were interested also in the most recent data.

3.3.1.3 Solar Lyman-α

The total flux in the solar Lyman-α spectral line is measured as the spectral flux integrated over a 1 nm interval from 120 to 121 nm (Woods et al. 1995, 1996; Woods et al. 2000). The Lyman-α radiation is formed in the chromosphere and transition region of the solar atmosphere, similarly as other EUV proxies. It is strongly correlated with the solar EUV flux in the waveband responsible for photoionization for H, He, Ne, O, and therefore it is a good candidate for a proxy. It is a spaceborn measurement, collected by instruments on various spacecraft almost continuously from 1977. In our studies, we used a composite series created by LASP, which is composed of measurements from various instruments, cross-normalized to common scale. The adjustment of the measurements to the common scale is required when the composite series is created to account for different levels of sensitivity of different detectors (see more in Pryor et al. 2013; Quémerais et al. 2013). Figure 3.1 in Paper B1 presents the components of the LASP composite Lyman-α time series. The gaps in the composite Lyman-α series are filled with the other EUV proxies, like $MgII_{c/w}$ and F10.7 data.

In our studies we use the composite Lyman-α line to reconstruct the photoionization rates for hydrogen Paper B1 and oxygen Paper B2, and to assess the radiation pressure acting on the H ENA inside the heliosphere, which we calculate based on the formulae developed by Tarnopolski & Bzowski (2009). The Lyman-α series are used to calculate the survival probabilities for H ENA flux following the approach given by Bzowski & Tarnopolski (2006); Bzowski (2008). The importance of the solar Lyman-α for the physics of the ISN gas in the heliosphere is given in Section *Radiation Pressure and Its Variations* in Paper B1.

3.3.1.4 SOHO/CELIAS/SEM

The SOHO/CELIAS/SEM has been monitoring the solar spectral flux at short wavelenghts from 1996 (Hovestadt et al. 1995). SEM is a transmission grating spectrometer which measures the absolute solar

EUV flux in two bandpasses: 0.1-50 nm at the central order and ±4 nm within the 30.4 nm HeII line at the first order. The central order measurement provides a direct measure of the solar EUV flux relevant for ionization of the neutral He at energies beyond the ionization threshold at 24.6 eV. The sensor was calibrated a few times by rocket flights (Didkovsky et al. 2010) and therefore considered as well-calibrated. However, an analysis we have made (Sokół et al. 2013a) showed unexpected trends in the correlation with EUV proxies, like, e.g., F10.7. The suspicions were confirmed by Wieman et al. (2014), who published an important correction needed in the SEM absolute calibration, which forced us to revise the photoionization rate model for helium published in Paper B2 and replace it with the new model, described in Sokół & Bzowski (2014).

3.3.1.5 TIMED/SEE

In 2002, with the launch of the TIMED mission, the direct, continuous, long-term measurements of the solar spectral flux in a broad wavelength range with high resolution has begun. TIMED was launched on a circular orbit at 625 km from Earth. The SEE instrument measures the solar spectral irradiance from 0.5 to 194.5 nm in 1 nm intervals (FUV, EUV, XUV) and its FOV is $\sim 12°$ (Woods et al. 2005). In the normal operation mode, SEE observes the Sun for about 3 minutes every orbit (with the orbital period of TIMED of $\sim$ 97 minutes, 14-15 measurements per day are usually obtained). During each 3-min observation, SEE obtains twenty 10-s integrations. The accuracy of daily measurements ranges from $10 - 20\%$ (Woods et al. 2005). A suborbital (sounding rocket) payload is flown approximately once a year to help maintain the TIMED/SEE absolute calibrations.

TIMED measurements fill the "EUV hole" in the continuous measurements of the solar spectrum at short wavelenghts (shorter than 115 nm) (Figure 2 in Woods et al. 2005). The primary mission goal is to characterize the sources of energy responsible for the thermal structure of the mesosphere, the lower thermosphere, and the ionosphere, but the spectral range of observations brings data essential for astronomical studies. The accuracy goal for the SEE data is 20%, and the measurement precision goal is 4%. The SEE experiment includes two instruments that together measure the solar vacuum ultraviolet (VUV) spectral irradiance from 0.1 to 194 nm. The EUV Grating Spectrograph (EGS) is a normal incidence Rowland circle spectrograph with a spectral range of 27 to 194 nm and 0.4 nm spectral resolution. The XUV Photometer System (XPS) includes nine silicon XUV photodiodes with thin film filters deposited directly on the photodiodes. This XUV photometer set measures the solar irradiance from 0.1 to 27 nm with each filter having a spectral bandpass of about 7 nm. Because of the malfunction of the XPS filter wheel, from day 205 of 2002 a spectral gap from 11 to 27 nm is present in the SEE observations. This gap in the publicly available data is filled by the SEE XPS $0.1 - 7$ nm channel, used as a proxy that is based on the earlier measurements by SEE XPS, and data from SORCE XPS, which is almost identical to TIMED SEE XPS.

Two data products from SEE are available to study the ionization processes: Level 3 and Level 3A. The SEE Level 3 data are daily-averaged solar spectral irradiances with removed flares. The SEE Level 3 data product is generated by combining the EGS and XPS Level 2 results with the EGS used longward of 27 nm and XPS shortward of 27 nm. The Level 3 product includes the solar spectrum at 1 nm intervals on 0.5 nm centers from $0.5 - 194.5$ nm, with the irradiances of 38 emission lines extracted from the EGS spectrum and with the background continuum removed, as well as the irradiances from the individual XPS photometers. The orbit averages are from 3-min observations with a repeat rate of about 97 minutes, that is with the duty cycle of 3%. The Level 3A data is an observation-averaged product with a $\sim$ 3 minute resolution in time and the flares are not removed because only few of them are observed by SEM in its duty cycle for solar observations. To construct the photoionization rates we used Level 3 data, which are corrected for atmospheric absorption and instrument degradation[9]. The removal of contribution of flares makes this data product suitable for long-term climatological study, as well as for the studies of modulation of ionization rates in the heliosphere. The flux is scaled to the distance of 1 AU from the Sun.

3.3.1.6 Construction of the photoionization rate model

Section A.1 in Appendix A in Paper B2 and Section *Photoionization* in Paper B1 present the algorithm to reconstruct the long-term, continuous, and homogeneous time series of photoionization rates for ISN He, Ne, O, and H inside the heliosphere that we developed. Here we briefly describe the procedure.

The primary data set was the TIMED time series. In the papers mentioned, the time range of the TIMED data was restricted to 26 and 73 first CRs for He and Ne, and H and O, respectively. This decision was made as a result of a suspected unaccounted degradation of the TIMED/SEE detector after the comparison with the SOHO/CELIAS/SEM data for the time of model development. The data set of the second priority were the SEM measurements, which due to its spectral range are best suitable for the study of photoionization for He, but also are useful for other ISN species. Unfortunately, after the model completion, Wieman et al. (2014) pointed out that the SEM data should be revised and confirmed our suspicions from our earlier analysis (Sokół et al. 2013a). Fortunately, the questions about the SEM data do not heavily bias the total ionization model for H, Ne, and O, but can affect He. Accordingly, we revised the model of long-term photoionization rates for He described in Paper B2 in Sokół & Bzowski (2014) (see more in the next section).

In the composite photoionization rate model presented in Paper B2 and Paper B1 a system of proxies after cross-normalization and cross-calibration was used for the years before the TIMED and SEM time series. First we used the $\mathrm{MgII}_{c/w}$ index, and next the F10.7 index, which enabled to reconstruct the data back to 1947. Additionally, for reconstruction of the photoionization rates for H and O, we used the Lyman-α series, which together with the SEM series correlated with the photoionization rates obtained directly from the TIMED spectra better than SEM data alone. When more than one proxy was available for a given time interval, we constructed the ionization model using several proxies. In lack of more than one proxy available, we used the only proxy available (e.g. F10.7). For each set of proxies a correlation between this proxy and the ionization rate obtained from TIMED observations was searched. We calculated the photoionization rates for given species by integrating the TIMED daily spectra multiplied by the cross section for a given wavelength, as in Equation A.1 in Paper B2. For the time interval out of the range of the TIMED data set (forward and backward in time), we constructed the photoionization rates using the SEM data and EUV proxies,

[9] ftp://laspftp.colorado.edu/pub/SEE_Data/level3/README_SEE_L3_011.TXT

but we proceeded in a different way for He and Ne, and for H and O.

In the case of He and Ne, we linearly correlated the daily SEM first and central order flux series with the daily photoionization rates calculated from TIMED measurements to obtain the formula which enables to calculate the photoionization rates from the SEM data (Equation A.2 in Paper B2). In the next step, we calculated the CR averages from the daily photoionization rate series obtained from the SEM data. Based on the SEM and TIMED data we were able to reconstruct the photoionization rate time series for the whole SC 23 and the beginning of SC 24. To further extend the model backwards in time, it is before 1996, we correlated the previously calculated CR averaged time series with other proxies. Because the core relation between the proxies and the photoionization rates are worse on a daily timescale (as evident in Figure 3 in Bochsler et al. (2014)), we decided to build the proxy-based part of the model on the CR averaged time series. First, we used a sum of CR-averaged series of a composite series of the $\mathrm{MgII}_{\mathrm{c/w}}$ index from LASP, available from 1978, and the F10.7 flux. The reconstruction was better for the $\mathrm{MgII}_{\mathrm{c/w}}$ series supplemented with a power law function of the F10.7 series (Equation A.3 in Paper B2). Finally, we used the F10.7 index to reconstruct the photoionization times series back to 1947. These studies showed that, in the case of He and Ne, the best relation to reconstruct the photoionization rates with the use of the F10.7 index is a power law relation with a power about 0.5 (Equation A.4 and Table A.3).

In the case of H and O, we constructed the composite photoionization rates in a different way, mainly because the initial set of TIMED data selected to the analysis was longer than the set used in the case of analysis of He and Ne. In the first step, we calculated the CR averages of the daily photoionization rates obtained from the integration of the TIMED measurements. In the next steps, we correlated these CR averages with the sum of CR averages of the SEM data and the composite Lyman-α series from LASP. We supplemented the correlation function with the Lyman-α time series using a linear relation, which gave the best reconstruction, and the series from SEM as a power law function, as indicated in Equation 3.23 in Paper B1 and Equation A.5 in Paper B2. We used the CR-averaged time series, because there is no clear correlation between the used data on the daily timescale. For the time interval when the SEM data were not available, we correlated the CR averages of the photoionization rates from TIMED with the CR averages of the composite $\mathrm{MgII}_{\mathrm{c/w}}$ index from LASP. Our studies showed that for H and O the best reconstruction is when the $\mathrm{MgII}_{\mathrm{c/w}}$ index is correlated linearly with the series of photoionization rates, as expressed in Equation 3.24 and Equation A.7 in Paper B1 and Paper B2, respectively. In the last step, for the time interval before 1978, we calculated the photoionization rates using the correlation between the CR averages of the photoionization rates obtained from TIMED and the F10.7 index. The studies showed that the best relation to reconstruct the photoionization rates for H and O is when the F10.7 index is again a power law relation with a power about 0.5 in the case of H and about 0.7 for O (Equation 3.25 in Paper B1 for H, and Equation A.8 for O in Paper B2).

With the use of direct solar EUV spectra measurements and a set of EUV proxies we were able to construct a homogeneous, continuous, and long time series of photoionization rates for He, Ne, O, and H inside the heliosphere going back to 1947. Each series of proxies or combination of proxies were correlated with the photoionization rates series constructed from either the SEM and TIMED data (as in the case of He and Ne) or TIMED data alone (as in the case for H and O), because they cover a long time interval that spans the solar cycle related variations. However, the studied time range contains also the unusual declining phase of SC 23 with a prolonged and deep solar minimum, which introduced many doubts to the EUV data series and rose questions on the effects of instrument degradation and absolute calibration of most of the EUV proxy series (e.g. Chen et al. 2011; Wieman et al. 2014; Snow et al. 2014). In the light of these papers, the models based on the SEM data series need to be updated to remove the shown inaccuracies in the data sets. The photoionization is the most effective ionization process for He and we revised the composite model for this species describing the results in Sokół & Bzowski (2014). The revision of the model for the remaining species will be a subject of the future work.

3.3.1.7 Updated model of photoionization rates for ISN He

Wieman et al. (2014) reported about an important correction needed in the SOHO/CELIAS/SEM data, identified based on a comparison with the measurements from the *EUV Variability Experiment* (EVE) instrument on-board the *Solar Dynamics Observatory* (SDO) mission (Woods et al. 2012). The irradiance values measured with the use of these two instruments differed by more than the expected uncertainties of the measurements. In consequence, Wieman et al. (2014) reprocessed the SEM data with the use of a new, more accurate response function, obtained from measurements performed using SEM clone instrument taken by a sounding-rocket after the SOHO launch, and a new measured solar reference spectra. The recalculation of the SEM data reduced the mean differences with the EVE measurements from about 20% to less than 5% in the 26 – 34 nm band, and from about 35% to about 15% for irradiances in the 0.1 – 7 nm band, extracted from the SEM 0.1 – 50 nm channel. However, the new corrected time series were not publicly available in an acceptable time manner and, in consequence, we were forced to remove the SEM data from the data sets used to the construction of the composite photoionization rate model for He.

Additionally, Snow et al. (2014) reported an improvement in the $\mathrm{MgII}_{c/w}$ data from SOLSTICE experiment. They found that after adjustments to the data from all of the instruments making daily measurements during the most recent solar minimum to account for instrumental effects, there are still discrepancies between the various time series. The data from the primary channel of the SOLSTICE requires a correction factor starting in early 2006 in order to bring it into agreement with the redundant SOLSTICE channel and with the other data sets. The discrepancy was increasing in time (see Figure 5 in Snow et al. 2014). The data were corrected and released for the public, but unfortunately, the SORCE has suffered also from degraded battery performance, and the last daily measurements of the $\mathrm{MgII}_{c/w}$ index from SOLSTICE were taken in July 2013. Because of this, we switched from the LASP composite $\mathrm{MgII}_{c/w}$ time series to the Bremen composite $\mathrm{MgII}_{c/w}$ time series.

We took into account all the required modifications and constructed a model of the photoionization rates for He based solely on the TIMED measurements of the solar irradiance and the F10.7 index time series for the time intervals when TIMED measurements are not available. We also improved the procedure to fit the relation between the CR averaged time series of photoionization rates and the F10.7 index data. We introduced a division into sectors and fit the power function to the averages for the sectors weighing by the standard deviation of the data inside the sector. We sectored the data sets because of nonuniform distribution of points on the photoionization rate - F10.7 scatter plot (see Figure 1 in Sokół & Bzowski (2014)). Such an uneven distribution of points along the correlation line may bias the fitted function. The sectors were defined according to the photoionization rate values, with an arbitrary, but constant step. For details of the model construction and the results we refer to Sokół & Bzowski (2014). The reconstruction of the photoionization rates for He, based solely on F10.7 index, gives rates about 10% higher than the proxy based model proposed by Bochsler et al. (2014) and differ up to 15% during solar maximum for the years before TIMED launch and more than 20% in the increasing phase of activity of SC 24 from the photoionization rates presented in Paper B2.

However, one should be aware that the reconstruction of the photoionization rates based on the measurements collected after maximum of SC 23 ($\sim$ 2000) and during the prolonged minimum $\sim$ 2008 should be performed with a special attention. The reported changes (decrease) in the solar particle and electromagnetic fluxes since SC 23 overlap with the secular degradation of the instruments that measure these quantities for a long time period. For example, Didkovsky & Wieman (2014) reported about a 12% decrease of the registered solar irradiance around the HeII line in the minimum of SC 23/24 in comparison to the minimum of SC 22/23. Such a decrease is not observed in some other solar quantities, like F10.7, but seems to exist in the CR averaged series of the $\mathrm{MgII}_{\mathrm{c/w}}$ index from the Bremen composite series. There exists a still unanswered question if the effect of a deeper minimum is a real physical phenomenon related to the changes on the Sun, or is it just an effect of degradation of detectors and cross-correlations between different instruments. Answering this question will only be possible in the future and is beyond the scope of this thesis.

3.3.2 Charge exchange with solar wind particles

The second important loss process for the ISN gas inside the heliosphere is the charge exchange with solar wind particles, mostly protons for He, Ne, and O, and also with alpha particles for He. The charge exchange for H is extensively discussed in Section *Charge Exchange* in Paper B1, but the theory applies to the other species, which are discussed in Paper B2 in Sections 2.2 and A.3. In our study we are interested solely in the charge exchange reaction in the supersonic solar wind, where the ISN gas atoms or ENAs created from the ISN gas interact with solar wind protons or alpha particles. If the ion encounters an atom at a sufficiently small distance, then an electron from the atom can be captured by the ion, producing an ion, which is picked-up by the local magnetic field, and an energetic hydrogen atom. The electron transfer can occur when the ion and the atom approach within $\sim 10^{-8}$ cm from each other and when their potential functions cross, then the reaction is a resonant charge exchange reaction. The reaction is considered in the frame of the mass center of the reacting particles and is more probable with an increase of the energy of reaction, which is inversely proportional to the impact parameter. In this kind of collision the momenta of the particles do not change and thus the particles maintain their trajectories immediately after the collision before they are modified by external forces (e.g., the solar gravity force or the Lorentz force due to the ambient magnetic field in the solar wind). As pointed out in Paper B1, the formula to calculate the charge exchange rate can be approximated by a product of the reaction cross section, which depends on the relative speed of the substrates, the relative speed of the substrates, and the density of the solar wind particles, in the case when the kinetic spread of the plasma is small as compared with the plasma flow velocity, as it is the case in the supersonic solar wind.

In our studies we used the method to assess the losses by charge exchange developed by Bzowski (2001, 2008) for H and Bzowski et al. (2012) for He. In the calculations of the rate of charge exchange in the supersonic solar wind we employed the model of the evolution of the solar wind speed and density in time and heliolatitude constructed as a part of this dissertation (Paper S1). In the case of H, He, and O the cross sections from Lindsay & Stebbings (2005) were used, and for Ne from Nakai et al. (1987). As presented in Figure 1 in Paper B2 and in Figure 3.7 in Paper B1, charge exchange is a significant ionization reaction for O and H, but it is practically negligible for the noble gases like He and Ne. For the noble gases it is at a level of $\sim$ 1% of the total rate, which is much less than the uncertainty in the photoionization rate. The charge exchange rate depends linearly on the solar wind density and consequently it features a decrease with the square of solar distance. Additionally, due to its direct dependance on the solar wind speed and density it features similar variations with time and heliolatitude as solar wind does, as illustrated in Figure 1 in Paper S3, where we demonstrate that the distribution of ISN O inside the heliosphere can be significantly affected by the latitudinal structure of the ionization rates. The dependence on solar wind speed is mitigated by the speed dependence of the reaction cross section, as illustrated in Figure 3.6 in Paper B1 for the case of H and in Figure A.7 in Paper B2, where the product of the speed and cross section for the studied species is presented. In Paper B2, the charge exchange for He, Ne, and O is discussed.

3.3.3 Electron impact ionization

Ionization by the impact of solar wind electrons is the third ionization process considered in our study. Its significance for the distribution of ISN gas in the heliosphere was pointed out by Ruciński & Fahr (1989, 1991) and further developed by Bzowski (2008); Bzowski et al. (2008). The electron impact ionization for H is described in Section *Electron Ionization* in Paper B1 and for He, Ne, and O in Sections 2.3 and A.2 in Paper B2. In our studies we follow the formula developed by Bzowski et. al for H and He, and extend them to the case of Ne and O, as presented in Appendix A in Paper B2. Electron impact ionization is calculated according the formula given in Equation 3.26 in Paper B1 (after Owocki & Scudder 1983), which depends on the energy of collision, energy distribution of the electrons in the solar wind, and the cross section for the ionization. In our study we use the cross sections given by analytic formulae in Lotz (1967b,a). The cross sections as a function of energy are illustrated in Figure A.6 in Paper B2. The procedure to calculate the ionization rate depends on the solar wind density, which in calculations comes from the solar wind density structure, developed in Paper S1.

Bzowski (2008) developed a model of electron ionization rate for H using measurements of electron distribution function from Ulysses. The distribution function of electrons with a cool core and a hot halo populations is approximated by a bi-Maxwellian model, with the abundance of the latter increasing towards increasing heliocentric distances. In general, the electron distribution function, with its all three components, core, halo, and strahl, should be approximated with the kappa function, like discussed in, e.g., Pierrard & Lazar (2010); Yoon et al. (2015). But for the case study of the ionization losses the approximations made by Bzowski (2008) are sufficient. The model of radial dependence of electron impact ionization rate was developed using the assumption of quasi-neutrality to obtain the electron density. The model values are proportional to solar wind density plus twice the alpha particle content. The Bzowski (2008) model gives formulae to calculate the electron impact separately for the fast and slow solar wind, and to follow this approach criteria for an unambiguous classification of the solar wind flow as slow or fast are required. For this, however, the knowledge solely about the speed and density is not sufficient, also other quantities, like the abundance of heavier species should be known (e.g. Thatcher & Müller 2011; Wawrzaszek et al. 2015; Xu & Borovsky 2015). In Paper S1 we do not classify unambiguously the solar wind into the fast and slow. By fast and slow we mean only high and low speed streams. Thus we are not able to distinguish between the fast and slow solar wind with the use of the model from Paper S1. Fortunately, the ISN gas atoms which IBEX observes travel close to the ecliptic plane at a few AU before detection, where the slow (i.e. low speed) solar wind dominates and the approximation of the electron impact ionization in the slow solar wind is sufficient.

Electron ionization plays a significant role in the ionization of He and Ne, for H and O it is almost negligible, as illustrated in Figure 1 in Paper B2 and Figure 3.7 in Paper B1. It needs special attention because it does not decrease with the solar distance as r^{-2}, like photoionization or charge exchange do. Figure 2 in Paper B2 compares the radial dependence of electron impact ionization derived from observations with the r^{-2}-dependence, the decrease is much faster. It is a consequence of the distribution function of the electron in the solar wind and its non-adiabatic cooling with solar distance. The abundance of the halo population relative to the core varies with heliocentric distance. The cooling rates of the two populations are also different and change with solar distance and the solar wind speed regime (see, e.g., a review given in Issautier 2009).

3.3.4 Survival probabilities

The ionization losses are inversely proportional to effective survival probabilities for ISN atoms inside the heliosphere. The procedure to calculate the survival probabilities is presented in Section 3 in Paper B2 for the case of ISN gas and in Appendix B in Paper M1 for the case of H ENAs observed by IBEX (see also Section 6 in this description). The theory of survival probabilities for atoms on Keplerian trajectories was presented by Blum & Fahr (1970) and Axford (1972) for the case of ionization rates constant in time and decreasing with the square of the solar distance, and subsequently developed by Ruciński et al. (2003) for the case of time-dependent ionization rates. In our calculations we followed the approach proposed by Bzowski & Tarnopolski (2006) and Bzowski (2008).

In general, survival probabilities of an atom on a given trajectory between two selected points are calculated by integration of the exposure of the atom to ionization along the trajectory inside the heliosphere (Equations 2 and 3 in Paper B2 and Equation B1 in Paper M1). The trajectories of atoms are governed by the joint action of solar gravity and, in the case of H, solar resonant radiation pressure due to solar Lyman-α photons. The total ionization rate was calculated as a sum of the rates of the relevant ionizing processes. The instantaneous ionization rate varies due to the changes in the heliocentric distance from the Sun (the spatial effect) and due to the evolution of the ionizing factors in time (the time effect). Figure 3 in Paper B2 presents the joint action of these two effects on the exposition, it is the integrand function for the survival probabilities in the case of numerical calculation with careful tracing of the time and spatial variation of the ionization rates along the trajectory compared to the analytical approach with ionization constant in time and falling down with squared distance from the Sun.

A further discussion of survival probabilities for H ENA flux observed by IBEX is presented in Section 6, and for ISN He, Ne, and O in Section 4. In the survival probability assessment we used the charge exchange with solar wind protons calculated with the use of the evolution of the solar wind heliolatitudinal structure, developed in Paper S1. The photoionization and electron impact ionization rates were calculated following the models described in Paper B1 for He and Paper B2 for He, Ne, and O.

3.3.5 Discussion of uncertainties

Sections 3.2 and 3.4 in Paper B2 present a discussion of the uncertainty of the ionization rate model and its influence on the calculated survival probabilities. To assess the uncertainties of survival probabilities two sources should be considered. First, the uncertainty of the ionization rates. Second, the uncertainty of the velocity vector of the inflow of ISN gas. The latter one is out of the scope of this description, a comprehensive discussion is presented by Bzowski et al. (2012) and Swaczyna et al. (2015). However, the uncertainty of the ISN flow velocity vector affects the survival probabilities in a systematic way, if only the inflow vector does not vary in time. In general, for a greater (smaller) speed, the exposure to ionization is shorter (longer) and, in consequence, the survival probabilities are higher (smaller), but the change is consistent for all species and independent on the phase of solar activity.

In Section 3.2 in Paper B2 we discuss the uncertainties of survival probabilities due to the uncertainties in the ionization rates by derivation of the uncertainties of the exposures to photoionization, charge exchange, and electron impact losses. The exposures are affected by the uncertainties of the measurements of the parameters that construct the given ionization rates. We assumed a normal distribution of these measurements, which enables us to use the error propagation approach (Equation 9 in Paper B2). Table 1 in Paper B2 summarizes the relative uncertainties of parameters adopted for the estimates based on the best knowledge we had following the literature and the documentation released with the data.

There are at least two sources of data uncertainties that should be taken into account. The uncertainty related with the measurements of the quantities we use in the calculations, which in the case of long time series may be affected by a change of the detector sensitivity, or in the case of a series composed from various sources, by different technique of sampling or instrumental differences between the detectors. The second uncertainty is the systematic uncertainty related to the cross sections used in the calculations and assumed distribution functions (Table 1 in Paper B2). These are known with a higher accuracy than the uncertainties of data sets.

In the case when the information of the uncertainties of the data sets we use in the calculation is not easily available we tried to assess it by the statistical analysis of the time series (e.g., for the case of TIMED data at the time when the composite photoionization rate model was constructed) or by the comparison of model results with the in-situ measurements, as we did in the case of solar wind speed and density constructed in Paper S1. In the latter one, we compare the results of the model with the Ulysses data. The comparison showed that the differences for the solar wind speed are up to 10% for most of the time with increase to $\sim$ 20% during solar maximum or when Ulysses scans the highest latitudes. For the solar wind density the agreement is worse, about 20 – 30% or higher during solar maximum. This is due to the approach we adopt to reconstruct the solar wind density from the solar wind speed, which is only a simplification; see also discussion in Section 3.2.3.

Figure 6 in Paper B2 presents the survival probabilities for ISN He, Ne, and O due to the individual ionization processes and the total effect together with the assessed uncertainty ranges. For ISN He and Ne the estimated uncertainty is about 10 – 20%, but for ISN O it is higher, up to 50%, and it does not vary significantly with the solar cycle. Figure 7 presents the modulation of the survival probabilities for the ratios Ne/He, O/He, and Ne/O together with the uncertainty range, in the case of O/He, the survival probability ratio is the much uncertain during the solar minimum and can vary from about 0.03 to 0.07.

The method to calculate the uncertainty of survival probabilities presented in Paper B2 is simplified and can be use to assess only the order of magnitude of the uncertainty. A much thorough study is required to correctly assess all sources of uncertainties and their variation in the solar cycle. Such an assessment of the uncertainties should be scope of future works.

3.4 Outline of applications

The model developed and described in Paper S1 is used to calculate charge exchange ionization rates for the ISN species presented in Paper B2, Paper S5, Paper S4, and Paper S3, and to calculate the probability of ionization for the H ENAs observed by IBEX-Hi that are discussed in Paper M1 and Paper M2. The model with higher resolution described in Paper S2 has not been employed yet for these purposes for the reasons given in Section 3.2.3.

The solar wind model developed in Paper S1 was implemented in the calculation of the charge exchange and electron impact ionization rates used to assess the ionization losses of ISN gas and ENAs inside the heliosphere. The photoionization rate model described in Appendix A in Paper B2 was used to calculate the losses due to the solar EUV radiation for He, Ne, O, and H. In the case of He, the update model described in Sokół & Bzowski (2014) has been in use since 2014. The ionization rates are used in the calculation of the survival probability correction, applied in the analysis of the ENAs observed by IBEX. The general review of H ENA maps from IBEX is presented by McComas et al. in Paper M1 and Paper M2. In these papers, in the respective Appendices B, the details of the used models are presented. The developed models of the ionization losses are also used to analyze the ISN gas in the heliosphere. In Paper S3, we study the density of ISN He, Ne, and O and their PUIs at the Earth's orbit over the period from the maximum of SC 23 to the maximum of SC 24. In Paper S4, the role of ionization rates for the analysis of the ISN He observed by IBEX-Lo is discussed.

In addition to the papers that construct the thesis, the composite model of photoionization rates for ISN gas inside the heliosphere was applied in several other studies[10]. It was used by Bzowski et al. (2012) to study the inflow direction of the ISN He from the first two years of IBEX-Lo operation. Chen et al. (2013) used it to analyze the interstellar He PUIs observed by ACE. The long, continuous, and homogeneous time series of photoionization rate for He were used in the review of investigations of ISN He flow since the space age, presented by Frisch et al. (2013, 2015). Fisher et al. (2016) used the ISN He densities and ionization rates to assess the production rate of He PUIs in the search for plasma waves produced by PUIs in the data from ACE.

The model of the evolution of the solar wind structure and the photoionization rate model were applied to the calculation of the ionization losses inside the heliosphere. They support the study by Galli et al. (2013) of the H ENAs from ASPERA-3 and ASPERA-4 experiments on the planetary missions Mars- and Venus-Express, respectively. Katushkina et al. (2013) used the heliolatitudinal structure of the solar wind speed to investigate via modeling the back-scattered solar Lyman-α intensity maps. The total ionization rates were applied by Kubiak et al. (2013) and Rodríguez Moreno et al. (2013, 2014) to detect the ISN D inside the heliosphere. Saul et al. (2013) used the ionization rates to the study of ISN H in the IBEX-Lo observations, whereas, Desai et al. (2014) and Schwadron et al. (2014) used the survival probabilities for H ENAs to study the heliosheath ENA populations and separate the IBEX ribbon from the globally distributed flux, respectively. Fuselier et al. (2014) and Galli et al. (2014, 2016) used them to study the low energy H ENA. Furthermore, Swaczyna et al. (2016)

[10] In this section we discuss only the articles in which Justyna M. Sokół is a co-author.

used the heliolatitudinally organized solar wind from Paper S2 to explain the energy dependence of the IBEX ribbon center.

The ionization rate model was implemented in the study of the ISN gas inside the heliosphere. Bzowski et al. (2014) used it to reanalyze the Ulysses *Interstellar Neutral Gas* (GAS) experiment measurements. The analyzed measurements covered nearly two solar cycles and the large time span and homogeneity of the ionization model was indispensable in this analysis. Bzowski et al. (2015); McComas et al. (2015a,b); Möbius et al. (2015a,b); Schwadron et al. (2015); Swaczyna et al. (2015) used the ionization rate model to the analysis of the first five years of IBEX-Lo observations of the ISN He and retrieval of the physical state of the matter in the LISM in front of the heliosphere. The model supported also the study by Kubiak et al. (2014); Kubiak et al. (2016) of the Warm Breeze population of neutral helium inside the heliosphere. The ionization rates for Ne and O were used to study of the possible contamination of the Ulysses observations of ISN He by ISN Ne and O, analyzed by Wood et al. (2015), and by Park et al. (2014) and Galli et al. (2015) to analyze the observations of ISN Ne and O by IBEX-Lo. Analysis of survival probabilities was particularly important in the study of Ne/O abundance ratio in the Local Interstellar Cloud (LIC) presented by Park et al. (2014), since the original ratio in the unperturbed gas is heavily modified due to differences in the survival probabilities of Ne and O in the heliosphere, as discussed in Paper B2.

4 ISN He, Ne, and O in Earth's orbit

The study of ISN He, Ne, and O is one of main subjects of the papers that construct the thesis. In Paper B2, the densities, fluxes, survival probabilities, and abundances of the ISN gas species at Earth and as observed by IBEX are discussed in detail; in Paper S3 the densities and pick-up ions in the vicinity of Earth over almost full solar cycle are discussed; and Paper S4 and Paper S5 present the modeling of the ISN He observed by IBEX-Lo. In Paper S4, the newest version of the Warsaw Test Particle Model (WTPM), in its current two operational versions, is presented. In Paper S5, we discuss the perspectives for observing hypothetical departures from the standard assumptions on the distribution function of the ISN He gas in the LIC in the case of IBEX observations. In Paper B2, we also present the significance of the ionization losses and the assumed inflow parameters of the ISN gas in front of the heliosphere on the Ne/O abundance in the LISM based on the measurements made by IBEX (a detailed discussion of the retrieval of the Ne/O abundance ratio is presented in Bochsler et al. (2012) and further developed in Park et al. (2014)).

The WTPM has been developed in Space Research Center PAS since 1990-ties, with the first version published by Ruciński & Bzowski (1995) and Bzowski et al. (1997). It is a hot model of ISN gas distribution in the heliosphere that follows the approach given by Thomas (1978); Fahr (1978); Wu & Judge (1979). The theoretical basis for the model is described in detail in Section 2 in Paper S4 and in Section *Brief Description of the Physics of the Neutral Interstellar Gas in the Inner Heliosphere* in Paper B1. Subsections 2.1 and 2.2 give a general picture and the following subsections discuss in detail the application to IBEX-Lo observations.

4.1 Densities and survival probabilities

Paper B2 presents in Figure 9 the densities of ISN He, Ne, and O at Earth for the portion of the orbit where the IBEX measurements of ISN gas are collected. The discussion is in support of an assessment of the abundances of the ISN species in front of the heliosphere and inside it, presented in Figure 11 there. In Paper S3, we studied the evolution of the ISN gas densities observed from the Earth's orbit due to the solar cycle modulation. We do not adjust the model to any spacecraft to study the signatures governed just by the ionization inside the heliosphere. The densities in both papers were calculated with the use of the hot model of the gas distribution, implemented in WTPM. In the calculations presented in Paper S3, the solar wind model from Paper S1 was used, and the photoionization rates were taken from integration of spectra measured by TIMED/SEE (e.g., Sokół & Bzowski 2014; Bochsler et al. 2014). In this paper we discussed the evolution of densities from the perspective of an observer moving with the Earth around the Sun, i.e., there was a strict correspondence between the calendar day and ecliptic longitude in the calculation scheme and, additionally, the observer never crossed the cone at its peak due to the inclination of the inflow direction to the ecliptic plane.

The modulation of the ISN He, Ne, and O densities as observed from the Earth's orbit from 2002 to 2013 is presented in Figures 2 and 3 in Paper S3. Figure 4 presents how different assumptions about the ionization rate used in the calculations affect the resulting density time series. As an example species we selected ISN O, because it is the most affected by charge exchange with solar wind protons, which varies significantly with latitude and time. Having discussed the role of individual effects in the formation of the density pattern encountered by Earth, we analyzed these patterns calculated using the model with all effects included. We showed that the expected densities of ISN gas at the Earth's orbit are significantly modulated in time due to variations of the ionization rate during the solar cycle (Figures 2, 3, and 6 in Paper S3).

The density of ISN He observed from the Earth's orbit is almost constant around the Sun, with a strong increase at the downwind side of the gas flow, where the focusing cone forms due to the action of solar gravity. In the cone region, the density for He increases a few times. The density for Ne varies similarly to He only during solar minimum, when ionization losses are small. During solar maximum, as well as the increasing and decreasing phases of solar activity, the density time series for Ne starts to transform at the upwind side into an enhancement, called a crescent. The upwind crescent is a feature that is the most pronounced structure in the density time series of ISN O. It exists in the ISN O density series independently of the phase of solar activity. Additionally, the cone for density of ISN O is modified so much that during solar maximum the observer at Earth may miss it almost absolutely. Since identical inflow velocity vectors and temperatures were assumed for all species, the different formation of cone and crescent structures in the ISN He, Ne and O time series may potentially be due to the differences in the thermal/bulk velocity ratio or the differences in the ionization intensity. Our analysis suggests it is the latter one that is responsible for these differences.

As presented in Figure 4 in Paper S3, the time and latitude dependent effects in the ionization rates are important, because they significantly affect the density time series. They are responsible for the modulation of the magnitude and the asymmetries in the crescent and cone. These features could serve as indicators of the ISN gas inflow direction if they could be directly observed. However, as presented in Figures 10 and 11 in Paper S3, the position of the cone peak for O is systematically shifted with respect to the ISN gas flow axis, whereas for He and Ne it indicates almost precisely the flow direction. Different conclusions come from the study of derivation of the inflow direction from the crescent structure. Its peak, derived from fitting a Gaussian function, deviates strongly from the expected value. The deviations seem to follow the solar cycle, but in a very faint way. The study illustrated in Figure 11 in Paper S3 suggests that this is due to the variability of the cone and crescent structures due to the modulation of ionization in time and in heliolatitude. Additionally, as we discuss in Paper S3, the retrieval of the peak position from the fit of the symmetric function is not adequate, because the features, especially, the broad cone, are not symmetric, because of gradients in density time series.

In Paper B2, we present a study on the variation of the ISN gas abundances in the heliosphere and possibilities of their assessment based on supporting values, i.e., survival probabilities or flux ratios. In Section 3 therein, we first discuss the survival probabilities for the ISN gas inside the heliosphere under the commonly made assumptions (simplifications) in their calculations, like, e.g., neglecting the variation in time or assuming spherical symmetry of the ionization rates based on the in-ecliptic values.

Figure 3 in Paper B2 illustrates the integrand function for the survival probability for O for two cases, with and without time dependence of the ionization rates along the particle trajectory inside the heliosphere. As clearly visible, the exposure to ionization (Equation 3 in Paper B2) can significantly differ. Figure 5, therein, presents the ratios of the survival probabilities calculated analytically and numerically for He, Ne, and O. This comparison indicates that the analytic treatment of the ionization losses inside the heliosphere is a good approximation for He and also for Ne, but only during solar minimum. For the times when the activity increases the simplifications break and may significantly affect the results. The analytic modeling of survival probabilities for O is not acceptable, because it introduces differences up to $\sim$ 40%. These conclusions are partially explained by inspection of Figure 4 in Paper B2, which illustrates the time series of survival probabilities for He, Ne, and O over the solar cycle in the top panel, and the solar cycle variation of its magnitude in the bottom panel. He is the least affected species among the three in question. Its flux can be reduced inside the heliosphere up to 50% during solar maximum, but this is much less than that of Ne and O. Only 5% of Ne atoms and less than 3% of O atoms survive the travel to the Earth's orbit. The amplitude of modulation of survival probabilities during the solar cycle is the largest for O and Ne, and the smallest for He. Section 3.2 in Paper B2 presents an assessment of uncertainties of survival probabilities (also in Section 3.3.5 in this description).

The ratio of survival probabilities for given pairs of species can be used to assess the abundance of these species in different parts of the heliosphere. If only these abundances are known at the termination shock in the upwind region of the heliosphere, the ratios of survival probabilities enable assessment of the abundances expected to be measured in the vicinity of the Sun (or Earth). With the known ratio of survival probabilities the study can be done in the opposite direction, it is an assessment of the abundances of given species at the termination shock if the ratio of fluxes is measured from the vicinity of Earth. The time series of the Ne/He, O/He, and Ne/O abundances are presented in Figure 7 in Paper B2. The Ne/He and O/He survival probability ratios vary with the solar cycle, being the smallest during solar maximum and the highest during solar minimum. The Ne/O survival probability ratio does not vary with solar cycle; its variation follows the long-term changes in the in-ecliptic solar wind.

The survival probability ratios depend not only on the variation of the ionizing solar factors inside the heliosphere, but also on the parameters of the flow of the ISN gas to the heliosphere. A variation of survival probabilities as a function of the inflow speed and ecliptic longitude of the ISN gas is presented in Figure 8 in Paper B2. The ratios increase with the increase with decrease in longitude and increase in speed. A similar study was done for densities and fluxes of the ISN gas inside the heliosphere. Results are presented in Figures 11 and 14 in Paper B2.

The knowledge of the ratio of survival probabilities for the ISN species inside the heliosphere enables assessment of the abundances in LIC. Bochsler et al. (2012) presented such an investigation based on the fluxes of Ne and O measured by IBEX. We used the measured Ne/O flux ratio and the filtration factor in the heliospheric interface from their analysis and studied how the abundances vary when the history of ionization rates inside the heliosphere is traced as precisely as we can do with our ionization model and when the parameters of the ISN gas flow are varied. The results are presented in Figure 17 in Paper B2. The Ne/O abundance in the LIC is lower than the values found by Bochsler et al. (2012) and is closer to the value expected on the Sun. In general, the Ne/O abundance increases with flow speed and decreases with the increase of the flow longitude. The most recent analysis of the Ne/O abundance based on the measurements of IBEX is presented in Park et al. (2014). Their study indicates that the Ne/O ratio is about twice the ratio found by Bochsler et al. (2012), which is due to a revision of the procedure to extract the Ne/O flux ratio from the IBEX measurements. The survival probability analysis in Park et al. (2014) was done using our model of the ionization rates, following the insight from Paper B2.

4.2 Pick-up ions

The ISN gas that enters the heliosphere is ionized by the solar corpuscular and electromagnetic radiation. AS a result of the ionization process, an interstellar atom loses an electron and becomes an ion that is picked-up by the ambient magnetic field. This way a population of interstellar PUIs is created inside the heliosphere. PUIs have been observed from the vicinity of Earth since 1980-ties (Möbius et al. 1985). The observed PUI flux is expected to reflect the structure of the density of the ISN gas close to the Sun and to serve as indirect indicator of the inflow direction. In consequence, the PUI flux has been extensively studied for many years with the use of data from various missions (*Active Magnetospheric Particle Tracer Explorers* (AMPTE), Ulysses, ACE, *Solar TErrestrial RElations Observatory* (STEREO)) to support other studies aimed to determine flow direction of the ISN gas in front of the heliosphere (e.g., Möbius et al. 1985; Gloeckler et al. 1993; Geiss et al. 1994; Gloeckler et al. 2004; Möbius et al. 2004; Drews et al. 2012).

The analysis of PUIs measured by STEREO published by Drews et al. (2012) indicated that the ISN gas direction inferred from the cone and crescent may be different from that published in other studies. This encouraged us to check if the observed shift could be due to the modulation of the ionization inside the heliosphere. We present and discuss the results in Paper S3. Potentially, the shifts in the PUI series may be due to either parent density, PUI production rate, or both of them. Thus we investigated both those hypotheses. The expected effects in the density series calculated using the full time and heliolatitude-dependent hot model of ISN gas inside the heliosphere were briefly presented in the previous section. Next we looked into the expected PUI production rates and count rates. In the calculation of the PUI production rate to be measured by an idealized detector, we followed the approach presented in Ruciński et al. (2003). The PUI count rate was calculated using the classical theory of the creation and evolution of the PUI distribution function in the solar wind, assuming a distance-independent solar wind speed, instantaneous pitch angle isotropization, and adiabatic cooling of PUIs. Instead of the typically made assumption of a zero injection speed of PUIs relative to the Sun, we assumed that their injection speed is equal to the local radial component of the ISN gas bulk velocity, characteristic for the heliocentric distance and ecliptic longitude of the injection location. We analyzed the evolution of the radial component of ISN He along the Earth's orbit (Figure 7 in Paper S3) and modifications of the PUI distribution function due to the finite injection speed. This latter effect was first discussed by Möbius et al. (1999). The derivation of the PUI production rate and the PUI count rate under these assumptions is given in Equations 6 and 7 and Appendix A in Paper S3.

Our results show that the longitudinal series of PUI production rates are in general similar to those of density series, whereas the PUI count rates may differ. While a two-peak structure of both the PUI production rate and the expected PUI count rate is evident for Ne and O, with broad maxima upwind (the crescent) and narrow peak downwind (the cone), the upwind crescent is absent for He. This upwind structure is visible only in count rate, which is proportional to the power $\frac{9}{2}$ of the PUI speed in the integrand (Equation 7 in Paper S3, compare with the definitions of the flux in Equations 6). The integration of the PUI distribution function leads to the creation of the crescent in the He PUI count rates.

It could be expected that the longitudes of the measured cone and crescent peaks will indicate the downwind and upwind longitudes of the ISN gas flow in the heliosphere. The peak positions derived from the cones and crescents observed by a stationary spacecraft at the Earth's orbit presented in Figure 10, for the case of ISN density and PUI production rate, and in Figure 11, for the case of the PUI count rates, indicate that there are expected shifts. They are due to the solar cycle modulation. The shifts are the smallest for He, the biggest for O. Results obtained for the cones are closer to the expected value than for the crescents. The peak positions for the downwind cone indicate a year-to-year variation and are scattered around the expected value for the case of He and Ne, and feature a systematic downward trend for O. The inflow direction derived from the crescent is less accurate and shows a solar cycle variation for Ne and O. The differences can be as much as a few degrees. The average value of the shifts over the solar cycle does not average to zero, because of a downward trend in the ionization rate superimposed on the solar cycle variation. Additionally, in our study we do not reach the peak of SC 24, and we could not find out if the downward trend in the inferred flow direction for the crescent would stop. The shifts of the crescent are mostly due to the non-balanced temporal trends in the global ionization rate during the calculation interval, and the shift in the cone is due to the departure of the charge exchange and electron impact ionization rate from spherical symmetry, which is most prominent for O, but weakly affects Ne and He.

5 ISN He in Earth's orbit: perspectives

The group in the *Laboratory for Solar System Physics and Astrophysics* in SRC PAS has been studing the ISN gas since 1990-ties, as already mentioned in Section 4. The team led by Maciej Bzowski participates actively in the analysis of the ISN He observed by the IBEX-Lo detector (e.g. Bzowski et al. 2012; Bzowski et al. 2015). The study revealed that in addition to the expected signal from the so-called primary population of ISN He[11], IBEX measures also a statistically significant signal, which very likely is the secondary population of the ISN He[12], dubbed the Warm Breeze by (Kubiak et al. 2014; Kubiak et al. 2016). The finding of an additional signal of the ISN He gas and the studies by Galli et al. (2014) and Fuselier et al. (2014) about the unexplained background in IBEX data encouraged us to look closer into the expected full sky distribution of the ISN gas, observed by IBEX. The results are presented in Paper S5 and in an extended version of the studies which were presented at the American Geophysical Union (AGU) Fall Meeting 2015 by Sokół et al. (2015a). In the research we used the analytic version of the WTPM software. The fundamentals of the WTPM, as well as a description of its two operational versions, analytic (aWTPM) and numerical (nWTPM), together with the discussion of the adjustment to the IBEX instrumentation and sampling geometry, are extensively presented in Paper S4.

The aWTPM software is implemented in the `Wolfram Research Mathematica` computional package and can be used on a personal computer. It follows the paradigm of the hot model of the gas distribution in the heliosphere, but without tracking of the history of ionization along the particle trajectory inside the heliosphere. Such an approach is justified in the modeling of ISN He because it does not bias the results significantly, as discussed in Paper B2 and illustrated in Figure 5 there. Additionally, we were interested in a qualitative, not quantitative study of the ISN He inside the heliosphere, and the fine scale affects could be neglected. In the research we focused on two aspects. Firstly, we checked whether the unexplained background and elevated wings in the ISN He observations made by IBEX could be a result of the distributed flux of the ISN gas inside the heliosphere. Secondly, we checked if it is possible that the observed signal interpreted as the Warm Breeze, modeled by using the source function given by the Maxwell-Boltzmann velocity distribution function, is not in fact a signature of the non-thermal distribution function of the ISN He in the LIC, given by the kappa function. This would drastically change the physical interpretation of the Warm Breeze and reveal the presence of departures of the ISN gas in the LIC from thermal equilibrium. Consequently, we also studied the possibilities to detect the departures from the standard assumptions about the distribution of the ISN He in the heliosphere in the IBEX data. As our results show, the observational signatures from such departures in the gas distribution are weak and IBEX is likely not able to provide definite answers, because of the lack of required signal to noise ratio and because the relevant parts of the signal are contaminated by the magnetosphere.

In Paper S5, we constructed full sky maps of the ISN He as seen by IBEX-Lo for various assump-

[11] The particles of interstellar gas that entered the heliosphere unperturbed by the heliospheric boundary region.

[12] The secondary population of ISN gas is composed of former interstellar ions that have been neutralized via charge exchange in the outer heliosheath. We follow the nomenclature proposed by Baranov et al. (1998).

tions about the distribution function of the gas in the source region and the energy sensitivity of the instrument. Figure 2 there presents the ISN He flux given by the Maxwell-Boltzmann distribution at the source as it would be seen by the detector at rest. Two peaks, the so-called fall and spring, are clearly visible. Figure 5 presents the same case, but for the real detection conditions, it is with the spacecraft motion taken into account. The motion of the detector with respect to the flow strongly reduces the fall peak and enhances the spring peak, the one that is used to infer the inflow parameters in the primary analysis of ISN He (Bzowski et al. 2012; Möbius et al. 2012; Bzowski et al. 2015; Möbius et al. 2015a,b; Schwadron et al. 2015). Figure 7 extends the case presented in Figure 5 and presents the map of the ISN gas given by two populations, the primary population and the Warm Breeze. Now, the signal features a bright and narrow peak around IBEX orbit 64 and a weak and broad fore-tail at the preceding orbits. Figures 6 and 8 in Paper S5 illustrate the maps of the ISN He gas modeled using the kappa distribution function in the LIC with different reference speeds (Livadiotis & McComas 2009, 2011, 2013). The pictures are similar, but differ in detail, especially for the region of fall peak and after the spring peak.

The map presented in Figure 9 in Paper S5 illustrates the observations. The campaign of observation of the ISN He gas is limited to nearly three months during a year. The signal is strong in the ram hemisphere and blank in the anti-ram hemisphere. Additionally, there is a high background in the energy band 2 (19 – 38 eV), which has been used in the analysis of ISN He. Figures 12 and 13 in the paper present the simulations of the global ISN He signal given by different distribution functions in the LIC adjusted to the energy band of the observations. The modeled structures are closest to the observations for the case of a signal given by the sum of the primary population and the Warm Breeze, both given by separate Maxwell-Boltzmann functions in the LIC. The map given by kappa distribution function in the LIC differs for the post-peak orbits and predicts that the signal should be higher there. These findings confirm the results of the preliminary study made by Kubiak et al. (2014) that the signal detected in the pre-peak orbits is very likely a secondary population of the ISN gas. However, the post-peak signal, which is still challenging to interpret, can hide a signature of the non-thermal gas distribution in the LIC. A more thorough study of the post-peak data and a more careful searching for the parameters of the kappa function is required.

Modeling of the ISN related signal observed by IBEX-Lo away from the peak was utilized to asses the low-energy threshold in the IBEX-Lo sensitivity to the He atoms. This element of the instrument calibration could not be done on ground before launch. We focused on the region of the sky where the fall peak of ISN He would be visible in the absence of the sensitivity threshold. This region was chosen because the kinetic energy of ISN atoms impinging on the detector is the lowest. We calculated the expected signal assuming that it comes up due to the primary ISN He and the Warm Breeze populations, and that the energy sensitivity of the IBEX-Lo is given by the step located at a number of energies. The differences between the expected signals for different values of the energy threshold are illustrated in Figures 7, 10, 12, and 14 in Paper S5, as well as in Figure 9 in Galli et al. (2015).

Based on a comparison of these model results with observations, Galli et al. (2015) found that the energy threshold in the IBEX-Lo sensitivity definitely exists, and the lower energy threshold for

He sputtering H lies between 25 and 30 eV. At this phase of research, it cannot be determined more precisely, because the more quantitative calculations depend on the adopted inflow parameters of ISN He and Warm Breeze. Nevertheless, the assessment of the sensitivity threshold was important in the determination of the Warm Breeze speed, temperature, and relative density, obtained by Kubiak et al. (2016). They found that the Warm Breeze parameters may be sensitive to this threshold and accordingly selected a subset of the data that, according to the modeling performed in Paper S5, are most likely insensitive to the sensitivity threshold value.

Studies of signals due to departures from the standard assumption about the ISN gas in the LISM will be continued. We plan to determine the most promising goals for the study with the use of the specification of the coming interstellar mission, a successor of IBEX, the *Interstellar Mapping and Acceleration Probe* (IMAP) [13].

[13]IMAP is planned to be the next Solar Terrestrial Probe mission of NASA's Heliophysics Division as defined by the National Research Council (NRC; an arm of the United States National Academies) "The 2013–2022 Decadal Survey for Solar and Space Physics (Heliophysics)".

6 Modulation of H ENA flux

The H ENAs observed by IBEX are created due to charge exchange between the ISN H and ions in the heliosheath. Only the IBEX ribbon ENAs likely originate beyond the heliopause. The parent population of ENAs is the interstellar gas that pass the heliosphere, and in consequence, ENAs can be used as tracers of the processes and physical state of the matter in the outer regions of the heliosphere (i.e., outward of the termination shock). The significance of ENAs for the study of the heliosphere and it interaction with the LISM was discusses by, e.g., Gruntman (1997); Gruntman et al. (2001) and in McComas et al. (2004); Fahr et al. (2007); McComas (2009), where the preparation for the first dedicated heliospheric ENA imager, IBEX, are described. Some other instruments, like *Ion and Neutral Camera* (INCA) onboard Cassini (e.g. Krimigis et al. 2009) or *High-Energy Suprathermal Time-of-Flight* (HSTOF) sensor of the CELIAS experiment on SOHO (e.g. Hsieh et al. 2004; Czechowski et al. 2005; Hilchenbach et al. 2006) or the *Analyzer of Space Plasmas and Energetic Atoms* (ASPERA) experiment on the Mars and Venus Express missions (e.g., Galli et al. 2013) also observed ENAs from the outer regions of the heliosphere, but their limited spatial and temporal coverage of the sky or their specific energy range make them less suitable for systematic studies of the heliosphere and its boundaries.

Paper M1 and Paper M2 present a summary of H ENA observation made by IBEX over the first three and five years, respectively. An important part of the analysis of the observed fluxes is the correction for the ionization losses, which enables to deconvolve the inside-heliosphere effects and infer the information about the ENA source region. The correction is performed by assessment of the survival probabilities for the atoms inside the termination shock.

The survival probabilities characteristic for individual pixels on the full sky map measurements collected by IBEX are calculated by integration of the ionization probabilities for individual atoms with the relative energy with respect to the spacecraft taken into account. The energy is equal to the center energy of the given energy step of the instrument in which enter the atom through the collimator. The individual contributions are weighted by the collimator transmission function for the given offset angle from the instrument boresight. Details such as transforming the velocity vector in the reference frame of the moving spacecraft to the heliocentric frame are addressed similarly as it is described for the case of integration of the ISN signal in Paper S4 (see Equation B7 in Paper M1). Ultimately, all details such as the spacecraft motion, orientation of the FOV, spacecraft position in the heliocentric frame, are taken in to account. In the last step the effective survival probability for a given pixel at a given orbit is averaged over the duration of the observation time for this orbit.

The heliolatitudinal structure of the solar wind is essential in the assessment of H ENA survival probabilities adopted to correct the full sky maps observed by IBEX. The magnitude of survival probabilities in the ecliptic plane follow the in-ecliptic changes of the solar wind and thus changes very little on a multi-year timescale. It is because, during the IBEX operation, long-term changes were practically absent in the equatorial solar wind, like those presented in Figure 35 in Paper M1. Figure 37 there illustrates the variation of in-ecliptic survival probabilities on the CR-averaged and yearly time scales since the beginning of the mission. Long time trends are not present. The situation is different for the polar lines of sight, which show a systematic decrease in time until 2012 for the north hemisphere and until 2013 for the south hemisphere. Afterward, the survival probabilities start to increase, as illustrated in Figure 33 (and in Figure 6) in Paper M2. The decrease and subsequent increase is present for all energies. They are related to the change in the global solar wind structure, which varies with the cycle of solar activity. The increase of solar activity in the second half of 2009 resulted in an expansion of the slow and variable equatorial solar wind to higher heliolatitudes. The expansion was north–south asymmetric, being faster in the north hemisphere than in the south. The variation of survival probabilities traces the variation of solar activity almost immediately because most of the ENA losses due to ionization occur within the last few weeks or months before the detection.

In Appendix B in Paper M1 we discuss the systematic effects and the evolution of survival probabilities with time in the case of IBEX observations. Figure 39 therein illustrates the spectra of the effective survival probabilities of H ENA for the LOS toward the north and south ecliptic poles and in the ram and anti-ram directions, as well as the ratios of these spectra. The survival probabilities increase with the increasing H ENA energy in the solar inertial frame. The in-ecliptic spectra vary very little with time, which is due to relatively small changes in the ionization rate in the equatorial band. The differences in time for polar spectra are much more pronounced and are due to the variation of the heliolatitudinal structure of the solar wind speed and density with the solar cycle.

Figure 39 in Paper M1 illustrates the importance of accurate correcting for ionization losses. Inaccuracies in survival probabilities are directly conveyed into inaccuracies of the spectral indices of ENAs, derived from IBEX measurements. The evolution of those spectral indices with time and their variation with the location in the sky provide important information on the processes operating in the ENA source region and have been studied in many papers, e.g., in addition to Paper M1 and Paper M2, by Dayeh et al. (2011); Dayeh et al. (2012, 2014); Desai et al. (2012); Desai et al. (2014); Desai et al. (2015); Fuselier et al. (2012, 2014); Galli et al. (2016), and also by Galli et al. (2013) for pre-IBEX ENA observations from Mars and Venus Express. The question of the continuously monitored ENA fluxes observed towards the north and south ecliptic poles, where the survival probabilites are needed on one hand to address the temporal changes at the highest available resolution, and on the other hand the north/south asymmetries must be compensated for, were studied by Allegrini et al. (2012) and Reisenfeld et al. (2012, 2016).

Figure 40 in Paper M1 presents the meridian cuts of the H ENA survival probability structure for first three years of IBEX observations. The north-south differences, as well as the annual ram vs. anti-ram variations are clearly visible. This confirm that a careful correction for the ionization losses is needed, especially for lower energies, when the global structure of H ENA flux is studied. Figures 8 and 9 and Figures 10 and 11 in Paper M1 shows full sky maps of the survival probabilities of H ENA calculated for IBEX-Hi and IBEX-Lo, respectively. Comparison of the ENA flux maps before and after the correction for survival probabilities enables to assess the modification of the observed signal due to inside-heliosphere processes. Figures 12, 13, and 14 therein, provide the individual and combined sky maps with the ionization losses correction applied equivalent to Figures 5, 6, and 7 before the correction. Figures with the fluxed corrected for the ionization losses illustrate the ENA flux in the heliosheath where they are expected to create.

The latitudinal structure of the solar wind is also suspected to be responsible for the variation of the flux along the IBEX ribbon. The ribbon is a region of enhanced ENA emission of unknown origin (McComas et al. 2009a). Before IBEX launch the models did not predict an existence of such a structure, while after its discovery many conceptions on its origin have be developed, a brief summary is given in McComas et al. (2010, 2014b). The intensity of the flux along the ribbon varies with energies and in time, thus the hypothesis that it is organized by solar wind was raised by McComas et al. in Paper M1, as illustrated in Figures 29 and 30 there. The ribbon ENAs are created mostly beyond the heliopause where the creation of the distributed flux ENA is unlikely. The correction for ionization losses for the ribbon ENAs are calculated identically as those for the distributed flux, since it is expected that losses within the inner heliosheath are negligible in comparison with the ionization losses that ENAs suffer inside the termination shock.

A realistic model for charge exchange rate between ISN H and solar wind protons is also important for the production of neutral solar wind (NSW). NSW are former solar wind protons that have exchanged charge with ISN H and are running away from the Sun almost radially, having energies identical to those of their parent protons. It is suspected that they are the parent population of ENAs in the secondary ENA emission mechanism, postulated to be responsible for the creation of the IBEX ribbon (McComas et al. 2009a; Schwadron et al. 2009; Heerikhuisen et al. 2010; Möbius et al. 2013; Schwadron & McComas 2013; Isenberg 2014). The evolution of the solar wind structure according to Paper S2 was used by Swaczyna et al. (2016) to model the variation of the IBEX ribbon center with energy. This analysis brought the conclusion that the secondary ENA emission from the region where interstellar magnetic field draped in the outer heliosheath and is perpendicular to the IBEX line of sight, is the most plausible explanation for the ribbon. The importance of accurate reproduction of the solar wind structure is illustrated by the fact that earlier attempts (e.g., Heerikhuisen et al. 2014; Zirnstein et al. 2015, 2016a,b), which neglected this effect, were unsuccessful in explaining the dependence of the ribbon center positions on energy.

7 Summary

Solar activity results in modulation of the latitudinal structure of the solar wind and in temporal variations of the solar EUV flux on time scales of decade and shorter. This solar output modulates the heliosphere as a whole as well as various populations of heliospheric particles, both neutral and charged. Studying the heliosphere requires taking these variations into account.

Based on available long-term measurements of solar wind and the solar EUV radiation, direct and indirect, ground-base and space-born, we compiled a model of the evolution of solar wind and the solar EUV flux in the waveband responsible for ionization of H, He, Ne, and O, spanning almost three past solar cycles. Within those, we developed a homogeneous system to calculate the ionization rates of the aforementioned species in the heliosphere and harnessed it in a system enabling calculating survival probabilities of neutral H, He, Ne, and O traveling in the supersonic solar wind with arbitrary energies from a few eV up to $\sim$ 6 keV.

Based on this model of the modulating factors, we modified the WTPM software to deploy the newly-developed system to calculate the ionization rates and survival probabilities on one hand, and to adjust one of the versions of the model for the model of interpretation of direct measurements of ISN gas on the other hand. The latter version of WTPM was used to assess the energy threshold of the IBEX-Lo sensor, and, more importantly, to investigate the signal from the far wings of the distribution function of ISN He in the LIC, as well as its possible departures from the Maxwell-Boltzmann form, i.e., hypothetical departures from thermal equilibrium. This was done by studying expected signal on IBEX due to kappa distribution function in the LIC, with various values of the parameter kappa, which describes the departures of the distribution form thermal equilibrium. We concluded that the currently adopted interpretation of the IBEX observations of ISN He, with two separate components (the primary and the secondary heliospheric populations) is more plausible than the hypothesis of just one ISN He population, kappa-distributed. However, it cannot be ruled out that the primary ISN He population deviates from thermodynamic equilibrium in the LIC. We identified the regions in the sky where the signatures of such deviations should be visible, however, they are in regions of relatively low signal to noise values in the available IBEX measurements.

Using the model of ionization rates and survival probabilities, we have calculated related corrections for all maps of H ENAs, observed by IBEX so far, which facilitate studies of the ENA flux distribution and spectra in the sky. Based on the newly developed model of ionization rates and the updated WTPM code, we studied the evolution of density distribution of ISN He, Ne, and O inside the Earth's orbit from the Sun. We investigated the ionization losses of these species between the termination shock and various locations along the Earth's orbit and determined the ionization-induced change in relative abundances of ISN He, Ne, and O. We used these estimates, along with available analysis of IBEX-Lo measurements, to determine the Ne/He, O/He, and Ne/O abundances in the outer heliosphere and in the LIC.

With the newly calculated densities and bulk velocities of ISN He, Ne, and O at and inside Earth's orbit, we studied the evolution of the PUI production rate during the solar cycle along the Earth's orbit, as well as the PUI count rate for these species, expected to be measured by an idealized spacecraft. For the first time, we calculated the PUI production rates using the full time- and heliolatitude dependent model of ISN gas densities for the heavy species, as well as the PUI distribution function computed with the finite PUI injection speed taken into account; up to now, this speed was assumed to be zero relative to the Sun. We studied the expected differences among the three species, which are almost solely due to the differences in the ionization rate. We found important differences among the species and their evolution during the solar cycle. We also investigated hypothetical systematic bias in the determination of ISN inflow velocity direction, obtained from analysis of the behavior of PUI count rates, measured by spacecraft orbiting the Sun at $\sim$ 1 AU. This method was used in the past and brought an estimate that differed from results obtained using different methods by a few degrees, which is a relatively large discrepancy. We found that the likely reason for this systematic effect may be the solar cycle-scale evolution of the PUIs, which is mostly due to the temporal solar cycle-scale variation in the densities of the parent ISN species and the ionization losses inside 1 AU. In the case of ISN O, particularly important in this context is the heliolatitudinal structure of the charge exchange ionization rate. This latter factor seems to be responsible for the bias in the determined longitude of inflow of ISN gas.

Results of the above-mentioned applications of our model of the heliospheric modulation factors, as well as results of the application of this model by other researches, briefly mentioned in Section 3.4, suggests, that the modulation of heliospheric neutral species and their derivative populations due to variations in solar activity is significant. We have developed the methodology to take it into account in the theoretical studies of the heliosphere as well as in the interpretation of heliospheric measurements and demonstrated that the accuracy of the conclusions is significantly increased in comparison with attempts where this modulation is neglected.

8 Outlook

As one of the results of the study that construct this PhD thesis, a model of the modulation of the ISN species inside the heliosphere was developed. It was used with success in a wide range of research (Section 3.4). However, we realize that a lot of work awaits to be done. Our priority is to make the high resolution model of the solar wind speed and density structure fully operational, to replace the model described in Paper S1 by the model developed in Paper S2. Additionally, we plan to develop a procedure to extrapolate the solar wind structure for short time scales forward, due to the almost one-year delay in retrieval of solar wind speed data from IPS observations. We will also monitor the development of the analysis of the IPS and EUV flux observations. Furthermore, we want to develop our study of the signals from the ISN gas inside the heliosphere, with a special attention paid to hypothetical anisotropies in the gas distribution from the thermal equilibrium in the source region. Additionally, with the aWTPM software, we have a tool to extensively study the distribution of ISN gas inside the heliosphere without the need to use an advanced computational resources. Thus it is a great opportunity to do a reconnaissance for the study of the distribution of He 58.4 nm and H Lyman-α helioglow inside the heliosphere.

This page is intentionally left blank.

References

Allegrini, F., Bzowski, M., Dayeh, M., et al. 2012, Astrophys. J. Letters, 749, L41

Asai, K., Kojima, M., Tokumaru, M., et al. 1998, J. Geophys. Res., 103, 1991

Aschwanden, M. J. 2005, Physics of the Solar Corona. An Introduction with Problems and Solutions (2nd edition) (Praxis Publishing Ltd., Chichester, UK; Springer, New York, Berlin)

Auchère, F., Cook, J. W., Newmark, J. S., et al. 2005a, Astrophys. J., 625, 1036

Auchère, F., Cook, J. W., Newmark, J. S., et al. 2005b, Adv. Space Res., 35, 388

Axford, W. I. 1972, in The Solar Wind, ed. J. M. W. C. P. Sonnet, P. J. Coleman, NASA Spec. Publ. 308, 609

Babcock, H. W. 1961, Astrophys. J., 133, 572

Bame, S. J., McComas, D. J., Barraclough, B. L., et al. 1992, Astron. Astrophys. Supp., 92, 237

Baranov, V. B., Izmodenov, V. V., & Malama, Y. G. 1998, J. Geophys. Res., 103, 9575

Baumjohann, W. & Treumann, R. A. 1996, Basic space plasma physics (London: Imperial College Press)

Bertaux, J. L. & Blamont, J. E. 1971, Astron. Astrophys., 11, 200

Bertaux, J. L., Kyrölä, E., Quémerais, E., et al. 1995, Solar Phys., 162, 403

Bertaux, J. L., Quémerais, E., Lallement, R., et al. 1997, in Proceedings of the Fifth SOHO Workshop, The Corona and Solar Wind near Minimum Activity, ESA SP- No. 404, 29–36

Bisi, M. M., Jackson, B. V., Buffington, A., et al. 2009, Solar Phys., 256, 201

Bisi, M. M., Jackson, B. V., Fallows, R. A., et al. 2010, Advances in Geosciences: Solar Terrestrial (ST), 21, 33

Bisoi, S. K., Janardhan, P., Ingale, M., et al. 2014, Astrophys. J., 795, 69

Blamont, J. E. & Vidal-Madjar, A. 1971, J. Geophys. Res., 76, 4311

Blum, P. W. & Fahr, H. J. 1969, Nature, 223, 936

Blum, P. W. & Fahr, H. J. 1970, Astron. Astrophys., 4, 280

Bochsler, P., Kucharek, H., Möbius, E., et al. 2014, Astrophys. J. Supp., 210, 12

Bochsler, P., Petersen, L., Möbius, E., et al. 2012, Astrophys. J. Supp., 198, 13

Bzowski, M. 2001, Space Sci. Rev., 97, 379

Bzowski, M. 2008, Astron. Astrophys., 488, 1057

Bzowski, M., Fahr, H. J., Ruciński, D., & Scherer, H. 1997, Astron. Astrophys., 326, 396

Bzowski, M., Kubiak, M. A., Hłond, M., et al. 2014, Astron. Astrophys., 569, A8

Bzowski, M., Kubiak, M. A., Möbius, E., et al. 2012, Astrophys. J. Supp., 198, 12

Bzowski, M., Mäkinen, T., Kyrölä, E., Summanen, T., & Quèmerais, E. 2003, Astron. Astrophys., 408, 1165

Bzowski, M., Möbius, E., Tarnopolski, S., Izmodenov, V., & Gloeckler, G. 2008, Astron. Astrophys., 491, 7

Bzowski, M., Möbius, E., Tarnopolski, S., Izmodenov, V., & Gloeckler, G. 2009, Space Sci. Rev., 143, 177

Bzowski, M., Sokół, J. M., Kubiak, M. A., & Kucharek, H. 2013a, Astron. Astrophys., 557, A50

Bzowski, M., Sokół, J. M., Tokumaru, M., et al. 2013b, in Cross-Calibration of Far UV Spectra of Solar System Objects and the Heliosphere, ed. E. Quémerais, M. Snow, & R.-M. Bonnet, ISSI Scientific Report No. 13 (Springer Science+Business Media), 67–138

Bzowski, M., Summanen, T., Ruciński, D., & Kyrölä, E. 2002, J. Geophys. Res., 107, 10.1029/2001JA00141

Bzowski, M., Swaczyna, P., Kubiak, M., et al. 2015, Astrophys. J. Supp., 220, 28

Bzowski, M. & Tarnopolski, S. 2006, in American Institute of Physics Conference Series, Vol. 858, Physics of the Inner Heliosheath, ed. J. Heerikhuisen, V. Florinski, G. P. Zank, & N. V. Pogorelov, 251–256

Carrington, R. C. 1858, Monthly Not. Royal Astron. Soc., 18, 169

Carrington, R. C. 1863, Observations of the Spots on the Sun: From November 9, 1853, to March 24, 1861, Made at Redhill, University of Chicago Digital Preservation Collection (Williams and Norgate)

Chamberlain, J. W. 1960, Astrophys. J., 131, 47

Chen, J. H., Möbius, E., Gloeckler, G., et al. 2013, Journal of Geophysical Research (Space Physics), 118, 3946

Chen, Y., Liu, L., & Wan, W. 2011, Journal of Geophysical Research (Space Physics), 116, 4304

Clette, F., Svalgaard, L., Vaquero, J. M., & Cliver, E. W. 2014, Space Sci. Rev., 186, 35

Coles, W. A. 1978, Space Sci. Rev., 21, 411

Coles, W. A., Grall, R. R., Klinglesmith, M. T., & Bourgois, G. 1995, J. Geophys. Res., 100, 17069

Coles, W. A. & Harmon, J. K. 1978, J. Geophys. Res., 83, 1413

Coles, W. A. & Kaufman, J. J. 1978, Radio Science, 13, 591

Coles, W. A. & Maagoe, S. 1972, J. Geophys. Res., 77, 5622

Coles, W. A., Rickett, B. J., Rumsey, V. H., et al. 1980, Nature, 286, 239

Covington, A. E. 1969, Journal of the Royal Astronomical Society of Canada, 63, 125

Czechowski, A., Hilchenbach, M., & Hsieh, K. C. 2005, Astron. Astrophys., 431, 1061

Dayeh, M. A., Allegrini, F., DeMajistre, R., et al. 2014, Astrophys. J., 797, 57

Dayeh, M. A., McComas, D., Livadiotis, G., et al. 2011, Astrophys. J., 734, 29

Dayeh, M. A., McComas, D. J., Allegrini, F., et al. 2012, Astrophys. J., 749, 50

Dennison, P. A. & Hewish, A. 1967, Nature, 213, 343

Desai, M. I., Allegrini, F., Dayeh, M. A., et al. 2015, Astrophys. J., 802, 100

Desai, M. I., Allegrini, F. A., Bzowski, M., et al. 2014, Astrophys. J., 780, 98

Desai, M. I., Allegrini, F. A., Dayeh, M. A., et al. 2012, Astrophys. J. Letters, 749, L30

Didkovsky, L. & Wieman, S. 2014, Journal of Geophysical Research (Space Physics), 119

Didkovsky, L. V., Judge, D. L., Wieman, S. R., & McMullin, D. 2010, in Astronomical Society of the Pacific Conference Series, Vol. 428, SOHO-23: Understanding a Peculiar Solar Minimum, ed. S. R. Cranmer, J. T. Hoeksema, & J. L. Kohl, 73

Drews, C., Berger, L., Wimmer-Schweingruber, R. F., et al. 2012, Journal of Geophysical Research (Space Physics), 117, 9106

Dudok de Wit, T., Bruinsma, S., & Shibasaki, K. 2014, Journal of Space Weather and Space Climate, 4, A260000

Dudok de Wit, T., Kretzschmar, M., Aboudarham, J., et al. 2008, Adv. Space Res., 42, 903

Dudok de Wit, T., Kretzschmar, M., Lilensten, J., & Woods, T. 2009, Geophys. Res. Lett., 36, L10107

Dudok de Wit, T., Lilensten, J., Aboudarham, J., Amblard, P.-O., & Kretzschmar, M. 2005, Ann. Geophys., 23, 3055

Elliott, H. A., Henney, C. J., McComas, D. J., Smith, C. W., & Vasquez, B. J. 2012, Journal of Geophysical Research (Space Physics), 117, A09102

Fahr, H., Fichtner, H., & Scherer, K. 2007, Rev. Geophys., 45, RG4003

Fahr, H. J. 1968, Astrophys. Space Sci., 2, 496

Fahr, H. J. 1971, Astron. Astrophys., 14, 263

Fahr, H. J. 1974, Space Science Reviews, 15, 483

Fahr, H. J. 1978, Astron. Astrophys., 66, 103

Fahr, H. J. 1979, Astron. Astrophys., 77, 101

Fahr, H. J. & Ruciński, D. 1999, Astron. Astrophys., 350, 1071

Fahr, H. J., Ruciński, D., & Nass, H. U. 1987, Ann. Geophys., 5, 255

Fayock, B. 2013, PhD thesis, The University of Alabama in Huntsville

Fayock, B., Zank, G. P., & Heerikhuisen, J. 2013, in American Institute of Physics Conference Series, Vol. 1539, American Institute of Physics Conference Series, ed. G. P. Zank, J. Borovsky, R. Bruno, J. Cirtain,

S. Cranmer, H. Elliott, J. Giacalone, W. Gonzalez, G. Li, E. Marsch, E. Moebius, N. Pogorelov, J. Spann, & O. Verkhoglyadova, 462–465

Fisher, M. K., Argall, M. R., Joyce, C. J., et al. 2016, Astrophys. J., 000:00, submitted

Floyd, L., Newmark, J., Cook, J., Herring, L., & McMullin, D. 2005, J. Atmos. Terr. Phys., 67, 3

Floyd, L. E., Prinz, D. K., Crane, P. C., & Herring, L. C. 2002, Adv. Space Res., 29, 1957

Fränz, M. & Harper, D. 2002, Planet. Space Sci., 50, 217

Frisch, P. C., Bzowski, M., Drews, C., et al. 2015, Astrophys. J., 801:61, (15pp)

Frisch, P. C., Bzowski, M., Livadiotis, G., et al. 2013, Science, 341, 1080

Fujiki, K., Kojima, M., Tokumaru, M., et al. 2003, Ann. Geophys., 21, 1257

Fujiki, K., Washimi, H., Hayashi, K., et al. 2014, Geophys. Res. Lett., 41, 1420

Funsten, H. O., Allegrini, F., Bochsler, P., et al. 2009, Space Sci. Rev., 146, 75

Fuselier, S. A., Allegrini, F., Bzowski, M., et al. 2014, Astrophys. J., 784, 89

Fuselier, S. A., Allegrini, F., Bzowski, M., et al. 2012, Astrophys. J., 754, 14

Fuselier, S. A., Bochsler, P., Chornay, D., et al. 2009, Space Sci. Rev., 146, 117

Galli, A., Wurz, P., Fuselier, S., et al. 2014, Astrophys. J., 796, 9

Galli, A., Wurz, P., Kollmann, P., et al. 2013, Astrophys. J., 775, 24

Galli, A., Wurz, P., Park, J., et al. 2015, Astrophys. J. Supp., 220, 30

Galli, A., Wurz, P., Schwadron, N., et al. 2016, Astrophys. J., 821, 107

Gapper, G. R., Hewish, A., Purvis, A., & Duffett-Smith, P. J. 1982, Nature, 296, 633

Geiss, J., Gloeckler, G., Mall, U., et al. 1994, Astron. Astrophys., 282, 924

Gloeckler, G., Geiss, J., Balsiger, H., et al. 1993, Science, 261, 70

Gloeckler, G., Möbius, E., Geiss, J., et al. 2004, Astron. Astrophys., 426, 845

Gnevyshev, M. N. 1963, Soviet Astronomy, 7, 311

Gringauz, K., Bezrukih, V., Ozerov, V., & Ribchinsky, R. 1960, Soviet Physics Doklady, 5, 361

Gruntman, M. 1997, Review of Scientific Instruments, 68, 3617

Gruntman, M., Roelof, E. C., Mitchell, D. G., et al. 2001, J. Geophys. Res., 106, 15767

Grzędzielski, S. 1968, Acta Astronomica, 18, 479

Grzędzielski, S. 1969a, Acta Astronomica, 19, 189

Grzędzielski, S. 1969b, Astrophys. Space Sci., 3, 139

Hathaway, D. H. 2015, Living Reviews in Solar Physics, 12

Heath, D. F. & Schlesinger, B. M. 1986, J. Geophys. Res., 91, 8672

Heerikhuisen, J., Pogorelov, N. V., Zank, G. P., et al. 2010, Astrophys. J. Letters, 708, L126

Heerikhuisen, J., Zirnstein, E. J., Funsten, H. O., Pogorelov, N. V., & Zank, G. P. 2014, Astrophys. J., 784, 73

Hewish, A., Dennison, P. A., & Pilkington, J. D. H. 1966, Nature, 209, 1188

Hewish, A., Scott, P. F., & Wills, D. 1964, Nature, 203, 1214

Hewish, A., Tappin, S. J., & Gapper, G. R. 1985, Nature, 314, 137

Hick, P. P. & Jackson, B. V. 2004, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 5171, Telescopes and Instrumentation for Solar Astrophysics, ed. S. Fineschi & M. A. Gummin, 287–297

Hilchenbach, M., Czechowski, A., Hsieh, K. C., & Kallenbach, R. 2006, in American Institute of Physics Conference Series, Vol. 858, Physics of the Inner Heliosheath, ed. J. Heerikhuisen, V. Florinski, G. P. Zank, & N. V. Pogorelov, 276–281

Holzer, T. E. 1970, PhD thesis, University of California, San Diego

Holzer, T. E. & Axford, W. I. 1970, Annual Review of Astronomy and Astrophysics, 8, 31

Holzer, T. E. & Axford, W. I. 1971, J. Geophys. Res., 76, 6965

Houminer, Z. 1971, Nature Physical Science, 231, 165
Houminer, Z. & Hewish, A. 1972, Planet. Space Sci., 20, 1703
Houminer, Z. & Hewish, A. 1974, Planet. Space Sci., 22, 1041
Hovestadt, D., Hilchenbach, M., Bürgi, A., et al. 1995, Solar Phys., 162, 441
Hsieh, K. C., Kóta, J., Czechowski, A., Hilchenbach, M., & Shaw, A. 2004, in American Institute of Physics Conference Series, Vol. 719, Physics of the Outer Heliosphere, ed. V. Florinski, N. V. Pogorelov, & G. P. Zank, 64–69
Isenberg, P. A. 1987, J. Geophys. Res., 92, 1067
Isenberg, P. A. 2014, Astrophys. J., 787, 76
Issautier, K. 2009, in Lecture Notes in Physics, Berlin Springer Verlag, Vol. 778, Turbulence in Space Plasmas, ed. P. Cargill & L. Vlahos, 223–246
Izmodenov, V. V., Katushkina, O. A., Quémerais, E., & Bzowski, M. 2013, in Cross-Calibration of Far UV Spectra of Solar System Objects and the Heliosphere, ed. E. Quémerais, M. Snow, & R.-M. Bonnet, ISSI Scientific Report No. 13 (Springer Science+Business Media), 7
Jackson, B. V., Hick, P. L., Kojima, M., & Yokobe, A. 1997, Adv. Space Res., 20, 23
Jackson, B. V., Hick, P. L., Kojima, M., & Yokobe, A. 1998, J. Geophys. Res., 103, 12049
Jackson, B. V. & Hick, P. P. 2004, in Astrophysics and Space Science Library, Vol. 314, Astrophysics and Space Science Library, ed. D. E. Gary & C. U. Keller, 355
Jackson, B. V., Hick, P. P., Buffington, A., et al. 2010, Advances in Geosciences, Volume 21: Solar Terrestrial (ST), 21, 339
Jackson, B. V., Hick, P. P., Buffington, A., et al. 2011, Journal of Atmospheric and Solar-Terrestrial Physics, 73, 1214
Jackson, B. V., Hick, P. P., Buffington, A., et al. 2003, in American Institute of Physics Conference Series, Vol. 679, Solar Wind Ten, ed. M. Velli, R. Bruno, F. Malara, & B. Bucci, 75–78
Joselyn, J. A. & Holzer, T. E. 1975, J. Geophys. Res., 80, 903
Kakinuma, T. 1977, in Astrophysics and Space Science Library, Vol. 71, Study of Travelling Interplanetary Phenomena, ed. M. A. Shea, D. F. Smart, & S. T. Wu, 101–118
Kakinuma, T., Washimi, H., & Kojima, M. 1973, Publ. Astron. Soc. Japan, 25, 271
Kasper, J. C. 2002, PhD thesis, Massachusetts Institute of Technology
Kasper, J. C., Lazarus, A. J., Steinberg, J. T., Ogilvie, K. W., & Szabo, A. 2006, Journal of Geophysical Research (Space Physics), 111, A03105
Kasper, J. C., Stevens, M. L., Korreck, K. E., et al. 2012, Astrophys. J., 745, 162
Katushkina, O. A. & Izmodenov, V. V. 2011, Advances in Space Research, 48, 1967
Katushkina, O. A., Izmodenov, V. V., & Alexashov, D. B. 2015, Monthly Not. Royal Astron. Soc., 446, 2929
Katushkina, O. A., Izmodenov, V. V., Quémerais, E., & Sok'oł, J. M. 2013, J. Geophys. Res., 1
King, J. H. & Papitashvili, N. E. 2005, J. Geophys. Res., 110, 2104
Kojima, M. 1979, Publ. Astron. Soc. Japan, 31, 231
Kojima, M., Fujiki, K.-I., Hirano, M., et al. 2004, in Astrophysics and Space Science Library, Vol. 317, The Sun and the Heliosphere as an Integrated System, ed. G. Poletto & S. T. Suess, 147
Kojima, M. & Kakinuma, T. 1990, Space Sci. Rev., 53, 173
Kojima, M., Tokumaru, M., Fujiki, K., Hayashi, K., & Jackson, B. V. 2007, Astronomical and Astrophysical Transactions, 26, 467
Kojima, M., Tokumaru, M., Watanabe, H., et al. 1998, J. Geophys. Res., 103, 1981
Krimigis, S. M., Mitchell, D. G., Roelof, E. C., Hsieh, K. C., & McComas, D. J. 2009, Science, 326, 971
Kubiak, M. A., Bzowski, M., Sokół, J. M., et al. 2013, Astron. Astrophys., 556, A39

Kubiak, M. A., Bzowski, M., Sokół, J. M., et al. 2014, Astrophys. J. Supp., 213, 29
Kubiak, M. A., Swaczyna, P., Bzowski, M., et al. 2016, Astrophys. J. Supp., 223, 35
Kyrölä, E., Summanen, T., Mäkinen, T., et al. 1998, J. Geophys. Res., 103, 14523
Lallement, R., Bertaux, J. L., & Kurt, V. G. 1985, J. Geophys. Res., 90, 1413
Lallement, R., Quémerais, E., Koutroumpa, D., et al. 2010, Twelfth International Solar Wind Conference, 1216, 555
Le Chat, G., Issautier, K., & Meyer-Vernet, N. 2012, Solar Phys., 279, 197
Lee, M. A., Fahr, H. J., Kucharek, H., et al. 2009, Space Sci. Rev., 146, 275
Lemaire, J. & Scherer, M. 1971, J. Geophys. Res., 76, 7479
Lindsay, B. G. & Stebbings, R. F. 2005, J. Geophys. Res., 110, A12213
Livadiotis, G. & McComas, D. J. 2009, Journal of Geophysical Research (Space Physics), 114, 11105
Livadiotis, G. & McComas, D. J. 2011, Astrophys. J., 741, 88
Livadiotis, G. & McComas, D. J. 2013, Space Sci. Rev., 175, 183
Lo Galbo, P. & Bouffard, M. 1992, ESA Bulletin, 71, 21
Lotz, W. 1967a, Astrophys. J. Supp., 14, 207
Lotz, W. 1967b, Z. Phys., 206, 205
Manoharan, P. K. 1993, Solar Phys., 148, 153
Manoharan, P. K. & Ananthakrishnan, S. 1990, Monthly Not. Royal Astron. Soc., 244, 691
McComas, D., Allegrini, F., Bochsler, P., et al. 2004, in American Institute of Physics Conference Series, Vol. 719, Physics of the Outer Heliosphere, ed. V. Florinski, N. V. Pogorelov, & G. P. Zank, 162–181
McComas, D., Bzowski, M., Frisch, P., et al. 2015a, Astrophys. J., 801, 28
McComas, D., Bzowski, M. Fuselier, S., Frisch, P., et al. 2015b, Astrophys. J. Supp., 220, 22
McComas, D. J. 2009, Space Sci. Rev., 143, 125
McComas, D. J., Allegrini, F., Bochsler, P., et al. 2009a, Science, 326, 959
McComas, D. J., Allegrini, F., Bochsler, P., et al. 2009b, Space Sci. Rev., 146, 11
McComas, D. J., Allegrini, F., Bzowski, M., et al. 2014a, Astrophys. J. Supp., 231, 28
McComas, D. J., Bame, S. J., Barker, P., et al. 1998, Space Sci. Rev., 86, 563
McComas, D. J., Barraclough, B. L., Funsten, H. O., et al. 2000a, J. Geophys. Res., 105, 10419
McComas, D. J., Bzowski, M., Frisch, P., et al. 2010, Journal of Geophysical Research (Space Physics), 115, A09113
McComas, D. J., Carrico, J. P., Hautamaki, B., et al. 2011, Space Weather, 9, 11002
McComas, D. J., Dayeh, M. A., Allegrini, F., et al. 2012, Astrophys. J. Supp., 203, 1
McComas, D. J., Ebert, R. W., Elliot, H. A., et al. 2008, Geophys. Res. Lett., 35, L18103
McComas, D. J., Elliott, H. A., & von Steiger, R. 2002, Geophys. Res. Lett., 29, 28
McComas, D. J., Gosling, J. T., & Skoug, R. M. 2000b, Geophys. Res. Lett., 27, 2437
McComas, D. J., Lewis, W. S., & Schwadron, N. A. 2014b, Rev. Geophys., 52
Meeus, J. 1998, Astronomical algorithms (Willmann-Bell)
Mejia-Ambriz, J. C., Jackson, B. V., Gonzalez-Esparza, J. A., et al. 2015, Solar Phys., 290, 2539
Meyer-Vernet, N. 2007, Basics of the Solar Wind (Cambridge University Press)
Möbius, E. 1986, Advances in Space Research, 6, 199
Möbius, E. 1996, Space Sci. Rev., 78, 375
Möbius, E., Bochsler, P., Heirtzler, D., et al. 2012, Astrophys. J. Supp., 198, 11
Möbius, E., Bzowski, M., Chalov, S., et al. 2004, Astron. Astrophys., 426, 897
Möbius, E., Bzowski, M., Fuselier, S. A., et al. 2015a, Journal of Physics: Conference Series, 577, 012019
Möbius, E., Bzowski, M., Fuselier, S. A., et al. 2015b, Astrophys. J. Supp., 220, 24

Möbius, E., Hovestadt, D., Klecker, B., Scholer, M., & Gloeckler, G. 1985, Nature, 318, 426
Möbius, E., Kucharek, H., Clark, G., et al. 2009, Space Sci. Rev., 146, 149
Möbius, E., Litvinenko, Y., Grünwaldt, H., et al. 1999, Geophys. Res. Lett., 26, 3181
Möbius, E., Liu, K., Funsten, H., Gary, S. P., & Winske, D. 2013, Astrophys. J., 766, 129
Nakai, Y., Shirai, T., Tabata, T., & Ito, R. 1987, Atomic Data and Nuclear Tables, 37, 69
Nerney, S. F. & Suess, S. T. 1975, Solar Phys., 45, 255
Neugebauer, M. & Snyder, C. W. 1962, Science, 138, 1095
Norton, A. A. & Gallagher, J. C. 2010, Solar Phys., 261, 193
Ogilvie, K. W., Chornay, D. J., Fritzenreiter, R. J., et al. 1995, Space Sci. Rev., 71, 55
Owens, M. J., Crooker, N. U., & Lockwood, M. 2014, Journal of Geophysical Research (Space Physics), 119, 36
Owocki, S. P. & Scudder, J. D. 1983, Astrophys. J., 270, 758
Panasenco, O. & Velli, M. 2013, in American Institute of Physics Conference Series, Vol. 1539, American Institute of Physics Conference Series, ed. G. P. Zank, J. Borovsky, R. Bruno, J. Cirtain, S. Cranmer, H. Elliott, J. Giacalone, W. Gonzalez, G. Li, E. Marsch, E. Moebius, N. Pogorelov, J. Spann, & O. Verkhoglyadova, 50–53
Paresce, F., Bowyer, S., & Kumar, S. 1974, Astrophys. J., 187, 633
Park, J., Kucharek, H., Möbius, E., et al. 2014, Astrophys. J., 795, 97
Parker, E. N. 1958, Astrophys. J., 128, 664
Pierrard, V. & Lazar, M. 2010, Solar Phys., 267, 153
Pryor, W. R., Holsclaw, G. M., McClintock, W. E., et al. 2013, in Cross-Calibration of Far UV Spectra of Solar System Objects and the Heliosphere, ed. E. Quémerais, M. Snow, & R.-M. Bonnet, ISSI Scientific Report No. 13 (Springer Science+Business Media), 163
Quémerais, E. & Bertaux, J.-L. 1993, Astron. Astrophys., 277, 283
Quémerais, E. & Izmodenov, V. 2002, Astron. Astrophys., 396, 269
Quémerais, E., Izmodenov, V., Koutroumpa, D., & Malama, Y. 2008, Astron. Astrophys., 488, 351
Quémerais, E., Sandel, B. R., Izmodenov, V. V., & Gladstone, G. R. 2013, in Cross-Calibration of Far UV Spectra of Solar System Objects and the Heliosphere, ed. E. Quémerais, M. Snow, & R.-M. Bonnet, ISSI Scientific Report No. 13 (Springer Science+Business Media), 141
Reisenfeld, D. B., Allegrini, F., Bzowski, M., et al. 2012, Astrophys. J., 747, 110
Reisenfeld, D. B., Bzowski, M., Funsten, H. O., et al. 2016, Astrophys. J., in preparation, 00
Rodríguez Moreno, D., Wurz, P., Saul, L., et al. 2014, Entropy, 16, 1134
Rodríguez Moreno, D. F., Wurz, P., Saul, L., et al. 2013, Astron. Astrophys., 557, A125
Rotter, T., Veronig, A. M., Temmer, M., & Vršnak, B. 2012, Solar Phys., 281, 793
Rottman, G. 2005, Solar Phys., 230, 7
Ruciński, D. 1985, PhD thesis, Centrum Badań Kosmicznych PAN
Ruciński, D. & Bzowski, M. 1995, Astron. Astrophys., 296, 248
Ruciński, D., Bzowski, M., & Fahr, H. J. 2003, Ann. Geophys., 21, 1315
Ruciński, D., Cummings, A. C., Gloeckler, G., et al. 1996, Space Sci. Rev., 78, 73
Ruciński, D. & Fahr, H. J. 1989, Astron. Astrophys., 224, 290
Ruciński, D. & Fahr, H. J. 1991, Ann. Geophys., 9, 102
Samson, J. A. R., He, Z. H., Yin, L., & Haddad, G. N. 1994, J. Phys. B: At. Mol. Opt. Phys., 27, 887
Samson, J. A. R. & Stolte, W. C. 2002, J. Electron Spectroscopy and Related Phenomena, 123, 265
Saul, L., Bzowski, M., Fuselier, S., et al. 2013, Astrophys. J., 767, 130
Schwadron, N., Möbius, E., Leonard, T., et al. 2015, Astrophys. J. Supp., 220, 25

Schwadron, N. A., Bzowski, M., Crew, G. B., et al. 2009, Science, 326, 966

Schwadron, N. A. & McComas, D. J. 2013, Astrophys. J., 764, 92

Schwadron, N. A., Moebius, E., Fuselier, S., et al. 2014, Astrophys. J. Supp., 215, 13

Scott, S. L., Coles, W. A., & Bourgois, G. 1983, Astron. Astrophys., 123, 207

Skupin, J., Weber, M., Bovensmann, H., & Burrows, J. P. 2005, in ESA Special Publication, Vol. 572, Envisat ERS Symposium

Smirnov, B. M. 1982, Negative Ions (McGraw Hiill, NY)

Snow, M., Weber, M., Machol, J., Viereck, R., & Richard, E. 2014, Journal of Space Weather and Space Climate, 4, A04

Sokół, J. M. & Bzowski, M. 2014, ArXiv e-prints

Sokół, J. M., Bzowski, M., Grzedzielski, S., et al. 2015a, AGU Fall Meeting Abstracts, SH41E-2407, `https://agu.confex.com/agu/fm15/meetingapp.cgi/Paper/62481`

Sokół, J. M., Bzowski, M., Kubiak, M., et al. 2015b, Astrophys. J. Supp., 220, 29

Sokół, J. M., Bzowski, M., Kubiak, M. A., & Bochsler, P. 2013a, talk at IBEX Science Team Meeting 17

Sokół, J. M., Bzowski, M., Kubiak, M. A., & Möbius, E. 2016, Monthly Not. Royal Astron. Soc., 458, 3691

Sokół, J. M., Bzowski, M., Tokumaru, M., Fujiki, K., & McComas, D. J. 2013b, Solar Phys., 285, 167

Sokół, J. M., Kubiak, M., Bzowski, M., & Swaczyna, P. 2015c, Astrophys. J. Supp., 220, 27

Sokół, J. M., Swaczyna, P., Bzowski, M., & Tokumaru, M. 2015d, Solar Phys., 290, 2589

Suess, S. T. & Nerney, S. F. 1973, Astrophys. J., 184, 17

Svalgaard, L. & Hudson, H. S. 2010, in Astronomical Society of the Pacific Conference Series, Vol. 428, SOHO-23: Understanding a Peculiar Solar Minimum, ed. S. R. Cranmer, J. T. Hoeksema, & J. L. Kohl, 325

Svalgaard, L. & Kamide, Y. 2013, Astrophys. J., 763, 23

Swaczyna, P., Bzowski, M., Kubiak, M., et al. 2015, Astrophys. J. Supp., 220, 26

Swaczyna, P., Bzowski, M., & Sokół, J. M. 2016, Astrophys. J., in press, 00

Tanaka, H., Castelli, J. P., Covington, A. E., et al. 1973, Solar Phys., 29, 243

Tappin, S. J. 1986, Planet. Space Sci., 34, 93

Tapping, K. F. 1987, J. Geophys. Res., 92, 829

Tapping, K. F. 2013, Space Weather, 11, 1

Tarnopolski, S. & Bzowski, M. 2009, Astron. Astrophys., 493, 207

Thatcher, L. J. & Müller, H.-R. 2011, Journal of Geophysical Research (Space Physics), 116, A12107

Thomas, G. E. 1978, Ann. Rev. Earth Planet. Sci., 6, 173

Thomas, G. E. & Krassa, R. F. 1971, Astron. Astrophys., 11, 218

Thompson, W. T. 2006, Astron. Astrophys., 449, 791

Tobiska, W. K., Bouwer, S. D., & Bowman, B. R. 2008, Journal of Atmospheric and Solar-Terrestrial Physics, 70, 803

Tokumaru, M., Kojima, M., & Fujiki, K. 2010, J. Geophys. Res., 115, A04102

Tokumaru, M., Kojima, M., & Fujiki, K. 2012, Journal of Geophysical Research (Space Physics), 117, 6108

Tokumaru, M., Kojima, M., Fujiki, K., et al. 2011, Radio Science, 46, RS0F02

Tokumaru, M., Kojima, M., Fujiki, K., Yamashita, M., & Jackson, B. V. 2007, Journal of Geophysical Research (Space Physics), 112, 5106

Tokumaru, M., Kojima, M., Ishida, Y., Yokobe, A., & Ohmi, T. 2000, Advances in Space Research, 25, 1943

Tyler, G. L., Vesecky, J. F., Plume, M. A., Howard, H. T., & Barnes, A. 1981, Astrophys. J., 249, 318

Ulrich, R. K. & Boyden, J. E. 2006, Solar Phys., 235, 17

Vasyliunas, V. & Siscoe, G. 1976, J. Geophys. Res., 81, 1247

Verner, D. A., Ferland, G. J., Korista, T. K., & Yakovlev, D. G. 1996, Astrophys. J., 465, 487

Viereck, R. A. & Puga, L. C. 1999, J. Geophys. Res., 104, 9995

Vitkevich, V. V. & Vlasov, V. I. 1970, Soviet Astronomy, 13, 669

von Steiger, R. & Geiss, J. 1993, Advances in Space Research, 13, 63

von Steiger, R., Schwadron, N. A., Fisk, L. A., et al. 2000, J. Geophys. Res., 105, 27217

Wang, Y.-M. & Sheeley, Jr., N. R. 1990, Astrophys. J., 355, 726

Wawrzaszek, A., Echim, M., Macek, W. M., & Bruno, R. 2015, Astrophys. J. Letters, 814, L19

Weber, E. J. & Davis, Jr., L. 1967, Astrophys. J., 148, 217

Weber, E. J. & Davis, Jr., L. 1970, J. Geophys. Res., 75, 2419

Weber, M. 1999, in European Space Agency, Vol. 572, Proc. European Symposium on Atmospheric Measurements from Space (ESAMS'99), ESTEC, Noordwijk, The Netherlands, 18-22 January 1999, WPP-161, 611–616

Weber, M., Burrows, J. P., & Cebula, R. P. 1998, Solar Phys., 177, 63

Weller, C. S. & Meier, R. R. 1974, Astrophys. J., 193, 471

Wenzel, K.-P., Marsden, R. G., Page, D. E., & Smith, E. J. 1989, Advances in Space Research, 9, 25

Wieman, S. R., Didkovsky, L. V., & Judge, D. L. 2014, Solar Phys., 289, 2907

Wimmer-Schweingruber, R. F. 2002, Advances in Space Research, 30, 23

Wood, B. E., Müller, H.-R., Bzowski, M., et al. 2015, Astrophys. J. Supp., 220, 31

Woods, T. N., Eparvier, F. G., Bailey, S. M., et al. 2005, J. Geophys. Res., 110, A01312

Woods, T. N., Eparvier, F. G., Hock, R., et al. 2012, Solar Phys., 275, 115

Woods, T. N., Prinz, D. K., Rottman, G. J., et al. 1996, J. Geophys. Res., 101, 9541

Woods, T. N., Rottman, G. J., White, O. R., Fontenla, J., & Avrett, E. H. 1995, Astrophys. J., 442, 898

Woods, T. N., Tobiska, W. K., Rottman, G. J., & Worden, J. R. 2000, J. Geophys. Res., 105, 27195

Wu, F. M. & Judge, D. L. 1979, Astrophys. J., 231, 594

Wurz, P., Saul, L., Scheer, J. A., et al. 2008, J. Appl. Phys., 103, 054904

Xu, F. & Borovsky, J. E. 2015, Journal of Geophysical Research (Space Physics), 120, 70

Yermolaev, Y. I., Nikolaeva, N. S., Lodkina, I. G., & Yermolaev, M. Y. 2009, Cosmic Research, 47, 81

Yoon, P. H., Kim, S., & Choe, G. S. 2015, Astrophys. J., 812, 169

Yu, H.-S., Jackson, B. V., Hick, P. P., et al. 2015, Solar Phys., 290, 2519

Zank, G. P. 1999, Space Sci. Rev., 89, 413

Zhao, L. & Landi, E. 2014, Astrophys. J., 781, 110

Zhao, L., Landi, E., Zurbuchen, T. H., Fisk, L. A., & Lepri, S. T. 2014, Astrophys. J., 793, 44

Zirnstein, E. J., Funsten, H. O., Heerikhuisen, J., & McComas, D. J. 2016a, Astron. Astrophys., 586, A31

Zirnstein, E. J., Heerikhuisen, J., Funsten, H. O., et al. 2016b, Astrophys. J. Letters, 818, L18

Zirnstein, E. J., Heerikhuisen, J., Pogorelov, N. V., McComas, D. J., & Dayeh, M. A. 2015, Astrophys. J., 804, 5

STATEMENTS OF CO-AUTHORS

This page is intentionally left blank.

ARTICLES OF THE THESIS