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20. SOLAR WIND COMPOSITION

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20.1. INTRODUCTION

Solar wind ion composition 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 up to the termination shock and beyond. During the last three years instrumentation originally designed to measure the composition of the solar wind has detected further pick-up ion species in the solar wind and thereby strongly motivated pick-up ion related research. This review therefore puts particular emphasis on pick-up ion observations and their theoretical interpretation.

20.2. SOLAR WIND

Average abundances of He, C, N, O, Ne, Mg, Si, S and Fe in the solar wind are known today to approximately 10% (Ogilvie and Coplan 1995). The Ulysses Mission has allowed direct measurement of solar wind originating from all regions where the corona expands. The majority of observational papers published during this review period present and discuss data collected by instruments on the ULYSSES and WIND missions, while exciting results from the SOHO mission are about to appear in the literature. Charge state measurements can be used to place constraints on the conditions in the lower corona, such as electron temperature and density, and the flow speed of the ions. The ability of the Solar Wind Ion Composition Instruments (SWICS) on Ulysses to return detailed information on solar wind ion charge states independent of the state of the solar wind has been particularly fruitful (e.g., Galvin et al. 1995). Ko et al. (1996) found that charge states of heavy ions observed by SWICS are most consistent with a suprathermal tail on the electron distribution which is not large (Kappa ≥ 5), thus claiming that such a small tail does not contribute significantly to the formation of the corona and the dynamics of the solar wind. For a discussion of this issue see Scudder (1994).

Papers covering Ulysses observations discuss in detail the three main regimes of solar wind flows: the quasi-stationary high speed streams (HSST's) emanating out of polar coronal holes, the inherently transient slow solar wind surrounding the HSST's, and the streamers which occur during the magnetic field reversals (Neugebauer, M. 1994; Phillips et al. 1994, Geiss et al. 1995a, Phillips et al. 1995, Feldman et al. 1996). Measurements of the solar wind abundances during the report period shed additional light on the overabundance of elements with low first ionization potential (FIP) relative to elements with high FIP. Not only could one extensively study the observation that the FIP effect is strongly reduced in fast solar wind streams (Geiss et al. 1995b, von Steiger et al. 1995) but these in-situ observations were complemented by closed system etching techniques of lunar soils in the laboratory. Wieler et al. (1995, 1996) investigated the fractionation of Xe, Kr and Ar and found interestingly that Xe with a FIP above 10 eV is overabundant relative to Ar by about the same factor as are elements with a FIP of less than 10 eV relative to high FIP elements. Diffusion models with a mass flow parallel to a vertical magnetic field, where the fractionation depends only on the ionization time and elastic collision frequency (Marsch et al. 1995, Peter 1996) can reproduce now the FIP effect not only in the slow but also in the fast solar wind. Additional information from spectroscopic data indicate that the element fractionation is an essential part of coronal formation (Sheeley 1996). Oetliker et al. (1996) could measure the isotopic composition of iron in the solar wind for the first time and found a ratio of 54Fe/56Fe which is 35% higher than a result coming from meteoritical material. Considering the uncertainty of the 54Fe/56Fe measurement one has to wait for results from

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the CELIAS/MTOF sensor on board of SOHO to decide whether this measurement indicates a different composition of the sun in comparison to meteoric material or the existence of a strong fractionation effect in the solar wind acceleration.

Still no theory of coronal solar wind acceleration and mass transport currently exists which can self-consistently model the observed ion composition and differential ion streaming. Part of the problem is the fact that the temperatures of solar wind, electrons, protons, and minor ions in the inner corona could not be measured yet. Therefore, the mechanism(s) which heat the solar plasma from chromospheric to coronal temperatures in the inner corona are still unknown. Only recently indirect evidence from Lyman-alpha observations (Kohl et al. 1995) indicated that the proton temperature in coronal holes might be significantly higher (approx. $7.6\ 10^6$ K) than was expected. This appears to be consistent with findings obtained with new models of the solar wind acceleration, namely multi-fluid approaches using general parametrized heating functions (Esser and Habbal 1995, McKenzie et al. 1995). The latter authors explicitly invoke the damping of ion cyclotron waves to explain the possibly high temperatures in the inner corona and the observed wind characteristics farther out ($r > 0.3$ AU).

20.3. PICK-UP IONS IN THE SOLAR WIND

The Pick-Up Ions (PUI) are an additional ion population in the solar wind with a distinct velocity distribution. The study of the dynamics and evolution of PUIs is important for our understanding of the Anomalous Cosmic Ray (ACR) component (le Roux et al. 1996) and of the interface structure between the solar wind and the Local Interstellar Medium (LISM) (Chalov and Fahr 1996). While the PUI velocity distribution is usually approximated as a spherical shell, there has been observational evidence (Gloeckler et al. 1995) that this assumption does not hold for a quasi-radial orientation of the heliospheric magnetic field.

20.4. ORIGIN OR PICK-UP IONS

Most of the PUIs are believed to be interstellar neutral atoms that penetrate through the heliospheric interface (Fahr et al. 1995) into the solar system. Once in the solar system they become ionized by charge exchange processes with the solar wind, by electron impact ionization, and by photoionization due to the solar EUV/UV radiation. The fluxes, velocity distributions and composition of interplanetary PUIs (H^+, He^+, O^+, N^+, Ne^+) were recently measured and compared with theoretical predictions (Geiss et al. 1994a,b; Gloeckler et al. 1994a,b, Mall et al. 1996). While it is fairly clear that the light elements, Hydrogen and Helium, are of interstellar origin, there may be additional sources for the heavier elements. A local increase in the PUI density has been observed at planets, comets, Moon and interplanetary dust. During the last three years, Krasnopolsky et al. (1994) observed He^+ at Mars, while Luhmann (1994) discussed the production of O at Jupiter and Gruntman (1996) pointed out the possibility to observe molecular Hydrogen from interplanetary dust. However, the main contribution for the species with high ionization potential (O, N, Ne, Ar) comes from the interstellar medium. A long-term variability in the PUI production rate produced by the solar cycle activity was studied by Rucinski and Bzowski (1995), Bzwoski and Rucinski (1995), Isenberg and Lee (1995), Rucinski et al. (1996).

20.5. DYNAMICS OF PICK-UP IONS

After the ionization of the neutrals, the PUIs undergo rapid pitch angle scattering, adiabatic deceleration, and slow energy diffusion. At larger solar distances they are subject to transit time damping and Alfvenic turbulences (Chalov et al. 1995). The evolution of the PUI velocity distribution, which is highly anisotropic at the time of injection, is accompanied by the generation of plasma waves (Williams and Zank 1994, Isenberg and Lee 1996). In the outer heliosphere the pressure induced by the PUIs becomes larger than the solar wind thermal pressure and can be determined from pressure balanced structures in the solar wind (Burlaga et al. 1996). This PUI pressure might reduce the expected deceleration of the solar wind in the outer heliosphere significantly (Fahr and Fichtner 1995). Another complication is the dependence of transport efficiency of the PUIs on the heliographic latitude. This is caused by a stronger decrease of the magnetic field at high latitudes which eventually results in a less efficient Fermi acceleration (Fichtner et al. 1996). Upcoming deep space missions (Cassini) will provide the opportunity to determine the orientation of the interstellar wind axis using pickup-ion measurements (Mall et al. 1996).

20.6. TERMINATION SHOCK AND ACCELERATION

When the PUIs reach the region of the termination shock they are accelerated to higher energies and leak back into the heliosphere. The structure of the heliospheric interface (Paul et al. 1995, 1996) influences the flux of the interstellar neutrals (Fahr and Osterbart 1995). Therefore, a detailed knowledge of the observed flux of the PUIs will lead us to a better understanding of the heliospheric interface and of the initial conditions of the LISM (Fahr et al. 1995). The interaction of the backflowing PUIs with the interface and their acceleration to ACRs (Giacolone et al. 1996) produces a complicated shock structure (precursors, subshocks, etc.). Different approaches include the three fluid model of Chalov and Fahr (1996), a test particle approach by Zank et al. (1996), and a hybrid code model by Kucharek and Scholer (1995).

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21. Transient Events In The Heliosphere: Interplanetary Consequences Of Coronal Mass Ejections

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The Sun's atmosphere and the solar wind are not homogenous and quasi-stationary in time due to the variability of the solar magnetic field. Solar flares and coronal mass ejections (CMEs) are dramatic manifestations of transient energy releases in the solar atmosphere. As a consequence of solar activity the interplanetary medium is frequently disturbed by transient flows of plasma and magnetic fields, interplanetary shock waves and large flux increases of energetic particles. These disturbances also affect the galactic cosmic rays which penetrate the heliosphere. Powerful solar disturbances can have direct impacts on the terrestrial environment in form of power outages, satellite failures or telecommunication problems. Solar energetic particles (SEPs) pose a serious health risk to humans in space. Recent observations of the solar atmosphere with space-borne telescopes, e.g. from Yohkoh, and spacecraft measurements in the interplanetary medium, e.g. Ulysses, have led to exciting new results in heliospheric physics.The Ulysses mission has provided the first observations of the uncharted third dimension of our solar system which led to a fundamental new understanding of the 3-D structure of the heliosphere and its spatial and temporal variations. This report aims to give a brief overview on the most recent developments and scientific highlights on transients in the heliosphere. Some references for further readings are included.

21.1. CORONAL MASS EJECTIONS (CMEs) IN INTERPLANETARY SPACE

Recent results from the Ulysses spacecraft have provided the first direct measurements of coronal mass ejections (CMEs) at high heliographic latitudes (Gosling 1994; Gosling et al. 1995a). The term CME is commonly used for both the interplanetary counterpart of the CME, i.e. for the ejected solar plasma and magnetic fields, as well as for the solar event itself. CMEs in interplanetary space can most reliable be identified by the counterstreaming of suprathermal electrons along the interplanetary magnetic field (IMF) (Gosling 1994). Striking new aspects of the observed high latitude CMEs were that all had high plasma speeds (≥700 km/sec) and that most of them were bounded by expansion shocks due to their high internal pressures. Ulysses observations have supported the view of CMEs as large-scale disturbances in the heliosphere. For the first time a CME has been detected over more than 40 degrees in heliographic latitude (Gosling et al. 1995b). Further study of CME properties at high latitudes will provide new insights into the acceleration processes of the solar wind and the interaction of CMEs with the ambient medium.

21.2. MAGNETIC TOPOLOGY AND 3-D STRUCTURE OF CMEs

Counterstreaming flows of suprathermal electrons along the IMF are commonly interpreted as evidence for closed magnetic field topologies within CMEs (Gosling, Birn & Hesse 1995). It is assumed that the flux rope topology found in about 1/3 of all CMEs (e.g. Bothmer & Schwenn 1996) is a consequence of reconnection processes within the legs of rising magnetic loops in the corona at times the CME lifts off from the Sun (Gosling 1994). Another explanation for the origin of the magnetic topology of these CMEs are outward expanding huge flux ropes in association with prominence eruptions. This view has been inferred from a comparison of the magnetic structure and helicity of CMEs with the helicity of the magnetic field at the site of erupting prominences (Bothmer & Schwenn 1994; Rust 1994). Rust (1995) and Rust and Kumar (1994) have proposed that such expanding flux ropes may arise as a consequence of twisted magnetic fields that emerge from below the solar surface. These recent studies of the topology of CMEs in interplanetary space have brought up new exciting aspects like the concept of magnetic helicity conservation in astrophysical plasmas or the reinvestigation of the physics of prominence formation (Priest 1996). A new observation derived from Ulysses measurements was the detection of intermittent intervals of counterstreaming electrons within some CMEs which has been interpreted by Gosling, Birn and Hesse (1995) and Bothmer et al. (1996) as evidence for open and closed magnetic field lines within these CMEs, presumably caused by three dimensional reconnection processes in the corona. Some theoretical models support the global picture of CMEs as large-scale magnetic flux tubes with a cylindrical rather than a spheroidal or spheromak topology (Farrugia, Osherovich and Burlaga 1995). In summary, the global 3-D structure of CMEs remains still unknown and is a subject of ongoing studies.

21.3. INTERPLANETARY SHOCK WAVES

Recent progress from both new and accumulated observations and models showed that there exist two major sources of shocks in the heliosphere: CMEs and stream interaction with distinct radial, latitudinal and temporal dependencies (Luhman 1995). A review on current research on shock waves in space plasmas can be found in Conference Proceedings edited by Russell (1995). CMEs drive shock waves if they propagate substantially faster than the ambient solar wind ahead (e.g. Gosling 1993a). At high latitudes a new class of forward/reverse shock pairs has been detected with Ulysses. These shock pairs were driven by the over-expansion of CMEs (Gosling et al. 1995a). Compared to transient shocks that have commonly been observed in the ecliptic the observed expansion shocks were found to be relatively weak. For completeness it should be mentioned that another source of forward/reverse shock pairs in the heliosphere are corotating interaction regions (CIRs). Usually these shocks develop at distances greater than ~2 AU from the Sun. Their latitudinal characteristics depend on the 3-D structure of the associated CIRs (Gosling et al. 1995c). CIRs are commonly treated as quasi-stationary rather than transient heliospheric features. However, the interaction of CMEs with CIRs and the evolution of CIRs during the solar cycle is certainly an important topic for future analyses. A summary on the different types of shocks observed by Ulysses has been given by Gonzalez-Esparza et al. (1996).

21.4. ENERGETIC PARTICLES AND GALACTIC COSMIC RAYS

Recent studies of measurements of energetic particles at MeV energies in interplanetary space have shown that there are basically two sources for solar energetic particle (SEP) events in the ecliptic: CMEs and solar flares (Reames 1994). Large flux increases of energetic ions with time durations of the order of several days are associated with interplanetary shocks driven by fast CMEs (Gosling 1993; Reames 1994). Short-time impulsive events with enrichments in heavy ions can be associated with solar flares near the footpoints of the interplanetary magnetic field (IMF) lines that connect an observer magnetically with the Sun. Outside the ecliptic a new class of particle events has been identified in association with the passage of CMEs over the Ulysses spacecraft (Bothmer et al. 1995). These events are evidence that CMEs can convect energetic particles from the Sun out into the high latitude heliosphere. It has been established that fast CMEs also cause intensity decreases (Forbush decreases) of galactic cosmic rays (Cane, Richardson and von Rosenvinge 1996). It should be remarked here that another source of large-scale energetic particle events are the corotating shock pairs of CIRs.

21.5. IMPLICATIONS FOR THE TERRESTRIAL ENVIRONMENT

Recent results from the analyses of spacecraft measurements in the interplanetary medium have unravelled that CMEs are the prime sources of major disturbances in the heliosphere and that they can significantly perturb the Earth's environment (Gosling 1993; Gosling 1993b; Tsurutani and Gonzalez 1994; Bothmer and Schwenn 1995; Webb 1995). It would be of enormous scientific value if the Sun-Earth connection and the dynamics of the Sun and heliosphere could be investigated by suitable equipped spacecraft positioned at large angles with respect to the Sun-Earth line. Such observations would allow the direct detection of solar and heliospheric disturbances propagating towards the Earth (Schmidt and Bothmer 1996).

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22. THE HELIOSPHERE: LATITUDINAL DEPENDENCIES REVEALED BY ULYSSES

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22.1. ULYSSES MISSION OVERVIEW AND SCIENCE OBJECTIVES

Ulysses, the first spacecraft to explore interplanetary space at high solar latitudes, was launched toward Jupiter on 6 Oct 1990. Encounter with Jupiter occurred on 8 Feb 1992, at which point the spacecraft was injected into a high-inclination heliocentric orbit that enabled it to pass through the Sun's polar regions. Ulysses first flew below the ecliptic, reaching a maximum southern heliographic latitude of 80.2 degrees on 13 Sep 1994. From this point Ulysses moved swiftly northward in latitude, passing perpendicularly through the ecliptic plane on 13 Mar 1995 and then up to its northernmost heliolatitude (again 80.2 degrees) on 31 July 1995. These high latitude observations were obtained near the minimum phase of the 11 year solar cycle. With its orbital period of 6.2 years, Ulysses is presently on track for a a second round of high latitude observations during solar cycle maximum in the years 2000-2001. Data coverage has averaged ~97% over the mission, making the Ulysses data base the most complete set of continuous interplanetary measurements ever recorded. The main scientific objective of the Ulysses mission is to characterize heliospheric fields and particles for the first time as a function of solar latitude, particularly the regions above the solar poles (Smith et al. 1991; Wenzel et al. 1992). The Ulysses payload carries, among others, instrumentation for studies of the heliospheric magnetic field, heliospheric radio and plasma waves, the solar wind plasma (including minor heavy ions), energetic particles, galactic and anomalous cosmic rays, cosmic dust, interstellar gas, and gamma-ray bursts (Marsden & Smith 1996a).

22.2. ULYSSES POLAR PASSES

The mission was designed for maximum duration of the polar passes (total of 234 days), defined to be those periods when the spacecraft was above 70 degrees heliographic latitude in either hemisphere. Ulysses executed its southern polar pass in the time period 26 Jun to 5 Nov 1994. A review of results from this first polar pass may be found in Marsden (1995) and in the collection of articles introduced by Smith et al. (1995c).

In contrast to the initial climb from low to high latitudes, which took more than 2 years and covered a range of radial distances (5.4 to 2.3 AU), the latitudunal scan from pole-to-pole was completed in less than a year at a

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more constant heliocentric distance. The end of the second (northern) polar pass on 29 Sep 1995 also marked the end of the prime mission. For the sake of brevity, only four specific topics are presented in this report. Recent descriptions of all Ulysses results gathered during the fast latitude scan may be found in special issues of the scientific literature following introductory papers by Smith & Marsden (1995), Marsden & Smith (1996b), and Marsden et al. (1996).

22.3. LATITUDE VARIATIONS IN SOLAR WIND SPEED AND DENSITY

A long history of remote sensing observations (e.g., interplanetary scintillations) indicated that Ulysses would encounter fast solar wind from the coronal holes over the poles. High speed streams can be observed in the ecliptic whenever coronal holes extend to low latitudes. Ulysses in situ observations of fast solar wind emanating from the polar caps confirmed this prediction (Phillips et al. 1994; McComas et al. 1995). Rather than a continuous increase of velocity toward the pole, however, two fundamentally distinct solar wind regimes with common, sharply delineated chromospheric and coronal boundaries were discovered. Slow wind was detected when Ulysses was near the heliospheric current sheet (HCS), which is the interplanetary extension of the streamer belt observed in the corona. Fast wind associated with (polar) coronal holes was found to flow at a very steady velocity near 750 km/s at high heliographic latitudes. The density, normalized to 1 AU, was also nearly constant (~3 electrons per cubic centimeter). This contrasted to the equatorial region where the velocity was low and the density was high (Phillips et al. 1995a; Phillips et al. 1995b; Gosling et al. 1995; Goldstein et al. 1996).

22.4. SOLAR MAGNETIC FIELDS AT HIGH LATITUDES

A surprising result emerging from the Ulysses polar passes was the nature of the heliospheric magnetic field. Based on an extrapolations of the photospheric magnetic field, as observed from Zeeman splitting of certain spectral lines, there was reason to expect a dipole-like field, perhaps tilted by about 10-20 degrees with respect to the Sun's rotation axis during the prevailing solar minimum conditions (Forsyth 1995). Ulysses, however, found no evidence of enhanced magnetic flux at the poles, implying that the dipole-like configuration of the Sun's surface field is not maintained in the solar wind (Balogh et al. 1995). Whereas a dipole field is twice as strong over the poles as at the equator, the Ulysses measurements found that the magnetic flux density in the solar wind was constant with latitude (Smith & Balogh 1995). It is suspected that pressure gradients near the Sun are responsible for redistributing the magnetic flux. In February/March 1995, Ulysses passed swiftly from the southern polar (toward, or negative polarity) magnetic sector into the northern (away, positive polarity) sector. The sector boundary (HCS) was encountered at equatorial heliolatitudes on seven occasions (Smith et al. 1995a). The direction of the high latitude magnetic field was found to be slightly more azimuthal (more tighly wound) than the predicted Parker spiral (Forsyth et al. 1995). Curiously, the magnetic field strength displayed no obvious latitudinal differences between the northern vs. the southern hemisphere (Forsyth et al. 1996).

22.5. COMPOSITIONAL DIFFERENCES OF FAST AND SLOW STREAMS

The stark latitudinal contrast between the fast wind over the polar regions and the slow wind near the HCS has helped reveal some fundamental differences in the respective sources and composition of these flow regimes (Geiss et al. 1995a). One obvious example is the abundance ratio (Mg)/(O) of two heavy ions in the solar wind, magnesium and oxygen, which is about twice as large in low speed wind as in high speed wind. Another difference is the abundance ratio of ionic charge states such as $(O^7)/(O^6)$ (i.e., seven and six times ionized oxygen atoms), which is a measure of the temperature in the solar atmosphere at the location where the ions were created. This temperature is distinctly higher in the low speed solar wind, indicative of a hot coronal source (Galvin et al. 1995).

At mid-latitudes, where both slow and fast wind were usually sampled during each 26-day solar rotation, the transitions between these two regimes were found to be quite sharp and well-defined even at the relatively large distance of Ulysses. This is especially surprising for the differences in temperature and composition, which are presumably governed by processes in the corona and chromosphere, respectively. This apparent causal relationship between conditions in the corona and processes in the chromosphere may be a clue to the creation process responsible for the observed bimodal solar wind (Geiss et al. 1995b).

22.6. COSMIC RAY AND ENERGETIC PARTICLE MODULATION IN THE 3D-HELIOSPHERE

One of the major objectives of Ulysses, the first spacecraft to explore the third dimension of the heliosphere, was to detect a more pristine sample of cosmic ray particles over the solar poles. It was argued that, because the heliospheric magnetic field at the poles is essentially radial rather then wound up in a tight spiral as observed near the equator, cosmic ray particles (which are restricted to move along magnetic field lines) should have easier access to the inner heliosphere at high latitudes. Particles entering the heliosphere would thus reach Ulysses with very little energy loss, giving scientists the opportunity to study cosmic ray composition and energy distribution over a much broader energy range than is possible in the ecliptic.

Although increases in the flux of cosmic rays by factors of 10 or more were predicted at the pole, a major surprise was that Ulysses detected only a mild enhancement of at most a factor of two (Simpson et al. 1995a; Sanderson et al. 1995). The absence of a significant latitude gradient may well be related to another Ulysses discovery about the high latitude background magnetic field, which was was continually disturbed by the presence of outward propagating Alfven waves with wave periods of up to over 10 hours (Smith et al. 1995b). It is thought that these waves are scattering the incoming cosmic ray particles, preventing their access to the high-latitude regions. The cosmic ray data also show an asymmetry, with 10 percent higher fluxes measured over the north pole than over the south. Overall, the Ulysses data imply a heliospheric north-south asymmetry of roughly 10 degrees with respect to the solar equator during the pole-to-pole transit (Simpson et al. 1995b).

The cosmic ray experience stands in direct contrast to the latitudinal variation of solar and interplanetary energetic particle fluxes. Prior to the Ulysses reconnaissance, it was generally expected that these would be low over the poles near solar minimum, principally because of the lack of high-latitude acceleration sites. Surprisingly, recurrent (~26-day) increases in particle intensity, which are observed at low latitudes in association with corotating shock waves formed by the interaction of long-lived fast and slow solar wind streams, continued to be recorded right up to the polar regions (Mueller-Mellin & Wibberenz 1995; Keppler et al. 1995; Lanzerrotti et al. 1995). The shocks themselves were not detected at the spacecraft, suggesting non-local acceleration followed by latitudinal transport. The fluxes showed very little variation over the solar poles, remaining essentially at background levels. One explanation for this may be that no energetic solar flares, which are thought to be required as an input source of low-energy particles, occurred on the Sun during these intervals (Keppler et al., 1996; Lanzerotti et al., 1996).

22.7. A LATITUDE DEPENDENCE AT SOLAR MAXIMUM?

The polar passes of Ulysses took place near the minimum in the current solar activity, when the coronal structure is dominated by the large coronal holes at the north and south poles with relatively few transient disturbances. The HCS, which has a low inclination at solar minimum, will be highly inclined and may consist of multiple sheets during the next Ulysses polar passes. It remains to be seen whether or not the solar wind density and speed will still be correlated with distance to the current sheet.

The interplanetary weather may well be dramatically different during solar maximum, especially over the polar regions, from the environment encountered during Ulysses' prime mission. The polar cap magnetic fields will be in the process of vanishing and then reversing polarity. Poleward-drifting unipolar magnetic regions will have the opposite polarity and will tend to reduce rather than enhance the polar fields.

Galactic cosmic rays will undoubtedly be more strongly modulated as solar activity increases. Ulysses will continue to monitor their intensity spectra at both poles and equator. It may be possible to infer the relative importance of drifts and merged interaction regions in the modulation process within the different heliospheric environment of solar maximum. At lower energies, the fluxes of solar energetic particles are likely to increase roughly in proportion to the frequency of solar flares.

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23. THE HELIOSPHERE: INTERSTELLAR GAS FLOW THROUGH THE INTERFACE REGION

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23.1. INTRODUCTION

The relative motion of the solar system with respect to the ambient interstellar medium forms a plasma interface region where the interstellar and solar wind plasma flows adapt to each other. Magnetohydrodynamically perturbed plasma flows interact in this region together with interstellar neutral atoms during their approach toward the inner heliosphere. The distribution functions of the neutral interstellar gas species in the heliosphere retain distinct imprints of the charge exchange processes from the perturbed moments in the interface region. The influence of this interface plasma on the helium/oxygen/hydrogen ratios has been recently investigated in the light of new pick-up ion and anomalous cosmic ray data. These ratios, being sensitive to the alternative forms of interface structures presently under debate, may help identify the best-fitting interface model. An adequate description of the interface requires careful consideration of the magnetic fields and the plasma pressure anisotropies in the counterflow configuration.

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23.2. THE SUN'S LOCAL ENVIRONMENT

Unfortunately, the thermodynamic state of the VLISM (Very Local Interstellar Medium) is still only poorly known (e.g., Cox & Reynolds 1987; Frisch 1990, 1995; Reynolds 1990; Lallement 1993). It is not even clear whether or not the VLISM exits in a quasistationary near-equilibrium state. If a supernova shock recently passed through the VLISM, we might expect to find a nonstationary, nonequilibrium state that still undergoes temporal changes in the temperatures and fractional degrees of ionization of the different atomic species. In this case, without knowledge of the time and nature of this shock event, there is no basis for predicting the fractional ionizations in the present VLISM.

The thermodynamic state of a cloudy interstellar medium subject to periodically repeating supernova shocks has been studied by McKee & Ostriker (1977) and McCray & Snow (1979). In contrast to the earlier result by Field et al. (1969), which predicted a two-phase interstellar medium purely on the basis of pressure equilibrium at the phase boundaries, they proposed an interstellar medium with essentially four co-existing phases: the cold phase, the warm neutral phase, the warm ionized phase, and the hot ionized phase. The latter phase was thought to be predominant (interstellar spatial filling factor $f = 0.8$), compared with the sum of the other phases ($f < 0.2$).

A few years ago it was found that the X-ray source Geminga, an X-ray pulsar with a rotation period of 0.23 s, is the nucleus of an earlier O-type star that exploded as a supernova event. Taking this pulsar's rotational slowdown rate and extrapolating it back to the relativistic minimum pulsar period, it turns out that the Geminga-associated supernova event took place about 340000 years ago (Teske 1993). Furthermore, when Geminga is retraced on the basis of its present peculiar motion over the same period, this event took place only about 300 light years from the solar system. The associated supernova shock carved out a huge region of complete ionization in the nearby interstellar medium and may be responsible for the so-called "local bubble", which can clearly be identified in interstellar absorption lines (e.g., Paresce 1984). If rapid ionization of the local medium occurred only 300,000 years ago, then stationary time-independent conditions cannot be expected because interstellar recombination times are considerably longer.

One should not exclude the possibility, however, that the VLISM may be characterized as a transition between two thermodynamically very different interstellar gas phases of the types discussed by McKee & Ostriker (1977). The solar system may be moving just now through a local interstellar cloud with a size of the order of 30 pc (Frisch & York 1983). One might thus expect strong temperature gradients and thus nonequilibrium ionization conditions (Slavin 1989; Boehringer & Hartquist 1987) at the periphery of this cloud where it borders on the surrounding tenuous and hot interstellar HII region. The degree of ionization would thus decrease systematically from the boundaries towards the center of the Local Interstellar Cloud (LIC).

Consequently, the ionization state of the VLISM depends critically on where the solar system is presently located with respect to the center of the LIC. Balbus (1986) and Boehringer & Hartquist (1987) have calculated stationary profiles in such interstellar transition regions between hot and cool ISM phases. The calculations reveal that the actual ionization state at any position in such a transition region is determined mainly by a local photoionization equilibrium governed by the local radiation field. Under this assumption, fairly different estimates of the local photoionization state have been carried out by Frisch (1990) and Reynolds (1990). The discrepancies become even more pronounced if less conservative assumptions are taken for the local X-ray background (Bloch et al. 1986). Furthermore, the results of these authors are very sensitive to the actual VLISM temperature. No definite conclusion can thus be drawn on the ionization state of the VLISM, particularly with respect to the fractional ionization of the elements other than hydrogen.

23.3. INTERFACE IMPRINTS ON THE NEUTRAL VLISM GASES

The neutral VLISM gas atoms are coupled to the locally perturbed plasma at the heliospheric interface by charge-exchange interactions that induce changes in the velocity moments of the neutral distribution. In other words, although the neutral gas atoms do not interact hydrodynamically, they still receive an imprint of the deviation of the magnetohydrodynamical VLISM plasma flow around the heliopause.

The problem of the penetration of neutral VLISM atoms through the perturbed plasma interface region has been studied in the stationary limit assuming full knowledge of the plasma state from one of the many available counterflow models in the literature (Parker 1963; Baranov et al. 1979; Fahr & Neutsch 1983; Fahr 1986; Fahr et al. 1988; Matsuda et al. 1989; Baranov 1990; Suess & Nerney 1990; Baranov & Malama 1993; Steinolfson et al. 1994; Scherer et al. 1994; Pauls et al. 1995; Baranov & Zaitzev 1995; Fahr & Scherer 1995; Khabibrakhmanov & Summers 1996). These models can be divided roughly according to type, namely one-shock interfaces (e.g., Parker 1963) and twin-shock interfaces (Baranov & Malama 1993). Explicit distribution functions for the VLISM neutrals have been generated by many authors (e.g., Ripken & Fahr 1983; Fahr & Ripken 1984; Fahr 1986, 1991; Osterbart & Fahr 1992; Fahr et al. 1995).

Regardless of the plasma interface model adopted for the calculations of effects on the VLISM neutrals, a generally accepted result is achieved for the predicted changes in the first velocity moments of the neutral interstellar species upon passage through this interface. The density and bulk velocity are decreased and the temperatures are increased.

23.4. CONCLUSIONS FROM COMPARISON OF THEORY WITH OBSERVATIONS

Based on the above mentioned theoretical studies, the recently obtained data on neutral VLISM gas atoms (Witte et al. 1993) or associated pick-up ions (Geiss et al. 1993; Gloeckler et al. 1993) support the following conclusions (see also Fahr et al. 1995):

(1) The heliocentric distance of the solar wind termination shock is not very sensitive to the pick-up flux data. One may conclude that a decrease of the theoretical hydrogen pick-up fluxes, which would yield a better fit to the data, could be achieved with a reduction of the shock distance from 80 AU to 50 AU. One should bear in mind, however, that a similar reduction could just as easily result from a cosmic ray modified, high-entropy termination shock (Barnes 1994, 1995; Chalov & Fahr 1994, 1995), leading as well to fairly high post-shock compression ratios and densities, and hence in line with an enhanced filtration.

(2) Pick-up ion fluxes are essentially insensitive to the fact whether or not an outer VLISM shock is formed. It is noted that the twin-shock interface tends to favor VLISM hydrogen penetration into the inner heliosphere, but also decreasing the oxygen-to-hydrogen density ratios in the process. Because the oxygen pick-up ion fluxes should be increased relative to the hydrogen pick-up fluxes in order to obtain better agreement with the data, it is suggested that the one-shock interface does provide a better theoretical representation of this fact.

(3) It is quite evident that an ionized VLISM component is definitely needed for a good representation of the pick-up ion data. It seems that higher fractional ionizations ($f > 0.3$) are favored for VLISM hydrogen. This fractional ionization is higher than the prediction of Reynolds (1990) with his conservative photoionization rate. Higher ionization would also favorably influence the oxygen-to-hydrogen ratios.

(4) An adequate description of the heliospheric interface can only be expected if the effects of interstellar magnetic fields are taken into account. VLISM magnetic fields induce (a) a tilt to the interface configuration with respect to the inflow of neutral VLISM gases (Fahr et al. 1988), and (b) temperature anisotropies of the plasma species which are then partially transferred to the neutrals.

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24. Kinetic Versus MHD Theory in Heliospheric Plasmas

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In the last few years, an increasing amount of work has appeared on the modification of MHD phenomena in heliospheric plasmas due to non-ideal effects, in particular kinetic effects. An overall understanding of several problems in magnetised space plasmas, such as magnetic structures, waves and turbulence in the solar wind, magnetospheric phenomena and solar wind-comet interactions, has already been gained using MHD equations. However, it is recognised that a detailed understanding of these features depends on incorporating more detailed microphysics than are described by fluid-type equations, in particular the effects of non-equilibrium particle distributions.

There are a number of areas where kinetic effects have recently been included, using both particle simulations and kinetic theory approaches. The equilibrium structure of tangential discontinuities has been analysed using steady state solutions of the Vlasov kinetic equation (Roth et al 1996). Such current layers in space, such as at the Earth's magnetopause and in the solar wind, may be only a few ion Larmor radii thick, so that kinetic theory is appropriate. The advance of the theory of reconnection in such current sheets is also recognised to require kinetic theory (Dungey 1994).

A large amount of data is now available on low frequency Alfven and magnetoacoustic waves and turbulence in the solar wind, which has been analysed mainly using MHD theory (e.g. Tu and Marsch 1995). Fluid theory appears to describe the predominantly outward propagation of Alfven waves from the Sun, and the creation of MHD turbulence due to instabilities associated with the differential motion of the streams in the solar wind plasma. However at short wavelengths where the turbulence ends up heating and accelerating the plasma, a kinetic description is required. An interesting recent development in the generalisation of the MHD approach to solar wind turbulence is the inclusion of the Hall term to describe higher frequency Alfven waves, around the ion cyclotron frequency (Axford and McKenzie 1992). These waves may play a role in the perpendicular heating of protons, the preferential heating and acceleration of heavy ions, and the heating of the solar corona. An observed steepening of the solar wind power spectrum above the ion cyclotron frequency has been simulated using Hall MHD (Ghosh et al 1996). Further modelling in this frequency range will clearly require more detailed kinetic effects. Non-ideal modifications of MHD theory such as the Hall and electron pressure terms have also been shown to remove the need for assuming an artificial resistivity in MHD simulations of the magnetospheric current system (Winglee 1994).

Another topic of much recent interest is the kinetic modification of the shear Alfven wave to the Kinetic Alfven wave (KAW), which, in contrast to the MHD wave, has an electric field component parallel to the magnetic field which breaks down the "frozen-in" condition. The KAW is an obliquely propagating wave modified by finite ion Larmor radius effects, and has for a decade been thought to play a role in particle transport and acceleration in the magnetospheric plasma. More recently the KAW has been invoked as a mechanism for heating of solar wind protons and alpha particles in the comet-solar wind interaction region: shear Alfven waves excited by the ring distribution of pickup cometary water ions are advected downstream into regions of strong magnetic field gradients and shear, and are mode converted into KAW modes which are strongly Landau damped by the solar wind plasma (Sharma and Papadopoulos 1995). A number of other finite ion Larmor radius effects as representing non-ideal terms in the MHD equations have been reviewed by Stasiewicz (1993). Such small-scale gyro-effects have been shown to possibly provide the mechanism for gyroviscous coupling between the solar wind and the magnetosphere, the triggering of the disruption of the magnetotail current layer, and the parallel electric field that accelerates auroral particles. In the Earth's magnetotail, the ion Larmor radius can be larger than the scale length of the magnetic field curvature, and the resulting finite Larmor radius effect can lead to the stochastic behaviour of ion trajectories and to deterministic chaos.

In summary, the pace of generalisation of MHD theory to include kinetic theory and other non-ideal effects as applied to heliospheric problems is accelerating, and should lead to further insights in the coming years.

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25. Charged Dust in Space Plasmas

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25.1. INTRODUCTION AND REVIEWS

Dust is an ubiquitous component of many astrophysical situations and often immersed in a plasma environment. As a result of primary electron and ion collection, photo-electric effects and various other mechanisms, the dust gets electrically charged. From the plasma point of view, the dust grains represent additional ionic species with unusual characteristics, being many orders of magnitudes heavier than ordinary ions, and with orders of magnitude larger and moreover time-dependent charges. On the other hand, charged dust reacts not only to gravitational forces but also to electromagnetic fields. For typically micron-sized dust the characteristic frequencies are much smaller than the corresponding electron or ion quantities, and give rise to new low-frequency eigenmodes, which might explain some of the lowest-frequency noise in space and astrophysical

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plasmas. The adequate description of fluctuating dust charges is a challenging problem, implying highly nontrivial source and/or sink terms, which lead to new electrostatic and electromagnetic instabilities (Melandso et al., 1993 Varma et al., 1993; Bhatt and Pandey 1994; Rao and Shukla 1994; Jana et al. 1995; Verheest and Meuris 1995).

Solar System applications include planetary rings, asteroid zones, cometary comae and tails, and even regions of Earth's lower magnetosphere. Intriguing phenomena observed in the 1980s by Voyager cameras and attributed to charged dust are radial spokes in the B-ring and braids in the F-ring of Saturn. Many papers (too many to cite all of them here) discuss waves and instabilities in dusty space plasmas, both with fixed and variable dust charges, at the linear (d'Angelo 1994; Li et al. 1994; Ma and Yu 1994; Rosenberg and Krall 1994, 1995; Ma and Shukla 1995; Rao 1995; Winske et al. 1995) and nonlinear level. The latter involve double layers, solitons and vortices (Mace and Hellberg 1993; Lakshmi and Bharuthram 1994; Rao and Shukla 1994; Popel and Yu 1995; Verheest and Shukla 1995; Meuris and Verheest 1996; Verheest and Meuris 1996). However, most studies are far ahead of what observations can corroborate, a situation not likely to change soon due to the paucity and long gestation times of coming solar system missions to planets and comets.

For the period 1993-1996 under discussion, we can refer to recent overviews by Mendis and Rosenberg (1994), Horanyi (1996), Shukla (1996) and Verheest (1996).

25.2. PLANETARY RINGS AND COMETS

Comparisons with observations are mostly in qualitative form rather than quantitative. In the previous triennium 1990-1993 several explanations were put forward for the occurrence of spoke-like structures in the B-ring of Saturn, involving charged dust grains following Keplerian orbits around the planet, imbedded in the corotating Saturnian magnetosphere. Without charged dust no satisfactory description can be given, but no clear choice has emerged yet between the different possibilities advanced: electromagnetic E cross B drifts forcing the dust from corotation distance, multistream dust charge density waves as waves of material density, or charged dust which enhances the growth and velocity ranges over which two-stream instabilities can occur (Bliokh et al. 1995).

In the plasma that connects Jupiter with its satellite Io, the detection of the electrostatic ion cyclotron instability would signal the presence of negative dust, as without it the mode would be stable (Chow and Rosenberg 1995). The only detailed, quantitative discussion of the braids and kinks observed in the F-ring of Saturn is given by Avinash and Sen (1994), showing them to be a consequence of the electromagnetic equilibrium of moving charged grains, and involving collective rather than single particle effects. The electrostatic pressure on the grains is balanced by the electromagnetic pinch produced by the dust ring current. Helical current filaments, with three strands as observed, are easily produced. Similar arguments allow one to reproduce the ringlets within the B-ring. From stability considerations it is further argued that the formation of these braids and filaments is a dynamic process, which critically depends upon local plasma conditions prevailing in the ring. This would explain why braids, kinks and spokes are not seen in all rings all the time.

Turning to comets, variable dust charges influence electromagnetic waves, the instabilities of which could generate spatial structures over a wide range of hundreds to tens of million kilometres in dusty cometary tails (Reddy et al. 1996). However, about the only cometary mission planned at present is the Rosetta mission, which will not reach comet 46P/Wirtanen before 2011, if all goes to plan. Delays would even worse this already not rosy picture. We also expect the Cassini/Huygens mission to yield additional information about the rings of Saturn.

While this dearth of observational data has lead to many, sometimes competing theoretical explanations, one would like to see a consensus between different views, if only to design new on board experiments to detect and measure charged dust grains and discriminate between different opinions. Traditional instruments study the impact ionization of dust grains. A novel Radio Dust Analyzer (Meuris et al. 1996) has been proposed to detect charged dust grains passing by a wire dipole antenna via changes in the induced electric potential. It turns out that grains with smaller velocities have better chances of being thus observed. That would make the Radio Dust Analyzer complementary to other dust detection methods, which work better for larger grain velocities.

25.3. SELFGRAVITATIONAL EFFECTS

Dust is also supposed to play a crucial role in the formation of stars, solar or planetary systems. If, as has been advocated by several authors in the past, solar systems are formed out of a dusty plasma, there is a need to selfconsistently adapt Jeans' instability criterion to the presence of charged grains. One can indeed no longer

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assume that astrophysical objects are only composed of electrically neutral material in the traditional sense, as they contain a significant amount of charged dust.

A first analysis of this problem has been given by Chhajlani and Parihar (1994) and indicates how charged dust grains in interstellar clouds could affect the fragmentation processes. For low-frequency modes the effect of the grains is important, decreasing the region of instability and increasing the critical Jeans' wavelength, rendering star formation more difficult. Pandey et al. (1994) obtained conditions for stable electrostatic levitation, condensation and dispersion of grains in a plasma background. As the grains start to condense under selfgravitation, an electrostatic field is set up due to charge separation between grains, electrons and ions. The electrons and ions rush to shield this field, creating density perturbations which if fast enough will tend to smooth out the effects and inhibit the condensation. However, the nonlinear evolution shows a condensation of grains, even when the effect of selfgravitation is annulled by electrostatic repulsion.

More generally, Avinash and Shukla (1994) have studied a purely growing instability, generalizing Jeans' instability, which can play a decisive role in levitation/condensation of grains in planetary rings as well as in the formation of galaxies and stars. The description includes a mixture of dust-acoustic and selfgravitational modes and leads to a rather robust, purely growing instability with a larger growth rate than the one of Pandey et al. (1994). The treatment, however, does not include fluctuations in the dust grain charges and it remains to be seen what this important modification will give.

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