COMPOSITION OF THE SOLAR WIND, SECONDARY ION GENERATION AND PICK-UP

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1. Introduction

The solar wind is an ionized gas which, as a consequence of a hot solar corona and a low fluid pressure in the interstellar space, continuously emanates from the Sun into space to define a region known as the heliosphere. Since the electrical conductivity of the solar wind is very high, diffusion of the magnetic field through the plasma is not taken into account. In this picture (the frozen-in approximation) one imagines that the solar magnetic field is dragged into the heliospheric space by the radially outflowing solar wind. The structure of the solar wind is therefore intimately related to the structure of the solar corona and the solar magnetic field. The solar wind plasma itself is composed of protons, electrons, alpha particles, and a minor fraction of heavy ions. The relevance of solar wind ion composition measurements is linked to the fact that such measurements are a unique tool to investigate solar system processes, ranging from the solar interior out to the heliospheric boundary. Compositional changes in the solar wind, which originates in the outer convective zone (OCZ) of the Sun, are produced in the transport of solar matter from the OCZ to the solar corona and in the process of lifting the coronal plasma out of the solar gravitational field. Average abundances of He, C, N, O, Ne, Mg, Si, S and Fe in the solar wind are known today approximately to 10% (Ogilvie and Coplan, 1995). While in-situ solar wind observations in the ecliptic have been made over more than a solar cycle, high altitude measurements have been made only after the Ulysses spacecraft left the ecliptic in 1992. While the flow speed was traditionally used to classify the solar wind into slow and fast wind, the Ulysses mission has allowed us to study in detail the characteristics of the slow and fast solar wind over extended periods of time. This is particularly important since one currently assumes that the slow and fast wind are accelerated and heated differently.

2. Solar Wind composition, secondary ion generation

New instrumentation is about to bring more than an order of magnitude improvement in mass resolution over conventional instrumentation. On the Solar and Heliospheric Observatory (SOHO) MTOF, the most powerful solar wind mass spectrometer flown to date uses time-of-flight (TOF) technology which translates sub-nanosecond TOF measurements into a mass resolutions of a fraction of an AMU. In addition, MTOF generates a 2 to 3 order of magnitude improvement in counting statistics, thanks to the fact that SOHO always looks in the solar direction and that a novel entrance deflection system requires only a few voltage steps to cover the entire energy-per-charge distribution of the solar wind. These kinds of improvements have made it possible not only to observe in-situ the elements ^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si, and ^{56}Fe, which were routinely observed by in-situ solar wind experiments, but to observe in addition, the Neon isotope ^{22}Ne, the element ^{23}Na, the Magnesium isotopes ^{25}Mg, ^{26}Mg, the element ^{27}Al, the Silicon isotopes ^{29}Si, ^{30}Si, the element ^{31}P, the element ^{32}S and its isotope ^{34}S, the element Chlorine ^{35}Cl and its isotope ^{37}Cl, the element Argon ^{36}Ar and its isotope ^{38}Ar, the Calcium element ^{40}Ca and its isotopes ^{42}Ca and ^{44}Ca, the element Titanium ^{48}Ti, the element Chromium ^{52}Cr and its isotope ^{53}Cr, the Iron isotopes ^{54}Fe and ^{57}Fe, the element Manganese ^{55}Mn, and the element Nickel ^{58}Ni and its isotopes ^{60}Ni and ^{62}Ni. While the above list

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shows the enormous progress made over the last few years in observing minor ions, one must not forget that there are still unsolved problems connected to the major ions in the solar wind. One of these has to do with the peculiarities of the ^{4} He content in the solar wind, e.g. the very low values around sector boundaries, the high variabilities in the slow wind, the relatively constant value in high-speed streams and the rather high values found in several coronal mass ejections.

Even when we restrict ourselves to charge state measurements of ^{4} He we find several ^{4} $He^+/^4$ He^{++} abundance ratio measurements reported in the literature which are in the range of 10^{-3} - 10^{-1}, although equilibrium computations of an expanding 10^6 K solar corona predict the ^{4} $He^+/^4$ He^{++} abundance ratios in a normal solar wind plasma to be of the order of 10^{-5}. Since we believe that the ionization state of the expanding multi-ion solar wind is mainly determined by the physical processes operating in the lower corona and that the ionic charge state distribution remains unaltered during the solar wind outflow into the heliosphere, we are led to investigate the interactions of the solar wind and solar EUV radiation with the gaseous and dusty matter in the heliospheric space. Although plasma dust interactions including residual ionization and recombination processes can only change marginally the abundances of the most abundant solar wind ions, the creation of several secondary minor components can enrich the composition of the solar wind (Rucinski et al., 1997). The relevance of such minor secondary ion components has to do with the fact that they may serve as useful tracers of various physical processes occurring in the heliosphere. In particular, the determination of their abundance may indicate possible contributions of non-solar sources (e.g. interstellar gas, dust, and cometary debris).

3. Neutral atoms

Among the non-solar sources, the interstellar gas is particularly interesting. Due to the motion of the solar system relative to the local interstellar medium (LISM), the solar system is exposed to a wind of neutral and ionized local interstellar matter. Since the neutrals are coupled to the plasma flow only by charge exchange reactions, there exists an inflow of interstellar gas into the heliosphere, first predicted by Fahr (1968), which becomes subject to the net gravitational force and ionization processes. As a consequence, a circumsolar structure with a pronounced upwind-downwind asymmetry is formed. The flow direction of interstellar matter relative to the Sun represents a symmetry axis for the distribution of the neutrals. Therefore, the neutral density depends upon two geometrical coordinates: the distance r from the Sun as well as the angle θ between the symmetry axis (also denoted as the upwind-downwind axis or heliospheric axis) and the direction from the Sun to the point in space at which the density is described. In general, the heliospheric density distribution $N(r, \theta)$ of a neutral gas in the heliosphere depends upon the density, temperature, and velocity of the neutral interstellar gas in the vicinity of the solar system. In addition, it depends upon the cross-sections of the interaction processes of the neutral gases with the solar wind and the solar radiation (charge exchange reactions with solar wind ions, electron impact ionization, and EUV-ionization), the intensity and angular distribution of both solar EUV- and corpuscular radiation as well as possible heating effects of the neutral gas as it approaches the Sun.

Research on the interstellar medium in which the solar system is embedded was, in the past, mainly carried out in an indirect way, using the fact that solar UV light, scattered at the atoms of the interstellar gas, can be measured by optical instruments. Such measurements led however to a wide range of parameters of the LISM. Over many years the results suggested that the temperature and relative velocities for the H and He component differed significantly (e.g. Dalaudier et al., 1984). More recently a reinterpretation of the He measurement suggested that such a difference may be an artefact of a Doppler shift of the profile of He line in the solar atmosphere (e.g. Chassefiere et al., 1988). These points make it clear that additional neutral gas measurements which measure the neutral gas directly would be important. Such a measurement which is experimentally an extremely difficult undertaking, was successfully accomplished with the GAS experiment (Rosenbauer et al., 1983, Witte et al., 1993). But direct neutral gas measurements would still not fully resolve the controversies. It was realized early that a counterstreaming of the solar wind and the magnetized LISM plasma causes a magnetohydrodynamic interaction of these two media due to the very short MHD interaction scale lengths. A contact discontinuity, called heliopause, across which pressure equilibrium is maintained, separates both media from each other. Inside and outside the heliopause different plasma flow regimes are established which have to be traversed by the neutral LISM components prior to their arrival at the inner solar system. The point of importance here is that in passing through these regions the LISM neutrals suffer specific losses (filtration) and gain processes that change their partial densities and velocity distributions (e.g. Ripken and Fahr, 1983, Baranov and Zaitsev, 1995). Luckily such filtration effects do not affect all atoms in the same way. Helium, for example, is not significantly affected by filtration and has the additional advantage that changes in radiation pressure and temperature are of minor importance so that it can be very well used to establish the physical state of the LISM. Hydrogen, on the other hand, is affected by filtration and in addition, changes in radiation pressure and temperature become important.

4. Pick-up ions (PUI's) in the Solar Wind

The idea, illustrated above, that the neutral component of the interstellar gas penetrates the boundary of the heliosphere and then becomes ionized, e.g. through ionization via solar UV radiation or collisions with electrons, reveals a way to obtain complementary information on the interstellar medium. The important point here is that through the process of ionization the neutral component of the interstellar medium, originally extremely difficult to measure, has transformed itself into a state that can directly be measured with instruments primarily designed to measure solar wind ions. This fact has important implications. By measuring the intensity of these newly created ions in a certain energy range in the heliospheric space we get a handle on the interstellar medium. We can gain information on the abundance, the temperature, and the relative velocity of each ion species in the interstellar gas just outside the solar system.

Let us examine how the physics of this process works. As soon as an interstellar gas atom has become ionized, it responds to the electromagnetic fields of the solar wind. In the reference frame moving with the solar wind, this response consists of a gyration of the new ions about the magnetic field, followed by a rapid isotropization by ambient or self-generated low-frequency fluctuations in the plasma. This isotropized particle population is convecting with the solar wind. One describes this fact usually by saying loosely that the newly created ions have been 'picked-up' by the solar wind or that pick-up ions have been created.

What is the key to the observation of PUI's and their experimental separation from solar wind ions? First, PUI's have distinctive velocity distribution functions with a sharp upper limit of twice the solar wind speed. In the solar wind rest frame, recently picked-up ions are found in an isotropic shell in phase space with a radius equal to the solar wind speed. Ions which have been picked-up closer to the Sun loose energy as they are convected outward in the expanding solar wind. While the number of newly created PUI's is steadily increasing, older ones are being cooled so that eventually a filled sphere in phase space is formed. Because in general the process of adiabatic cooling, also known as adiabatic deceleration, is more efficient than acceleration processes, the phase space density falls sharply for particles with speeds greater than the solar wind speed. However, in the disturbed solar wind, e.g. close to corotating interaction regions, the effect of acceleration processes can clearly be observable (Gloeckler et al., 1994).

Second, PUI's have very different charge states compared to solar wind ions. They carry only one or two charges. Third, PUI's have a different spatial distribution in the heliosphere compared with solar wind ions. Despite these clear criteria, PUI's were not identified before 1985 and even then, only He^+ was found.

To understand one has to keep in mind the role the ionization rate plays. On the one hand, the ionization rate determines and shapes the distribution of the interstellar gas in the vicinity of the Sun by destruction of the neutrals. On the other hand, the ionization rate determines the fraction of ions which are created as PUI's, by ionizing neutral atoms. This means that at 1 AU only PUI species can be observed whose 'parent neutral gas population' has not been depleted too much. Because He (with a small loss rate) is more difficult to ionize than interstellar neutral H or O, inflowing He can penetrate closer to the Sun than other LISM species so that a substantial fraction of the He survives to within the orbit of the earth. This fact formed the basis for the first observation of interstellar PUI's by Moebius in 1985 (Moebius et al., 1985). Another reason for the relativly late discovery of PUI's was that sensitive plasma instrumentation was still in its early stage of perfection. Plasma spectrometers which combine TOF technology with energy/charge analyzers allow a mass/charge state analysis with simultaneous low background, a requirement for making PUI measurements.

The advent of the Ulysses mission with its unique flight path and new generation of instrumentation allowed from 1993 on to find the missing different PUI species. The SWICS instrument on Ulysses could clearly detect H^+, $^4He^{++}$, $^3He^+$, N^+, O^+ and Ne^+. By doing so, the SWICS and GAS (Witte et al., 1992) experiments on Ulysses measuring the pick-up ions and the neutral interstellar atoms are now in a position to deliver new complementary information, thus providing new constraints for the basic LISM parameters using a new approach with different systematic errors.

References

Baraov, V.B., and Zaitsev, N.A. (1995) On the problem of the solar wind interaction with magnetized interstellar plasma, *Astron. Astrophys*, **Vol. no. 304**, pp. 631–637

Chassefiere, E., Dalaudier, F., Bertaux, J.L. (1988) Estimate of interstellar helium parameters from Prognoz 6 and Voyager 1/2 - EUV resonance glow measurements taking into account a possible redshift in the solar line profile, *Astron. Astrophys*, **Vol. no. 201**, pp. 113–122

Dalaudier, F., Bertaux, J.L., Kurt, V.G., Mironova, E.N. (1984) Characteristics of interstellar helium observed with Prognoz 6 58.4-nm photometers, *Astron. Astrophys*, **Vol. no. 134**, pp. 171–184

Fahr, H.J. (1968), On the influence of neutral interstellar matter on the upper atmosphere, *Astrophysics and Space Science*, **Vol. no. 2**, pp. 474–495

Geiss, J., Gloeckler, G., Mall, U., von Steiger, R., Galvin, A., Ogilvie, K.W. (1994) Interstellar oxygen, nitrogen and neon in the heliosphere, *Astron. Astrophys*, **Vol. no. 282**, pp. 924–933

Gloeckler, G., Geiss, J., Balsiger, H., Fisk, L.A., Galvin, A. Ipavich, F.M., Ogilvie, K.W., von Steiger, R., Wilken, W. (1993) Detection of Interstellar Pick-Up Hydrogen in the Solar System, *Science*, **Vol. no. 261**, pp. 70–71

Gloeckler, G., Geiss, J., Roelof, E.C., Fisk, L.A., Ipavich, F.M., Ogilvie, K.W., Lanzerotti, L.J., von Steiger, R., Wilken, B. (1994), Acceleration of interst. PUI's in the disturbed solar wind observed on Ulysses, *J. Geophys. Res.*, **Vol. no. 99**, pp. 17637–17643

Moebius, E.D., Hovestadt, B., Klecker, D., Scholer, M., Gloeckler, G. (1993), Direct observation of He^+ pick-up ions of interstellar origin in the solar wind, *Nature*, **Vol. no. 318**, pp. 426–429

Ogilvie, K.W. and Coplan, M.A.,(1995), *NASA progress report*

Ripken, H.W., and Fahr, H.J. (1983), Modification of the local interstellar gas properties in the heliospheric interface, *Astron. Astrophys*, **Vol. no. 122**, pp. 181–192

Rosenbauer, H., Fahr, H.J., Keppler, E., Witte M., Hemmerich P., Lauche, H., Loidl, A., Zwick, R. (1983), The ISPM Interstellar Neutral - Gas Experiment, *In: The International Solar Polar Mission - Its Scientific Investigation*, **ESA SP-1050**, pp. 123–139

Rucinski, D., Bzowski, M. Fahr, H.J. (1997) Minor helium components in the expanding solar wind, *Astron. Astrophys*, in press

Witte M., Rosenbauer H., Banaszkiewicz, M., Fahr, H.J., (1993) The Ulysses neutral gas experiment - Determination of the velocity and temperature of the interstellar neutral helium, *Adv. Space Res.*, **Vol. no. 13, (6)**, pp. 121–130