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COMMISSION 49: INTERPLANETARY PLASMA AND HELIOSPHERE

(PLASMA INTERPLANETAIRE ET HELIOSPHERE)

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Preface

M. Vandas
President of the Commission 49
Astronomical Institute, Academy of Sciences, Boční II 1401, 14131 Praha 4, Czech Republic (vandas@ig.cas.cz)

The triennial report of Commission 49 consists of several discrete articles treating remote sensing of the inner heliosphere, interplanetary coronal mass ejections, physics of solar system dusty plasmas, and outer heliosphere. We express our gratitude to the authors who introduce us to some advances in our scientific field during the period 1999-2002.

1. Remote Sensing of the Inner Heliosphere

S. Ananthakrishnan[1] and M. Kojima[2]
[1] *NCRA-TIFR, Pune University, India 410007 (ananth@ncra.tifr.res.in)*
[2] *STELAB, Nagoya, Japan (kojima@stelab.nagoya-u.ac.jp)*

The spatial structure of coronal plasma fluctuations in the solar wind near the Sun were studied extensively during the conjunctions of the Venera-15 and Venera-16 spacecraft in mid 1984 while the velocity distribution of the solar wind in the distance range 4–40 $R_\odot$ was obtained during the solar conjunction of the Ulysses spacecraft in 1991 and 1995. The data have shown that the typical values of the anisotropy coefficient are < 2 for solar distances ≥ 15 $R_\odot$ and > 2 for solar distances < 15 $R_\odot$ (Janardhan et al. 1999, Efimov et al. 2000). Solar occultations of quasars and water masers and sounding measurements from the Ulysses spacecraft were used to study solar wind flow structures corresponding to different types of magnetic topology in the solar wind source area (Lotova et al. 2002). P-band VLA observations of motion associated with a solar flare at 26000 km s^{-1} have been reported implying a magnetoacoustic Mach Number in excess of 40 (White et al. 2000).

Recent, extensive interplanetary scintillation (IPS) observations of propagating transient heliospheric disturbances using the Ooty Radio Telescope (ORT) have clearly shown that fast, energetic, flare associated Type II shocks produce easily detectable interplanetary disturbances in the distance range 0.2–0.9 AU on a one-to-one basis (Ananthakrishnan et al. 1999, 2002). Recent coordinated simultaneous observation of several carefully selected radio sources, using the EISCAT and the ORT have shown that two-stream velocities derived from the EISCAT system match well with single station velocities derived from model fitting of IPS power spectra that show two Fresnel knees which indicate different velocity streams crossing the line-of-sight to the source (Moran et al. 2000).

Observations of IPS at 327 MHz on a grid radio sources, obtained from the ORT and the Solar-Terrestrial Environment Laboratory (Japan), have been effectively used to infer size, speed, and density fluctuations of coronal mass ejections (CMEs) in the entire Sun–Earth distance range. The evolution of the size of the IP CME in the inner heliosphere, i.e., $a_{CME} \sim R^{1.0}$, suggests a dynamic pressure balance maintained between the moving mass and the ambient solar wind plasma. The results on the speed of the CME have been useful in inferring the physics of CME initiation at low coronal level (Manoharan et al. 2000). An Earth-directed CME associated with the X5.7/3B flare on 2000 July 14 has been studied in detail using remotely sensed data from the solar radio observations, IPS images of the interplanetary medium from Ooty, and white-light data from space coronagraphs. The expansion of the CME, formation of the halo in the low corona, and its speed history in the interplanetary medium suggest a driving energy, which is likely supplied by the twisted magnetic flux rope system associated with the CME (Manoharan et al. 2001).

A scenario for the sigmoid expansion related CME events is proposed that twisted magnetic configurations with some magnetic complexity are good candidates for being source region of CMEs (van Driel-Gesztelyi et al. 2000).

Using IPS observations, the origin of low-speed wind (Kojima et al. 1999b, 2000; Ohmi et al. 2001), latitudinal solar wind structure (Kojima et al. 1999a, 2001), radial distance dependence of the fast solar wind speed (Yokobe et al. 2000), and structure and dynamics of CME propagation (Tokumaru et al. 2000a,b; Watanabe et al. 2000) have been studied. The relations between solar wind speed and expansion rate of the coronal magnetic field have been examined to study the solar wind acceleration mechanism (Hakamada & Kojima 1999; Hakamada et al. 2002). Based on the IPS observational results, theoretical works on velocity fluctuations in the IPS pattern (Chashei et al. 2000a), anisotropy of magnetosonic turbulence (Chashei et al. 2000b), and small scale density fluctuations (Chashei et al. 2002) have been made. By comparing 17 GHz microwave images from the Nobeyama Radioheliograph and the LASCO C2 coronagraph near the solar maximum (1999–2000), trajectories of 50 prominence eruptions are examined in order to address how prominence motions affect or reflect the surrounding coronal structures (Hori & Culhane 2002).

An emerging flux trigger model was proposed for solar flares and coronal mass ejections (Chen & Shibata 2000; Chen et al. 2001). As an extension of this model, a model has been proposed to explain coronal and interplanetary type II radio bursts (Magara et al. 2000). The detailed analysis of X-ray plasmoid ejections has been performed using radio data (Kundu et al. 1999) and statistical data of X-ray plasma ejections (Ohyama & Shibata 2000). Heating mechanisms of spicule and corona has been studied by MHD simulation (Saito et al. 2001; Takeuchi & Shibata 2001a,b).

The Solar Mass Ejection Imager (SMEI) that has been initially designed and developed by the solar and heliospheric group at the University of California's Center for Astrophysics and Space Sciences (CASS) (Jackson et al. 1997) has been integrated onto the Coriolis spacecraft and is ready for a launch scheduled in early 2003. The SMEI instrument is expected to measure CMEs and other heliospheric structures providing precise arrival time forecasts of CMEs heading from the Sun up to three days in advance. Work on a tomographic analysis technique (Jackson et al. 1998) that will eventually be used for SMEI has continued during this period. This tomographic program that originally provided views of heliospheric corotating structure (Jackson & Hick 2002) has been upgraded so that it can now operate in a "time-dependent" version.

The evolution of the large-scale structure of the solar wind with solar cycle has been studied using a combination of IPS and space-based instruments (Breen et al. 1999, 2000b,d, 2002a; Moran et al. 2000). An exciting result, confirmed by IPS observations from Toyokawa and in-situ results from Ulysses, was the existence of an asymmetry between the northern and southern hemispheres of the Sun, with the southern polar fast stream surviving closer to solar maximum than the northern stream (Breen et al. 2002b). The change from a solar minimum to a solar maximum wind between 1998 and 2000 was much more abrupt than the change from maximum to minimum-type wind in the declining phase of cycle 22 (Fallows et al. 2002).

Measurements from the LASCO instruments on SOHO, from EISCAT and from the Wind and Ulysses spacecraft have revealed significant changes in the longitudinal structure of the solar wind between 25–60 solar radii and the orbits of the spacecraft (Breen et al. 1999, 2000d). Velocities measured by IPS were generally consistent with those seen in-situ, except in cases when large longitudinal gradients in solar wind speed were seen in the in-situ data. In these cases the IPS results suggested that solar wind velocities varied much more near the Sun than they did at the spacecraft (Breen et al. 2002a). It is suggested that the underlying mechanism is stream-stream interaction between narrow regions of solar wind with different velocities, converting the highly non-uniform slow wind close to the Sun into the steadier flow seen at 1 AU and beyond.

Direct comparisons of the drift velocities of density features observed by white light instruments and turbulent-scale structures measured by EISCAT and MERLIN IPS have established that structures on spatial scales of 10000 km and 100 km drift at similar speeds in the slow solar wind, even close to the Sun. Observations of fast streams suggest that close to the Sun the small-scale turbulent structure giving rise to IPS may be moving faster than the background flow (Breen et al. 2000a,c, 2002b).

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2. Interplanetary Aspects of CMEs

David F. Webb
ISR, Boston College, 140 Commonwealth Ave., Chestnut Hill, MA 02467-3862, USA
(David.Webb@hanscom.af.mil)

2.1. Introduction

Coronal mass ejections (CMEs) are an important factor in coronal and interplanetary dynamics. They can inject large amounts of plasma and magnetic fields into the heliosphere causing major geomagnetic storms and interplanetary shocks, a key source of solar energetic particles. Much of the plasma observed in a CME is entrained on expanding magnetic field lines which can be modeled as a flux rope. During this reporting period, studies have improved our knowledge of the coronal properties of CMEs and their source regions, their characteristics in the solar wind, and their importance to space weather. Halo CMEs are of special interest for space weather because they suggest the launch of a geoeffective disturbance toward Earth.

Since early 1996 the SOHO LASCO coronagraphs have provided the most recent white light observations of CMEs, with coverage now through the first half and maximum (2000) of cycle 23. During this period, the LASCO observations of CMEs have been complemented by other SOHO coronal instruments, especially EIT, UVCS and CDS, and the TRACE and *Yohkoh* spacecraft. Studies have also involved in-situ observations of CMEs in the interplanetary medium, called ICMEs (Burlaga & Russell 2001), from the ACE and *Wind* spacecraft near Earth and *Ulysses*, NEAR, *Nozomi* and *Voyager 2* outside of Earth's orbit. All these missions were launched before mid-1999. A new solar wind mission, *Genesis*, was launched in August 2001. The *Yohkoh* satellite failed in Dec. 2001 after 10 years of operation.

2.2. Workshops, Meetings and Reviews

During this period many workshops and other meetings involving ICME topics were held and some of the Proceedings published. Some of the most important, with their Proceedings in ( ) were: the IUGG/IAGA General Assembly in Birmingham, UK (Schmieder et al. 2000), Chapman Conf. on Space Weather in Clearwater, FL (Song et al. 2001), Intl. Conf.

on Solar Eruptive Events in Washington, DC (Gopalswamy 2001), IAU Symp. No. 203 in Manchester, UK (Brekke et al. 2001), First S-RAMP Conf. in Sapporo (Omura 2002), Intl. Solar Cycle Studies meeting in Longmont, CO, Chapman Conf. on Storm-Substorm Relationships in India, SOHO-11 in Davos (Wilson 2002), Solar Wind X in Pisa, Italy, and the annual SHINE Workshops. Recent review papers discussing ICMEs and space weather include Crooker (2000), St. Cyr et al. (2000), Gosling (2000), Webb (2000a,b, 2002), Russell (2001), Webb et al. (2001) and Plunkett et al. (2002).

2.3. General Solar Wind Signatures of CMEs

The coronal magnetic fields and plasma from CMEs can be detected by remote sensing and in-situ spacecraft observations. A single spacecraft will see certain distinctive signatures, but with a great degree of variation from event to event (e.g., Crooker 2000; Gosling 2000). These signatures include transient interplanetary shocks, depressed proton temperatures, cosmic ray depressions, flows with enhanced helium abundances, unusual compositions of ions and elements, and magnetic field structures consistent with flux rope topologies. A widely used single-parameter signature of ejecta is the occurrence of counter-streaming suprathermal electrons, usually interpreted as signatures of closed field lines and, thus, a good proxy for ICMEs. An important multiple-parameter signature of an ICME, is a magnetic cloud, defined as long-duration flows with large-scale rotations of unusually strong magnetic field accompanied by low ion temperatures.

2.4. Magnetic Structure of ICMEs

The magnetic field data from clouds often provide good fits to flux rope models, e.g., Russell (2001); Lepping & Berdichevsky (2000). The original models assumed that the clouds' fields were force-free with cylindrically symmetric topologies. However, recent models of magnetic clouds relax the force-free condition, and include data from multiple spacecraft suggesting that cloud ropes are more curved and nonsymmetric, wider than they are thick, and more non force-free near their ends (Mulligan et al. 1999; Hidalgo et al. 2000; Mulligan & Russell 2001). There is evidence of occasional twin flux ropes possibly arising from the same solar event (Lepping et al. 2001; Webb et al. 2000a), or a single flux rope having dual polarities (Osherovich et al. 1999; Vandas & Geranios 2001). Mulligan et al. (2001) (also Crooker 2000) show that the leading polarity of ICME flux ropes is controlled by the large-scale (dipole) solar field and their axial orientation is controlled by the orientation of the neutral line at the source surface.

These surface neutral lines often parallel filaments, large dense, cool structures suspended along the magnetic field in the corona. These occasionally erupt, becoming the lower, slower part of "3-part" CMEs. Many, if not most CMEs erupt through preexisting streamers (Plunkett et al. 2000), which form the base of the heliospheric current sheet (HCS). Solar filaments tend to reflect the dominant magnetic helicity in each solar hemisphere and their orientation and helicity can be related to that of associated ICME flux ropes. Sigmoids, best observed in X-rays by Yohkoh, are sinuous surface brightenings associated to some degree with erupting filaments and CMEs (Canfield et al. 2000), and with geoeffective magnetic clouds (Leamon et al. 2002). Rust (2001) argues that, over their lifetime, filaments accumulate helicity and, with CMEs, carry off much of the toroidal magnetic flux and helicity from the Sun built up over the solar cycle.

Using an earlier technique with electron heat flux data to determine the "true" polarities of the IMF, Kahler et al. (1999) found that many intervals of counterstreaming electrons lay within magnetic sectors, often carrying the sector boundary. However, these ICMEs were not always near the HCS. Shodan et al. (2000) found a complicating factor, that the degree of counterstreaming within clouds varies from 0% to 100%, i.e., clouds can range from fully closed to partially open to fully open. One new possibility for explaining how CME fields become open is interchange reconnection (Crooker et al. 2002). This mode involves merging between the closed fields in the leg of a CME and adjacent open fields;

along with disconnection of internal CME fields, this mechanism can explain the lack of flux buildup in the heliosphere due to CMEs.

2.5. Solar Wind Composition of ICMEs

Another class of ejecta plasma signatures are the abundances and charge state compositions of elements and ions which are systematically different in ICMEs compared with other kinds of solar wind (Galvin 2001). As the corona expands, the electron density decreases so rapidly that the plasma becomes collisionless and the relative ionization states are "frozen in", reflecting the conditions of origin in the corona. The charge states of minor ions ($Z>2$) in ICME flows often imply relatively 'hot' coronal source conditions (i.e., >2 MK), especially as enhanced Fe^{16+} (Lepri et al. 2001) and O^{7-8+} (Henke et al. 2001). However, ICMEs exhibit a large variability in their structure and composition, including the detection of unusually *low* ionization states of He (e.g., enhanced He^{+}) and minor ions (Gloeckler et al. 1999; Skoug et al. 1999; Ho et al. 2000; Klecker et al. 2000). This admixture of hot and cool material was most evident in the May 2–4, 1998 period (Gloeckler et al. 1999; Skoug et al. 1999; Popecki et al. 2000).

In many of the events having low ionization states, an erupting filament-halo CME could be associated with either a dense and compact 'plug' or an extended flow of cool plasma in the trailing edge of a magnetic cloud. Six such events had enhancements of the isotope ^{3}He (Ho et al. 2000). Such material is likely from the filament itself, consistent with near-Sun observations showing that erupting filaments lag well behind the leading edge of their associated CMEs. In a recent study of Wind magnetic clouds, Lepping & Berdichevsky (2000) find that half show a significant increase in density toward the rear of the cloud. Mass fractionation has also been observed in several such events (Wurz et al. 2000). These ICMEs show a strong enhancement of heavy elements increasing monotonically with atomic mass, possibly due to a preferential loss of lighter elements in the preeruptive coronal region. *Genesis* is a solar wind sample return mission which is at the L1 point collecting and categorizing different types of solar wind flows, including ICMEs (Wiens et al. 2002). These samples are to be returned to Earth in late 2004 for high-precision isotopic and elemental analysis.

2.6. ICME Observations Beyond 1 AU

The *Ulysses*, *Voyager 2* and *Nozomi* spacecraft have encountered ICMEs beyond 1 AU, helping us to understand the long term evolution of ICMEs. Gosling & Forsyth (2001) summarize the characteristics of ICMEs found at high southern latitudes by *Ulysses* during its 1st and 2nd polar orbits. During the first orbit 6 CMEs were observed in the high speed solar wind. All exhibited overexpansion due to their high internal pressure and had no distinct heavy ion compositions. During the recent orbit 20 CMEs were observed, and these were typical of CMEs observed near the ecliptic around solar activity maximum. *Ulysses* and *Voyager 2* observations have been compared for the same ICMEs to better understand how CMEs and their shocks propagate in the outer heliosphere and how merged interaction regions (MIRs) form (Richardson et al. 2002; Wang et al. 2001). At the great distance of *Voyager*, ~58 AU, He abundance enhancements are one of the best indicators of ICME flows. The Japanese *Nozomi* mission was launched in 1998 and is on its way to Mars. Ihara et al. (2001) discuss observations of the July 12–14, 2000 flares from *Nozomi* at 1 AU but off the solar east limb as viewed from Earth. These suggest continuing connection to the Sun of the foot of a huge (~4 AU) ICME flux rope for at least 2 days.

2.7. Complex Ejecta

Based on earlier work, Burlaga et al. (2001) studied "fast ejecta" which were transient, high speed flows containing either a magnetic cloud or complex ejecta. The latter have some ICME signatures but have disorganized magnetic fields, and can last for days. Most were associated with multiple halo CMEs that may have been interacting (Gopalswamy et al. 2001). Such interactions are more likely near maximum and could explain some of the compositional anomalies of ICMEs.

2.8. ICMEs and Space Weather

Geomagnetic activity tends to track the sunspot activity cycle in amplitude, but with more variability. Geoactivity tends to have two main peaks, near sunspot maximum and during the declining phase of the cycle. The first peak is considered to be associated with transient solar activity, i.e., CMEs, and the later peak with recurrent high speed streams from coronal holes. Richardson et al. (2000, 2001) studied the relative contributions of different types of solar wind structures to the *aa* index from 1972–1986. They identified CME-related flows, corotating high-speed streams, and slow flows near the Earth, finding that each type contributed significantly to average *aa* at all phases of the cycle. For example, CMEs contribute ~50% of *aa* at solar maximum and ~10% outside of maximum, and high speed streams contribute ~70% outside of maximum and ~30% at maximum.

CMEs, however, are responsible for the most geoeffective solar wind disturbances and, therefore, the largest storms. Enhanced solar wind speeds and southward magnetic fields associated with interplanetary shocks and ICMEs are known to be important causes of storms. Strong southward fields can occur either in magnetic clouds or in the preceding post-shock regions, or both. For example, Wu & Lepping (2002) found that the geoeffective southward field in>80% of Wind magnetic clouds occurred in either or both of these regions (see also Webb et al. 2000b). Interacting streams and their shocks can also cause enhanced southward fields and lead to intense magnetic storms (Gonzales et al. 2002). Slower CMEs not driving shocks are probably associated with many smaller storms.

Since the launch of SOHO, halo CMEs have been used to study the influence of Earth-directed CMEs on geoactivity. Analyses of the relation between halo CMEs and geomagnetic storms were carried out by Webb et al. (2000a), Cane et al. (2000) and St. Cyr et al. (2000) and indicate a high degree of correlation near solar minimum and a decreased association near the current maximum. Webb et al. (2000a) compared the onset times of frontside halo events in early 1997 with storms at Earth (peak Dst < -50 nT) 2–5 days later, finding that all the frontside halo CMEs with surface sources within 0.5 R_s of Sun center were associated with magnetic cloud-like structures at 1 AU and moderate-level storms. St. Cyr et al. (2000) found similar, but weaker associations between halo CMEs and storms. They studied halo CMEs from 1996 to mid 1998, and concluded that 83% (15 of 18) of intense storms, were preceded by frontside halo CMEs. However, 25 of the frontside halo CMEs did not produce such large storms and were, therefore, false alarms. Cane et al. (2000) found that only about half of frontside halo CMEs were associated with ejecta (ICMEs) at Earth and their geoeffectiveness depended on the strength of the ejecta southward field. Ejecta with no preceding halo CMEs were not very geoeffective.

All these prior studies included partial halo CMEs. Webb (2002) summarized statistical studies of only full (360°) halo events, those most likely to be directed along the Sun-Earth line. In a study of 89 frontside full halos observed from 1996-2000, he found that ~70% of the halos were associated with shocks and/or counterstreaming electrons or other ICME signatures at 1 AU. Magnetic clouds were involved with $\geq$60% of the halos. The average travel time from the onsets of the halo CMEs to the onsets of the storms at Earth was 3.3 days. From solar activity minimum to maximum the average CME rate and speeds increased and the travel time from the Sun to 1 AU decreased, as expected for more energetic events. Although the degree of association between the full halo CMEs and moderate or greater storms decreased from 1997 through 1999, it increased in 2000, yielding an overall average of ~65%. Confirming previous studies, Webb (2002) found that ~70% of the most intense storms (Dst < -150 nT) of this cycle were associated with one or more halo CMEs.

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3. Modeling CMEs in the Solar Wind

Pete Riley
SAIC, 10260 Campus Point Drive, San Diego, CA 92121-1578, USA (pete.riley@saic.com)

3.1. Introduction

Heliospheric models of Coronal Mass Ejection (CME) propagation and evolution provide an important insight into the dynamics of CMEs and are a valuable tool in the interpretation of interplanetary in situ observations. Moreover, they represent a virtual laboratory for exploring conditions and regions of space that are not conveniently or currently accessible by spacecraft. Fast CMEs, in particular, have been identified as the leading cause of non-recurrent geomagnetic storms (Gosling 1997) and can also enhance the geoeffectiveness of recurrent storms (Crooker & Cliver 1994), making their study of practical importance.

In this report we summarize recent advances in modeling the properties and evolution of CMEs in the solar wind. We describe the current state of research and we suggest what topics will likely be important for models to address in the future. We focus on the physics described by the models and not specifically on the models themselves. Given the need for brevity, references will be selective and illustrative, rather than comprehensive. Other reviews that complement the present one have been given by Linker et al. (2002), Cargill & Schmidt (2002), and Riley (1999). While we emphasize fluid and MHD modeling in this report, we note that other modeling approaches have been used with success. The extension of force-free flux rope fitting (Lepping et al. 1990) to include the effects of expansion (Osherovich et al. 1993; Marubashi et al. 1997) and multiple spacecraft (Mulligan et al. 2001), for example, have allowed further classification of this important subset of CMEs. Hybrid codes have also been used to model the interaction of fast CMEs with the ambient solar wind allowing ion-kinetic effects to be explored (Riley et al. 1998).

Since the basic mechanism(s) by which CMEs erupt at the Sun (Forbes 2000; Klimchuk 2001) is (are) not well known, it is therefore not surprising that models developed to investigate the initiation and evolution of CMEs both near the Sun and in the solar wind tend to be idealized. In fact, to make problems tractable, significant approximations must be made. For example, consider the placement of the inner radial boundary. For many years, this was chosen to be beyond the outermost critical point (e.g., Hundhausen & Gentry 1968; Dryer et al. 1989; Riley et al. 1997; Odstrcil & Pizzo 1999a,b,c; Cargill & Schmidt 2002; Vandas et al. 2002). Modeling CME propagation and evolution beyond this point is a much simpler task than including the initiation process and evolution through the lower corona. Given accurate boundary conditions at say 20–30 R_S, the physics of the medium is simpler and better understood, and the magnetofluid equations used to describe the system are easier to solve. Further, the minimum time step required to advance the solutions are also typically much larger than would be required if the lower corona were included. Unfortunately, it is difficult to measure the plasma and magnetic field properties in this region, leading to the specification of ad hoc boundary conditions. Moreover, such an approach completely avoids the question of CME initiation.

A second, often used approximation is to neglect the magnetic field (e.g., Hundhausen & Gentry 1968). Thus strictly speaking the simulations are valid only for high-β CMEs. The characteristic speeds at which pressure disturbances propagage in the simulation are less than in the real solar wind, and magnetic forces are not included. Obviously such studies cannot address questions related to the magnetic structure of the CME. Nevertheless, they have proven to be extremely useful in illuminating the fundamental aspects of the processes by which both transient and corotating disturbances evolve in the solar wind (see, for example, reviews by Hundhausen (1985) and Gosling (1996)). Currently there is a trend toward "modular" modeling of space-plasma systems, where several specialized codes are integrated together, with the output from one model providing the input to the next model (e.g., http://ccmc.gsfc.nasa.gov). In some cases, such as the ionosphere-magnetosphere system, this can lead to a complex feedback loop. On the other hand, the coupling of solar coronal models with interplanetary models is considerably simpler owing to the supersonic nature of the flow at the boundary (Odstrcil et al. 2002).

Algorithms are constantly being updated to include more and more realistic physics. The methods of solution are also being improved on to take advantage of new developments in numerical techniques as well as new computing paradigms. Adaptive Mesh Refinement (AMR), for example, is a technique that allows both large- and small-scale structure to be resolved within a single simulation (e.g., Odstrcil et al. 2002; Manchester et al. 2002). The Message Passing Interface (MPI) is an approach to computing that allows one to utilize a large number of processors simultaneously, leading to simulations at significantly higher resolution than previously possible.

3.2. Modeling CMEs Outside the Critical Point

A major drawback of initiating CMEs at an arbitrary boundary outside the outermost critical point is one of self-consistency. Virtually any kind of perturbation can be inserted. With this freedom comes the ability to "tweak" the parameters so that a good match is found between simulation results and observations. On one hand this can be an instructive exercise, allowing you to narrow down the initial configuration of the pulse; however, particularly when non-reversible processes such as at shocks are present, there is no guarantee that the correct one has been found. Moreover, when coupled with other questionable assumptions, such as neglecting the magnetic field and/or reducing the system to cylindrical or spherical symmetry, the initial configuration may be significantly different in reality. It is likely, for example, that magnetic pressure is responsible for driving the expansion of the so-called "over-expanding" CMEs observed by Ulysses at high heliographic latitudes (Gosling et al. 1994; Gosling et al. 1998). Thus the one-dimensional, gas-dynamic simulations that used enhanced density to mimic the initial high pressure were probably not accurate initial configurations, even though the dynamic evolution of the ejecta, and the development of associated disturbances are undoubtedly qualitatively correct.

Nevertheless 1-D gasdynamic simulations continue to be useful tools in probing the large-scale dynamics associated with CME evolution. For example, they have been applied to the evolution of CMEs at large heliocentric distances (Riley & Gosling 1998), the acceleration of CMEs near the Sun (Gosling & Riley 1996), and the relationship between density and temperature within CMEs and its implications for the polytropic index of the plasma (Riley et al. 2001).

3.3. Modeling CMEs from the Solar Surface to Earth

As we have noted, modeling the solar environment below the critical points is more complicated because information can now travel in both directions. Nevertheless several groups are modeling the Sun's extended Corona from 1 R_S to 1 AU, and beyond. Wu et al. (1999), for example, generated a CME from the eruption of a helmet streamer using an ad hoc increase in the azimuthal component of the magnetic field. The University of Michigan group (e.g., Groth et al. 2000; Manchester et al. 2002) have developed a finite-volume, AMR scheme to study CME evolution from the Sun to Earth. The CME is "initiated" in one of several ways. Groth et al. (2000) applied a localized density enhancement at the solar surface, essentially mimicking a pressure pulse. In contrast, Manchester et al. (2002) superimposed the magnetic and density solutions of the 3-D Gibson & Low (1998) flux rope within the coronal streamer belt; the CME being driven by the resulting force imbalance.

As with the simulations initiated beyond the super-critical points, "inserting" a CME near the solar surface and allowing it to evolve from that point allows enormous freedom to adjust the initial parameters to fit the observations. It may turn out that for the purposes of space weather prediction, such an approach is the most practical. A particular set of observations, for example, may suggest an appropriate initial configuration and perturbation to produce a CME that reproduces observations near Earth. However, it is unlikely that we will uncover the underlying eruption mechanism(s) from these ad hoc boundary conditions. Instead, we must constrain these free parameters, to produce more self-consistent models. Toward this goal, Linker & Mikić (1997) initiated an eruption through differential rotation and followed its evolution out to 1 AU. Odstrcil et al. (2002) described a coupled 2.5-dimensional MHD simulation of a CME erupted at the solar surface using flux cancellation (Linker et al. 2001) and propagated out into the solar wind. In spite of the idealized nature of the eruption process and ambient solar wind, the solution was remarkably rich and complex. These results were used by Riley et al. (2002a) to interpret the plasma and magnetic field signatures of a CME observed by both ACE and Ulysses, which were aligned in longitude, but separated significantly in radial distance and latitude. These simulations also suggested that a jetted outflow, driven by post-eruptive reconnection underneath the flux rope occurs and may remain intact out to 1 AU and beyond (Riley et al. 2002b). Comparison between simulations and observations of a magnetic cloud with similar signatures suggested that velocity and/or density enhancements observed at trailing parts of magnetic clouds may be the signatures of such reconnection, and not associated with prominence material, as has previously been suggested.

3.4. Modeling CMEs at High Heliographic Latitudes

One of the fundamental discoveries of the Ulysses mission was a new class of CMEs in the solar wind (Gosling et al. 1994). While at latitudes above 35°S, during its initial poleward excursion, Ulysses became immersed in quiescent, tenuous, high-speed solar wind and observed CME profiles that were fundamentally different from those at low latitudes. They appeared to have begun life as high pressure pulses that coasted out with the fast ambient solar wind, driving forward and reverse shocks ahead and behind them, respectively. As with their lower-latitude counterparts, some contained flux ropes while others did not. It is likely that most — if not all — of these events were high-latitude extensions of larger-scale structures. In fact at least 3 events were observed at different latitudes by two spacecraft (Hammond et al. 1994; Gosling et al. 1995; Riley et al. 2002b). Thus the cartoons presented by Gosling et al. (1994) and the simulation results by Cargill et al. (2000) suggesting isolated "bubbles" are almost certainly oversimplifications of structures that are considerably more complex in reality. Two- and 3-D simulations (Riley et al. 1997; Odstrcil & Pizzo 1999a,b,c) have highlighted the role of the ambient solar wind in interacting with, and deforming the ejecta as it moves away from the Sun.

3.5. Observational Selection Effects

It has long been known that the particular trajectory taken by a spacecraft through a CME and its associated disturbance can radically alter the observed profiles. In fact, the recent classifications of CMEs into "simple" and "complex" (Burlaga et al. 2001) may be, at least in part, a consequence of such observational selection effects. Marubashi (1997) illustrated how a single event could be seen by one spacecraft as a non-flux-rope CME while at another it would appear as a magnetic cloud. Does this again imply that the delineation between magnetic clouds (or flux ropes) and CMEs is an artificial one? The CMEs observed by Ulysses and Wind/ACE had significantly different profiles at the two spacecraft, so much so that only by global modeling could we confidently infer that the events observed at the two spacecraft were one and the same.

Vandas et al. (2002) simulated the evolution of a flux-rope CME in three dimensions from 30 R_S. The initial state of the magnetic cloud was that of a section of a toroid. Since the feet of the flux rope were tied to the Sun, solar rotation caused the loop to wind up and deform. Measurements made by hypothetical spacecraft at different inertial longitudes were radically different, and in particular, it was possible to traverse the event twice. This may provide an explanation for the double-peak structures sometimes seen in the observations (e.g., Vandas et al. 1993).

3.6. Interacting CMEs

As CMEs move away from the Sun they interact with their local environment. Fast CMEs plow through slower wind ahead sweeping it up, compressing it, and driving a shock ahead. Behind it, an expansion wave, or rarefaction region forms as the fast CME outruns the slower plasma behind. In addition, CMEs may interact with one another (Burlaga et al. 2001; Gopalswamy et al. 2001). Active regions on the Sun can be the origin of multiple CMEs. A fast CME launched shortly after a slower one can lead to a complex interaction (Gopalswamy et al. 2001). Depending on the relative orientation of the magnetic field lines within the ejecta, it may be possible for the two ejecta to reconnect producing a new aggregate structure (Odstrcil & Pizzo 2002). It may also be possible for the same CME to interact with itself. One can imagine that, under the right ambient conditions, the leading portion of the CME simulated by Vandas et al. (2002) could interact with the trailing portion of the loop.

3.7. Future Directions of CME Modeling Research

Predicting the path of future research is clearly speculation, undoubtedly driven, at least in part, by our current interests. Nevertheless, it may be of some use to list several likely topics that may be pursued in the upcoming years.

One challenge will undoubtedly involve the ability to self-consistently model CMEs with a range of properties. How do we initiate slow and fast CMEs, for example? Are they generated by the same mechanism, or are there two (or more) mechanisms that are responsible? Self-consistent models currently can only produce flux-rope CMEs. What are the underlying differences between these and CMEs that don't contain a flux rope? Is it an observational selection effect or are there intrinsically different mechanisms for producing each type?

We may be entering a new era of CME modeling. In the future, we will see models becoming increasingly capable of modeling specific events. This will require capabilities to accurately reproduce a disparate set of remote and solar observations. We may see some of these models transition from research tools to operation tools, capable of predicting the onset of geo-effective phenomena (although see Cargill & Schmidt (2002) for a more conservative opinion on this).

It is important to remember that these models are only tools that allow us to better understand CME phenomena. To close, we provide an illustrative selection of questions that we may be able to answer using the models described here. What are the fundamental evolutionary distinctions between CMEs and magnetic clouds? What topology is predicted for CMEs in the heliosphere by various initiation mechanisms? What is the relationship between the 3-part structure of CMEs as seen in coronagraph observations and their interplanetary counterparts? What processes control the solar connectivity of field lines embedded within CMEs? How do the properties of the ambient solar wind modify the evolution of the ejecta? How does the internal magnetic structure of a flux rope affect its distortion in the solar wind? How do in situ signatures (as would be seen by a spacecraft) change depending on where the simulated CME is sampled? What differentiating observational signatures do the models predict?

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4. Dusty Plasmas in the Heliosphere

Frank Verheest

Sterrenkundig Observatorium, Universiteit Gent, B–9000 Gent, Belgium
(Frank.Verheest@rug.ac.be)

4.1. Introduction

Dusty plasmas is the name coined a decade ago for ionized gases laden with fine dust grains. Both components are ubiquitous, and occur in a wide variety of cosmic and terrestrial environments, like planetary rings, comets, Earth's ionosphere and interstellar molecular clouds. Charged dust has been observed in laboratory plasmas, including etching and deposition processes, and in dust plasma crystal experiments. Typical micron-sized dust grains are much more massive than ordinary ions and can carry high charges, totally outside the framework of standard treatments. Not only are new plasma eigenmodes possible at the very low-frequency end of the spectrum, but charges are determined by the plasma potentials and can fluctuate with these. In addition, dust comes in all sizes, masses and charges, so that distributions have to be dealt with. Dusty plasma physics is thus highly fascinating and deeply challenging at the same time.

While theoretical developments have been impressive, there is a lack of suitable space observations to constrain the wilder flights of imagination that tend to crop up in the literature. Indirect Voyager observations are still being digested, and we are waiting for the Cassini-Huygens and several cometary mission results to come in. Further details about dusty plasmas can be found in general introductions (Verheest 2000; Shukla & Mamun 2002) and reviews (Verheest 1999; Rosenberg 2000, 2001). In this brief overview of the period 1999–2002 we can only concentrate on problems and results in space physics that relate to charged dust and to predictions that use dusty plasma physics as possible diagnostic tools in a heliospheric context.

4.2. Planetary Magnetospheres

Several papers address possible distributions of charged dust in planetary environments, focussing mainly on Jupiter and Saturn. Reviewing recent in situ and remote sensing observations, and theoretical advances in understanding dust plasma interactions in Jupiter's magnetosphere, Horányi (1998) details how dust grains exposed to plasmas and UV radiation collect electrostatic charges and how their dynamics are altered by electric and magnetic fields. Hence, magnetospheric effects shape the size and spatial distributions of micron-sized and smaller dust grains. The ring/halo region, the dust streams and the captured ring at Jupiter are recent examples where dust plasma interactions can best explain the observations (Horányi 1998). Based on the observations and the theory of the dust streams ejected from Jupiter's magnetosphere, analogous processes are expected to operate at Saturn (Horányi 2000). Stability loci are calculated for both dielectric and conducting grains, in prograde and retrograde orbits, with the sign of the charge determined by the plasma environment, local photoionization and magnetospheric charging currents. The results indicate that nonequatorial halo orbits are dominated by positively charged grains (Howard et al. 1999), and very small submicron grains in positive retrograde orbits are most likely to be found by the Cassini orbiter, whereas negatively charged grains are dynamically excluded (Howard & Horányi 2001).

Furthermore, dust diffusion across a magnetic field due to random charge fluctuations are shown to be one of the most effective processes to transport particles in the inner Jovian magnetosphere (Khrapak & Morfill 2002). Dynamics of the E ring dust grains in Saturn's magnetosphere have been investigated, taking solar radiation pressure, planetary oblateness, the Lorentz force due to variable dust charges and the plasma drag into account (Dikarev 1999). The Lorentz force leaves the eccentricity unaltered, but causes precession or regression of the orbit. The main drag force in the inner magnetosphere of Saturn is found to be due to heavy ions like O^+ or OH^+. However, the plasma drag changes the semimajor axis enough to allow submicron-sized grains ejected from Enceladus to survive against recollision with the parent satellite. Combined with radiation pressure this effect also leads to growth of the eccentricity of the E ring grain orbits (Dikarev 1999).

Dust particles on near-Keplerian orbits in planetary rings drift relative to the corotating background plasma, and this relative streaming may drive several modes unstable. Besides vertical oscillations out of the ring plane near synchronous orbit, due to small grains, of importance for the evolution of spokes in Saturn's rings (Li & Havnes 2000), there are also dust-induced magnetosonic instabilities of a two-stream nature farther away from synchronous orbit, although the estimates vary about the growth rates (Li & Havnes 2000; Verheest & Hellberg 2001).

A potentially powerful diagnostic tool is the possibility of extracting information on the dusty plasma conditions in planetary rings by observing the V-shaped Mach cone pattern around a charged body moving through or close to a layer of dusty plasma. Existing theories for dust-acoustic waves and accelerations of dust orbits at the front of the body yield information on the dust sizes and distributions, number and material density, when the normal plasma parameters are known (Havnes et al. 2001). More refined theories for the dust-acoustic wave and bow shocks, including a dust size distribution, should allow additional and more accurate information on the total plasma conditions.

4.3. Comets

There is much less news to report on dusty plasma processes near comets. The interaction of the solar wind with weak comets, leading to the formation of cometary magnetospheres with different types of structures, has been simulated for a wide range of gas production rates and for an interplanetary magnetic field perpendicular to the incoming solar wind (Lipatov et al. 2002). Weak gas production forms a strong cycloid-type tail, whereas for stronger production the cometary atmosphere forms a cone-type tail and structuring of the coma occurs. This may be applied to other weak massloading sources, such as dusty plasmas and cometary ion dynamics in the inner coma, AMPTE releases, and to nonmagnetic bodies like Phobos, Deimos or even Pluto. Furthermore, the results are relevant for the ionized environment near a future 'Solar Probe' spacecraft.

Čadež & Verheest (2000) have treated surface eigenmodes when the charged dust is confined to a uniform slab with non-uniform smooth boundary layers. The dust component can flow with respect to the background plasma, as a model for cometary tails, since in the comet frame there is a notable difference between the fast flowing solar wind and the slow moving dust tail. Besides plasma surface waves unaffected by the dust flow, there are convective surface modes, which become unstable for large flow speeds, akin to Buneman-type instabilities. The resonant processes in the boundary layers, including damping and growth, might help to interpret future comet tail observations.

4.4. Heliosphere and Earth's Magnetosphere

Three regions have attracted attention here, the outer heliosphere, the neighbourhood of the Sun and the terrestrial magnetosphere. In the outer region of the heliosphere, beyond 20 AU, the neutral gas density becomes larger than the solar wind plasma density, and neutral gas drag plays an important role in the evolution of dust grains. However, the monodirectional inflow velocity of the interstellar gas is very much different from the radial solar wind velocity, generating asymmetric forces on the dust particles that rapidly change their eccentricity and semimajor axis. Consequently, the lifetime of dust grains in the Edgeworth-Kuiper Belt is not determined by the electromagnetic or plasma Poynting-Robertson effect but by the drag of neutral gas, leading to lifetimes of the order of half a million years for a 10 micron particle (Scherer 2000). Another diagnostic tool is the deflection of interstellar dust grains by the magnetic field near the heliopause, depending on their electric charge. Kimura & Mann (1999) have studied the electric charging of dust grains with emphasis on the secondary electron emission, because of its importance in the hot plasma environment near the heliopause. Model calculations of the grain charge, combined with in situ measurements of interstellar dust in the heliosphere, place an upper limit on the magnetic field strength, showing the perpendicular component to be less than 0.4 nT.

Based on estimates for dust transport to the near-solar region, Mann et al. (2000) have obtained the spatial distribution of different dust populations within 10 solar radii from the Sun. For the radial structure, moderate enhancements are consistent with eclipse observations, most of which have not shown any peak features in the F-corona brightness at several solar radii. For the vertical structure of the dust cloud, grains larger than 10 microns remain in a disk of typically 10 degrees' thickness, whereas smaller grains fill a broader volume, tilted off ecliptic by an angle depending on the solar activity cycle. Submicrometer-sized grains, however, form a nearly spherical halo of more than 10 solar radii around the Sun. Moreover, from present knowledge the existence of an additional halo of larger grains cannot be excluded, depending on how effective long-period comets are as sources of dust, and a simple extrapolation of the interplanetary dust cloud to the solar vicinity does not properly describe the dust cloud there (Mann et al. 2000).

Ending with the terrestrial environment, Earths' magnetosphere acts on cosmic dust as a shield with an efficiency that depends on sizes and velocities of the incoming dust particles. This reduces the flux of interplanetary and lunar dust particles smaller than 0.1 microns, but the shielding is much less effective for cometary dust grains, owing to their high average approach velocity (Juhász & Horányi 1999). Finally, the diffusion of macroparticles, charged by solar radiation under microgravity conditions, has been studied by analyzing experimental data obtained on the MIR space station (Vaulina et al. 2002). A comparison of experimental and theoretical estimates shows that the short-time dynamic behaviour of the macroparticles can be explained by observing the ambipolar diffusion. Similar experiments are planned aboard the International Space Station, where also dust plasma crystals are studied under microgravity conditions.

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5. The Outer Heliosphere and Heliospheric Interface

Vladislav V. Izmodenov

*Lomonosov Moscow State University, Department of Aeromechanics,
Faculty of Mechanics and Mathematics, Vorobevy Gory, 119899, Moscow,
Russia (izmod@ipmnet.ru)*

5.1. Introduction

The solar wind flow in the outer heliosphere is determined by its interaction with the local interstellar cloud (LIC). The interaction region is called *the heliospheric interface.* The solar wind meets the interstellar charged component at the heliopause, where the solar wind pressure balances the pressure of the LIC. Since the solar wind is a supersonic flow, the heliospheric termination shock (TS) should be formed to make the solar wind subsonic before it reaches the heliopause. The bow shock (BS) is formed in the supersonic (V ~26 km/s, T ~ 7000 K) local interstellar plasma flow. Interstellar atoms of hydrogen interact with the charged component by charge exchange and significantly influence the heliospheric plasma interface. The interstellar atoms of hydrogen penetrate the heliospheric interface and can be measured indirectly inside the heliosphere. Since the atoms are disturbed in the interface they can serve as remote diagnostics of both the local interstellar gas and the heliospheric interface plasma properties. Theoretical models should be used in such an analysis.

5.2. Models of the Heliospheric Interface

The difficulties to model the heliospheric interface are connected with 1) the multi-component nature of both the LIC and the solar wind, 2) kinetic behavior of interstellar atom flow in the interface.

Evolution of velocity distribution function of the interstellar atoms in the heliospheric interface was studied by Izmodenov (2001a), Izmodenov et al. (2001) based on self-consistent two-component model of the heliospheric interface (Baranov & Malama 1993). It was shown that all hydrogen atoms in the interface can be separated into four populations. Velocity distributions of all populations are not Maxwellian. Similar research was performed by Müller et al. (2000), but their model used Maxwell-approximation of H-atoms to calculate source terms into the plasma equations. This approximation introduces a systematic error, which is difficult to estimate.

The LIC consists of at least five components: plasma (electrons and protons), hydrogen atoms, interstellar magnetic field, Galactic cosmic rays, and interstellar dust. The heliospheric plasma consists of original solar particles (protons, electrons, alpha particles, etc.), pickup ions and the anomalous cosmic ray component. The influence of the Galactic cosmic rays on the heliospheric interface structure was studied recently by Myasnikov et al. (2000). The study was done in the frame of two-component (plasma and GCRs) and three-component (plasma, H atoms and GCRs) models. For the two-component case it was found that cosmic rays could considerably modify the shape and structure of the solar wind termination shock and the bow shock and change the positions of the heliopause and the bow shock. At the same time, for the three-component model it was shown that the GCR influence on the plasma flows is negligible as compared with the influence of H atoms. The exception is the bow shock, a structure that can be strongly modified by the cosmic rays. It was also found (Fahr et al. 2000; Alexashov, private communication) that an anomalous component does not have a significant effect on the position of the termination shock. However, ACRs may significantly reduce compression at the termination shock (Fahr et al. 2000). For recent review on ACRs see Fichtner (2001).

Effects of the interstellar magnetic field on the plasma flow and on distribution of H atoms in the interface were studied by Alexashov et al. (2000) in the case of magnetic field parallel to the relative Sun/LIC velocity vector. It was shown that effects of the interstellar magnetic field on the positions of the termination and bow shocks and the heliopause significantly decrease as compared to model with no atoms. The calculations were performed with various Alfvén Mach numbers in the undisturbed LIC. It was found that the bow shock straightens out with decreasing Alfvén Mach number (increasing magnetic field strength in LIC). It approaches the Sun near the symmetry axis, but recedes from it on the flanks. By contrast, the nose of the heliopause recedes from the Sun due to tension of magnetic field lines, while the heliopause in its wings approaches the Sun under magnetic pressure. As a result, the region of compressed interstellar medium around the heliopause (or "pileup region") decreases by almost 30 %, as the magnetic field increases from zero to 3.5×10^{-6} G. It was also shown in Alexashov et al. (2000) that H atom filtration and heliospheric distributions of primary and secondary interstellar atoms are virtually unchanged over the entire assumed range of the interstellar magnetic field (0–$3.5 \cdot 10^{-6}$ G). The magnetic field has the strongest effect on density distribution of population 2 of H atoms, which increases by a factor of almost 1.5 as the interstellar magnetic field increases from zero to $3.5 \cdot 10^{-6}$ G.

A new non-stationary model of the solar wind interaction with two-component (H atoms and plasma) LIC was proposed by Zaitsev & Izmodenov (2001). In this model the primary and secondary interstellar atoms (populations 3 and 4) were treated as quasi-stationary kinetic gases. Population 1 of atoms originating in the supersonic solar wind was considered as zero-pressure fluid. The calculations show that the qualitative features of the non-stationary SW/LIC interaction established in Baranov & Zaitsev (1998) remain, but the effect of the solar activity cycle is quantitatively stronger because the interface is closer to the Sun than in the model with no atoms. The motion of the termination shock during the solar cycle on the axis of symmetry is about 30 AU. Due to the solar cycle variations of the neutralized solar wind (i.e., atoms of population 1) the region between the heliopause and the bow shock widen and the mean plasma density in the region becomes smaller than for the stationary problem.

Recent reviews on the modelling of the heliospheric interface are given by Zank (1999), Izmodenov (2001b). Many recent results on the global modelling of the outer heliosphere are reported in the Proceedings of COSPAR Colloquium "The Outer Heliosphere: The Next Frontiers" (Scherer et al. 2001) and in the Proceedings of the International Conference "Progress in Cosmic Gas Dynamics" (Myasnikov 2000).

5.3. Remote Diagnostics of the Outer Heliosphere

At present time there is no direct observation inside the heliospheric interface. Voyager spacecraft are moving away from the Sun at 3.6 AU per year, approaching the termination shock believed to be roughly around 100 AU. In January 2003 Voyager 1, the most distant spacecraft, will be at $\sim$ 87 AU.

Measurements of pickup ions of hydrogen and helium, which are created from interstellar atoms in the supersonic solar wind are used to derive the number densities of interstellar atoms in the distant heliosphere (at the TS) with small uncertainties, $n_{H,TS} = 0.097 \pm 0.015$ cm^{-3} and $n_{He,TS} = 0.016 \pm 0.002$ cm^{-3} (Gloeckler & Geiss 2001). Then employing heliospheric interface model one can derive interstellar H atom and proton number densities (e.g., Lallement 1996; Gloeckler et al. 1997). Velocity and temperature of interstellar H atoms are disturbed in the heliospheric interface by charge exchange. Those parameters can be deduced from measurements of solar backscattered Lyman α profiles. The profiles can be obtained from H cell SOHO/SWANS measurements. Preliminary results were reported by Quemerais et al. (1999), Costa et al. (1999). Photometric measurements of backscattered Lyman α radiation on board of Voyager and Pioneer spacecraft are also important source of information (Quemerais et al. 2000). Quemerais (2000) has shown that radiative transfer effects must be taken into account in interpretations of backscattered Ly-α radiation. New important results on ionization of hydrogen and helium in LIC were reported by Wolff et al. (1999).

Theoretical models predict deceleration of the solar wind by pickup ions, which is now confirmed by measurements of the distant solar wind speed. Richardson (2001) reported 40 km/s deceleration at 60 AU. Other methods to put constraints on the heliospheric interface include anomalous cosmic ray gradients (Stone 2001 and reference therein), kHz radio emission measured by Voyager (Cairns & Zank 1999; Zank et al. 2001), absorption in Lyman α toward nearby stars (Wood et al. 2000; Izmodenov et al. 1999a). Recent estimates of the location of the heliospheric termination shock using transient decreases of cosmic rays observed by Voyager 1 and 2 also provide constraints on the location of the termination shock (Stone 2001) were reported by Webber et al. (2001). However, simultaneous analysis of different types of observational constraints on the base of unique heliospheric interface model has not been done yet. First attempt to reconcile different diagnostics was done by Izmodenov et al. (1999b).

Among newly suggested methods to diagnose of the interface region are heliosheath imaging in ENAs (Gruntman et al. 2001) and heliopause imaging in Oxygen O^{+} ion 83.4-nm resonance line emission in EUV (Gruntman & Fahr 2000).

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