Neutral solar wind properties: Advance warning of major geomagnetic storms

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Abstract. Coronal mass ejections (CMEs) have been identified as a trigger for large geomagnetic storms. A clever idea to provide advance warning of a high-speed CME approaching the Earth was recently proposed by Hsieh et al. (1992): ejected solar matter decelerates on its way from the Sun to Earth, energetic neutral atoms (ENAs) are formed in the CME plasma due to recombination, ENAs pass the decelerating CME plasma and arrive first at the Earth. We evaluate the idea to use ENAs for advance detection of the high-speed Earth-approaching CMEs and consider the processes involved. Charge exchange between solar wind ions and interplanetary neutral atoms contribute effectively to ENA production. Characteristics of neutral gas within Earth's orbit are updated for both neutral atoms of interstellar origin and from outgassing from interplanetary dust. Computer simulation of CME-produced ENAs shows that the total flux of CME-produced ENAs is slightly smaller than the intensity of the quiescent neutral solar wind (NSW) while significantly higher ENA energies make them easily distinguishable from NSW atoms. Arrival of the CME-produced ENAs is expected 3-4 hours before the start of a large geomagnetic storm, which provides a basis for advance storm warning and prediction of storm magnitude. The progress in development of ENA measurement technique suggests that both the quiescent NSW and CME-produced ENAs can be reliably measured.

1. Introduction

Coronal mass ejections (CME) have been identified as a trigger for large nonrecurrent geomagnetic storms [e.g., *Gosling et al.*, 1991; *Gonzalez and Tsurutani*, 1992; *Tsurutani et al.*, 1992a; *Gosling*, 1992, 1993a, b; *Tsurutani and Gonzalez*, 1993]. An ejection of large quantities of fast moving (50 to $\geq$ 1200 km/s) solar material into interplanetary space occurs sporadically, and approximately 1 % to 10 % of all solar wind plasma measurements were made in CMEs during solar minimum and maximum respectively [e.g., *Gosling*, 1992]. The Earth intercepts annually about 70 CMEs at solar activity maximum and less than 10 CMEs near solar activity minimum. Only a fraction of intercepted CMEs causes major geomagnetic storms, which also require the presence of an intense long-duration southward interplanetary magnetic field [e.g., *Gosling*, 1993a, b; *Tsurutani and Gonzalez*, 1993].

Major geomagnetic storms create electrical power outages, disrupt communications, damage and reduce the lifetime of Earth-orbiting satellites, and pose health hazards to airline passengers at high altitudes [e.g., *Tsurutani et al.*, 1992a; *Lanzerotti*, 1992]. Although a clear understanding of the relation between the disturbed space weather conditions and adverse effects on technological systems has yet to be achieved [*Lanzerotti*, 1992; *Tsurutani et al.*, 1992b], an advance warning of large geomagnetic storms and prediction of storm magnitude are highly desirable and would help reduce storm-related damage.

The phenomenon of CME is not completely understood, and no easily observable phenomenon at the Sun, such as solar flares, has yet been identified that allows a reliable advance warning of a large CME approaching the Earth. Obviously, CME patrol can be provided by a spacecraft somewhere between the Earth and the Sun. The Lagrangian point L1 (of the Sun-Earth system) is a convenient place for such a monitor. However, this point is only 1.4×10^6 km from the Earth, allowing only 30-min advance warning before a CMEs impingement upon the magnetosphere.

CMEs are reliably observed by white light coronagraphs that measure solar light scattered (Thomson scattering) by plasma near the Sun [e.g., *Hundhausen*, 1993]. A deployment of spacecraft well ahead and behind the Earth in its orbit around the Sun would allow the detection and velocity determination of a CME leaving the solar surface and directed towards the Earth [*Gosling et al.*, 1991]. Optical detection of such CMEs from a spacecraft near Earth was discussed by *Jackson et al.* [1991].

A clever idea to provide an advance warning of a high-speed CME approaching the Earth was recently suggested by *Hsieh et al.* [1992]. They proposed to take advantage of the fact that ejected solar matter decelerates on its way from the Sun to Earth. Some of the plasma protons would recombine with electrons producing energetic neutral atoms (ENAs) moving with the local plasma velocity. ENAs move independently of the plasma, and some of the ENAs would eventually overtake the leading edge of the decelerating CME and arrive first at the Earth. Thus by measuring an ENA flux one can obtain a precursor signal of the approaching CME before its impingement upon the magnetosphere.

As it was pointed out by D. McComas (private communication, 1994), a shock preceding the bulk of CME plasma

would reach the magnetosphere earlier than the CME. We should note here that (1) not all shocks in interplanetary space are accompanied or produced by CMEs and (2) the region between the forward shock and CME is filled by hot fast-moving plasma which would also generate fast ENAs. Consideration of complex effects of the forward shocks preceding CMEs is beyond the scope of this work and we assume here that geomagnetic storms start when the CME plasma impinges on the magnetosphere.

It should be made clear that a significant fraction of CMEs do not undergo any deceleration, and many undergo acceleration, through their interaction with the solar wind. The large and major geomagnetic storm categories are of most interest for advance storm warning. It is suspected that "the initial speed of a CME relative to the ambient solar wind ahead is probably the most important factor in determining if an earthward directed event will be effective in exciting a large geomagnetic disturbance" [Gosling, 1993a, p.2644]. Therefore we limit our consideration in this work to high-speed CMEs only.

The estimates of the ENA flux obtained by Hsieh et al. [1992] were incomplete and did not allow the feasibility evaluation of the proposed technique for several reasons. First, the neutral component is permanently present in the "regular," quiescent solar wind - the neutral solar wind (NSW). The CME-produced ENA flux has to be compared with the stationary NSW since the enhancement of ENA flux, and not just its appearance, as suggested by Hsieh et al. [1992], would be a precursor of the approaching CME. (We will further refer to such CME-produced ENAs as CME/ENAs to distinguish them from the ENA flux in the stationary solar wind, i.e., NSW). Second, both the quiescent NSW and CME/ENAs are formed by contributions from several processes and the recombination in the expanding solar plasma is only one source of ENAs. It is not yet clear how other sources compare with the recombination in the CME plasma: the recombination provides a minor contribution to the quiescent NSW [e.g., Holzer, 1977], but higher number densities and lower electron temperatures typical for CME plasma may (or may not) change the relative importance of different processes. Finally, the model used by Hsieh et al. [1992] did not take into account spherical divergence of the CME/ENA flux which would lower their ENA flux estimates by 1-2 orders of magnitude at 1 AU from the Sun.

The goal of this work is to follow the original suggestion by Hsieh et al. [1992] to use ENAs for advance detection of high-speed CMEs approaching the Earth and consider in detail the processes involved. This would allow the feasibility evaluation of the proposed technique for advance geomagnetic storm warning and prediction of storm magnitude and lead to the determination of requirements for corresponding spacecraft instrumentation. We should also note that ENA measurements in the solar wind is a natural way of experimentally studying the evolution of CMEs as they propagate outward from the Sun. Change of CME size, speed, plasma temperature and number density would manifest itself in the temporal variations of the intensity and energy distributions of the CME/ENA flux.

First, we will briefly review the concept of the NSW, then update neutral particle number densities inside the Earth's orbit and calculate the stationary NSW flux. Then, characteristics of CME/ENA flux is obtained and finally, an

experimental approach to the CME detection is briefly discussed.

2. Phenomenon of Neutral Solar Wind

Interactions between charged and neutral particles are common phenomena in space plasmas. In the solar wind these are manifested by the presence of a solar wind neutral component (NSW). It was speculated long ago that a large number of neutral atoms could be present in the solar wind as transients due to ejection of solar matter in violent events [Akasofu, 1964a, b]. Neutral hydrogen atoms in solar prominences are observed optically, and it is argued that they may reach 1 AU [Illing and Hildner, 1994]. The probability to reach 1 AU without ionization depends strongly on hydrogen atom velocity, solar EUV radiation, and plasma electron temperature and it does not exceed 0.01. The question whether a substantial amount of hydrogen atoms is present at 1 AU is open. In any case, if neutrals ejected from the Sun reach the Earth, they would provide an ENA flux in addition to the flux considered in this paper. In this case the advance warning technique would be even more efficient.

A small fraction of plasma particles is neutral even at high-temperature conditions in the solar corona. For example, neutral atoms are present in the expanding solar corona due to recombination, the process invoked by Hsieh et al. [1992]. There is, however, another process that contributes to a buildup of the NSW: charge exchange collisions between solar wind ions and neutral particles filling interplanetary space. The realization of the fact that interplanetary space is filled with neutral atoms led to the development of a concept of a permanently existing NSW. The two major sources of neutral gas inside the Earth's orbit are interstellar gas (ISG) penetrating the solar system from the local interstellar medium (LISM) and neutralization of solar wind ions by interplanetary dust. ENAs born in a region of the heliospheric interface would provide only a small contribution. Outgassing of planets produces local enhancements of neutral particle number density and can be disregarded in the frame of the present work.

The NSW atoms, born in recombination and charge exchange processes, move in an antisunward direction with the solar wind velocity. The NSW atoms are lost in collisions with the solar wind electrons and ions and due to photo-ionization by the solar extreme ultraviolet (EUV) radiation. A relatively high velocity of the solar wind (~500 km/s) allows many ENAs to travel large distances without ionization and eventually leave the heliosphere.

The NSW flux composition, intensity, and energy distribution depend upon the solar wind characteristics and distribution of neutral particles inside the Earth's orbit around the Sun. A development of the model of solar system penetration by ISG allowed one to calculate the expected neutral atom number densities in interplanetary space [Fahr, 1968a]. This model was used to obtain an NSW flux [Fahr, 1968b; Blum and Fahr, 1970] due to charge exchange between solar wind protons and interstellar hydrogen atoms. Later it was recognized that charge exchange of protons with interplanetary helium atoms may provide a significant contribution to the NSW in the region within several astronomical units (AU) from the Sun [Gruntman, 1980]. A computer simulation of the NSW angular

characteristics (NSW isofluxes as observed from the moving Earth) was performed by Bleszynski et al. [1992] (this work was actually done almost 10 years ago, although published only recently). V.B.Leonas (private communication, 1987) draw attention to the fact that the cross section for simultaneous transfer of two electrons to solar wind alpha particles in collisions with helium atoms is fairly high. The consequence of such a double electron charge transfer is a nonnegligible helium atom component in the NSW, especially at distances of several AU from the Sun, and a presence of doubly charged helium ions among the solar wind pickup ions is expected.

The ISG fills the entire heliosphere on a global scale. Another source of neutral atoms, confined to the inner part of the Earth's orbit, is interplanetary dust which congregates toward the Sun close to the ecliptic plane. This latter source was considered in detail by Banks [1971]. Solar wind bombardment of a dust grain results in a penetration of hydrogen and helium ions into the surface layer to the depth of several hundred angstroms. This layer soon (less than few years) becomes saturated by intruder ions, and outgassing of neutral atoms and molecules from the grain maintains the equilibrium. The estimates of this neutral particle source suffer from a large uncertainty in dust grain population and outgassing process details [Banks, 1971; Holzer, 1977; Fahr et al., 1981]. Banks [1971] first estimated the NSW flux due to charge exchange of the solar wind protons on the dust-produced neutrals.

The neutral component in the solar wind constitutes a rather small fraction, $\sim 10^{-4}$, of the solar wind at 1 AU from the Sun (see section 4). As the solar wind expands further toward the boundaries of the heliosphere, this fraction gradually increases to 0.1-0.2 at the solar wind termination shock and plays an important role in global processes in the heliosphere. While the solar wind supersonic plasma flow is believed to be terminated by the shock, the NSW atoms easily penetrate the region of the heliospheric interface, enter the LISM and interact (via charge exchange) with the approaching flow of interstellar plasma. The result of this interaction may become especially important if the flow of interstellar plasma is supersonic and forms the bow shock (two-shock model [e.g., Baranov, 1990]) in front of the heliosphere. In this case the interstellar plasma flow is not supposed to "learn" about an obstacle ahead, that is, the heliosphere, until reaching the bow shock. However, the NSW atoms, "sneaking" outside the heliosphere, would disturb the interstellar plasma. Hence the LISM is modified by the NSW even beyond the bow shock. The boundary of the region of the Sun's influence is thus pushed further into interstellar space and the inference of the "pristine" LISM parameters from interplanetary glow observations becomes increasingly complicated. This NSW effect on the LISM was first predicted by Gruntman [1982] and confirmed later by a detailed computer simulation of Baranov and Malama [1993].

The NSW flux has never been studied experimentally, and there are no direct experimental data on the NSW. The measurement of pickup ions in the solar wind [e.g., Gloeckler et al., 1993, and references therein], some of them being another product of the same process that gives rise to the NSW, is an independent, though indirect, confirmation of the validity of our understanding of the processes involved.

Direct experimental study of the NSW faced seemingly unsurmountable experimental difficulties. However, experimental techniques to measure low-energy ($<$ 10 keV) ENAs have been gradually developing since the late 1960s [e.g., Wax and Bernstein, 1967; Bernstein et al., 1969; Gruntman and Morozov, 1982; McEntire and Mitchell, 1989; McComas et al., 1991; Hsieh et al., 1991; Gruntman, 1993; Funsten et al., 1993]. An experimental concept to measure the NSW was proposed and developed in the early 1980s [Gruntman and Morozov, 1982; Gruntman and Leonas, 1983; Gruntman et al., 1990]. A dedicated NSW experiment was included in the scientific payload of the Soviet RELIKT-2 mission which was originally scheduled for the second half of the 1980s and has not yet been launched.

3. Neutral Atoms Inside Earth's Orbit

Dilute neutral gas inside the Earth's orbit provides collision partners for charge exchange, which is the major process in the formation of the NSW. Important sources of neutral particles inside the Earth's orbit are the ISG, outgassing from interplanetary dust, and ENAs from a region of the heliospheric interface. Since we are interested in the parameters of the NSW reaching the Earth, we will concentrate on neutral gas in the ecliptic plane only. While number density of neutral particles due to dust outgassing is distributed isotropically in the ecliptic plane, interstellar and heliospheric neutrals are highly anisotropic with a vector of the LISM velocity relative to the Sun providing an axis of symmetry. The most comprehensive discussion of neutral gas parameters inside the Earth's orbit can be found in the works by Holzer [1977] and Fahr et al. [1981]. We will update their results and present neutral particle densities within the Earth's orbit as it pertains to the NSW.

3.1. Interstellar Gas

The interaction of the Sun and the LISM is manifested by the build up of a heliosphere [e.g., Dessler, 1967; Axford, 1973; Fahr, 1974; Holzer, 1977; Thomas, 1978; Bertaux, 1984; Baranov, 1990]. It is currently believed that the interstellar wind comes from the direction of ecliptic longitude 252° and latitude +7° [e.g., Lallement et al., 1990]. (We will further assume that the interstellar wind relative velocity is in the ecliptic plane.) The Earth is positioned in the upwind direction in the beginning of June each year. It is convenient to use the spherical coordinate system, (R,Θ), with the Sun at the origin and angle Θ measured from the upwind direction (Figure 1).

Our calculations are made here on the basis of the widely accepted "hot" model of ISG penetration in the solar system.
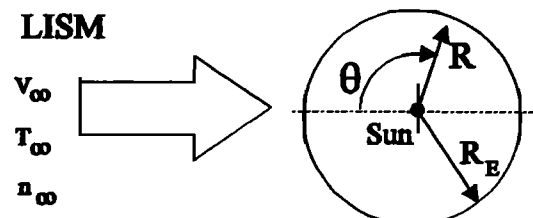

Figure 1. Motion of the local interstellar medium (LISM) relative to the Sun; angle Θ is measured from the upwind direction; $R_E = 1$ AU is the radius of the Earth's orbit.

Number density distributions of neutral atoms in interplanetary space depend on the undisturbed (i.e., "at infinity") ISG parameters, density, velocity, temperature, and upon solar radiation pressure, and atomic ionization rates. The ISG mainly consists of hydrogen and helium atoms, and solar radiation pressure is usually described by a ratio, μ, of the average radiational-to-gravitational forces acting on individual atoms. The solar wind is assumed to be a steady, spherically symmetric radial flow with constant velocity, $V_{sw}(R) = V_{sw} = $ const, and with flux and number density inversely proportional to the square of the distance from the Sun,

$$F_{sw,I}(R) = F^E_{sw,I} \, (R_E/R)^2 \qquad (1)$$

$$N_I(R) = N^E_I \, (R_E/R)^2. \qquad (2)$$

$F^E_{sw,I} = F_{sw,I}(R_E)$ and $N^E_I = N_I(R_E)$ are the flux and number density at $R_E = 1$ AU, that is, at the Earth's orbit. The subscript I stands for solar wind ions, either $H+$ or $He++$; a capital letter N is reserved for ion number densities, while a small letter n will denote the number density of neutral particles.

Ionization of hydrogen and helium atoms is assumed to be due to photoionization by the solar EUV radiation and charge exchange with the solar wind ions. Neutral gas within 1 AU is essentially optically thin for solar radiation and the probability of experiencing two consecutive charge exchanges by the same particle is negligible. Radial dependences for ionization rates are $\beta_H(R) = \beta_H(R_E) \, (R_E/R)^2$ and $\beta_{He}(R) = \beta_{He}(R_E) \, (R_E/R)^2$, where $\beta_H(R_E)$ and $\beta_{He}(R_E)$ are ionization rates of hydrogen and helium atoms at 1 AU from the Sun. The predominant mechanism for helium ionization is photoionization, while both charge exchange and photoionization are important for hydrogen atoms. Therefore the hydrogen ionization rate is $\beta_H = \beta^{PH}_H + \beta^{CX}_H$, where β^{PH}_H is the photoionization rate, $\beta^{CX}_H = F_{sw,H+} \, q_{H+,H}$ is the ionization rate due to charge exchange with solar wind protons (predominant channel), and $q_{H+,H}$ is the charge exchange cross section between protons and hydrogen atoms. Such assumptions are widely accepted for study of interplanetary glow, but they should be used with caution when applied to neutral atoms inside the Earth's orbit. Two additional ionization processes may become important in the Sun's vicinity (R < 0.5 AU): ionization by solar wind electrons [e.g., Rucinski and Fahr, 1989] and two-step photoionization by solar photons [Gruntman, 1990]. These two effects can be disregarded for the purpose of the present work.

According to the "hot" model, number density distributions of interstellar atoms in the heliosphere can be given by

$$n_{H,He}(R,\Theta) = n_{H,He}(\infty) \, f_{H,He}(R,\Theta) \qquad (3)$$

where the number densities are scaled by their corresponding unperturbed ISG values, $n_{H,He}(\infty)$. Functions $f_{H,He}(R,\Theta)$ have been calculated by many authors, [e.g., Fahr, 1974; Meier, 1977; Wu and Judge, 1979]; the computer code used in this work was developed by D.Hall (private communication, 1992).

A selection of the ISG parameters at infinity, number density, velocity, and temperature, requires special consideration. Until recently, it was a common assumption that the

velocity and temperature of the ISG, $V(\infty)$ and $T(\infty)$, were identical for both hydrogen and helium components, a natural approach for a gas in equilibrium. However, there is a growing perception that the heliospheric interface region at a distance of 70-150 AU from the Sun plays an important role in filtering neutral atoms and changing their characteristics. This effect, first pointed out by Wallis [1975], may substantially change the parameters of interstellar hydrogen without affecting those of interstellar helium atoms [Ripken and Fahr, 1983; Baranov, 1990; Fahr, 1990; Baranov and Malama, 1993]. The physical mechanism responsible for this interaction is charge exchange between plasma ions and neutral atoms. A significant difference in cross sections determines the difference in the magnitude of the effect between interstellar hydrogen and helium atoms. Recently performed simulation of the solar wind interaction with the LISM, that for the first time self-consistently accounted for ionized and neutral components, spectacularly demonstrated the importance of this effect [Baranov and Malama, 1993].

The major implication of charge exchange in the heliospheric interface is that velocity and temperature of interstellar hydrogen and helium at infinity, as derived from observation of ISG in the inner part of the solar system (< 30 AU) and based on the conventional hot model, correspond to different states of the ISG. In case of helium the derived parameters, $n_{He}(\infty)$, $V_{He}(\infty)$, and $T_{He}(\infty)$, correspond to "genuine" interstellar helium parameters in the unperturbed LISM while in case of hydrogen, the parameters, $n_H(\infty)$, $V_H(\infty)$ and $T_H(\infty)$, actually correspond to those of hydrogen already modified by passage through the heliospheric interface region. This was convincingly confirmed by recent measurements of the ISG velocity and temperature in the LISM beyond 1000 AU [Lallement et al., 1993; Bertin et al., 1993]. The values obtained, $V_H(\infty) = 26$ km/s and $T_H(\infty) = 7000$ K, are in excellent agreement with interstellar helium parameters derived from direct helium flux measurements by Ulysses [Witte et al., 1993], but they significantly disagree with the interstellar hydrogen parameters derived from "conventional" interplanetary glow experiments [e.g., Bertaux et al., 1985; Ajello et al., 1987]. Insight into processes modifying interstellar hydrogen can be provided by Lyman alpha measurements from the Voyager and Pioneer spacecraft at large distances from the Sun [e.g., Hall et al., 1993] and by proposed direct measurements of interstellar hydrogen atoms [Gruntman, 1993] and heliospheric ENAs [Gruntman, 1992].

The above arguments do not mean that the hot model has completely lost its validity and usefulness for hydrogen. It is of little help in determining interstellar hydrogen characteristics in the unperturbed LISM, since a detailed model allowing for the effects of the heliospheric interface has yet to be developed. However, it can be reliably used for the kind of estimates required in this work providing certain modifications are made. The straightforward way to improve the model is to use different values of velocities and temperatures for the LISM hydrogen and helium components at infinity. For helium the parameters of the unperturbed ISG can be used, and for hydrogen the effective velocity and temperature consistent with the interplanetary glow experiments (performed in the inner solar system) should provide reasonable results. We also use a higher value of the helium-to-hydrogen number density ratio than exists in the unperturbed LISM, the latter is believed to be close to

~0.1. Such modifications should allow one to continue to use the well developed and relatively simple hot model of the ISG for our purposes.

An apparent gap exists between modelling the transformation of interstellar hydrogen characteristics in the unperturbed state in the LISM and the state of hydrogen still far away from the Sun, but after its passage through the termination shock. One should keep in mind that currently even the most developed model of *Baranov and Malama* [1993] is limited since it does not take into consideration magnetic field, cosmic rays, and temporal variations (heliosphere "breathing"), and it is restricted to the case of a two-shock configuration. Incidentally, this gap in modeling has an important implication for heliospheric studies. Most of the experimental data on interplanetary glow are obtained from spacecraft near the Sun ($R < 5$ AU). Consequently, all attempts to improve the best fit of experimental data to the unperturbed ISG parameters by an elaboration of the hot model (for example by introduction of anisotropy and temporal variation of the solar wind and solar Lyman alpha radiation) have limited value. The velocity distribution function of hydrogen atoms far away from the Sun but inside the termination shock is essentially non-Maxwellian, being determined by the structure and physical processes in the heliospheric interface.

In our calculations the following parameters are used for interstellar hydrogen and helium atoms:

$$n_H(\infty) = 0.1 \text{ cm}^{-3} \qquad n_{He}(\infty) = 0.02 \text{ cm}^{-3} \qquad (4a)$$
$$V_H(\infty) = 20 \text{ km/s} \qquad V_{He}(\infty) = 26 \text{ km/s} \qquad (4b)$$
$$T_H(\infty) = 14{,}000 \text{ K} \qquad T_{He}(\infty) = 8000 \text{ K} \qquad (4c)$$
$$\mu_H = 0.8 \qquad \mu_{He} = 0 \qquad (4d)$$

The ionization rate of helium atoms, which is determined by photoionization, is $\beta_{He}(R_E) = 0.8 \times 10^{-7} \text{ s}^{-1}$ at the Earth's orbit. The photoionization rate of hydrogen atoms is $\beta_H^{PH}(R_E) = 2.0 \times 10^{-7} \text{ s}^{-1}$, the charge exchange ionization rate is $\beta_H^{CX}(R_E) = F_{SW,H+}^E q_{H+,H} = N_{H+}^E V_{SW} q_{H+,H} = 3.75 \times 10^{-7} \text{ s}^{-1}$, and the total loss rate $\beta_H(R_E) = \beta_H^{CX} + \beta_H^{PH} = 5.75 \times 10^{-7} \text{ s}^{-1}$. Solar wind parameters at 1 AU are assumed to be $N_{H+}^E = 5 \text{ cm}^{-3}$ and $V_{SW} = 500 \text{ km/s}$; the charge exchange cross section is $q_{H+,H} = 15 \times 10^{-16} \text{ cm}^2$.

The calculated radial dependent number densities of interstellar atoms are shown in Figures 2a and 2b for $\Theta = 0$, 60°, 120°, and 180°. Differences between distributions of hydrogen and helium are due to the effects of solar radiation pressure and ionization loss. One can see that interstellar hydrogen is strongly ionized and only a small fraction reaches the region inside the Earth's orbit. The downwind region (around $\Theta = 180°$) is practically devoid of interstellar hydrogen atoms. For interstellar helium the situation is reversed. Helium number density is substantially enhanced in the downwind region by gravitational focusing, and the smaller ionization rate allows helium atoms to easily reach the inner part of the Earth's orbit.

The number density of interstellar helium atoms is higher than that of hydrogen atoms although the helium abundance is much smaller than that of interstellar hydrogen in the unperturbed LISM. The relative increase of the interstellar helium abundance inside Earth's orbit requires one to consider effects involving collisions of solar wind ions with neutral helium atoms. Helium atoms can often be disregarded further away from the Sun due to much smaller charge
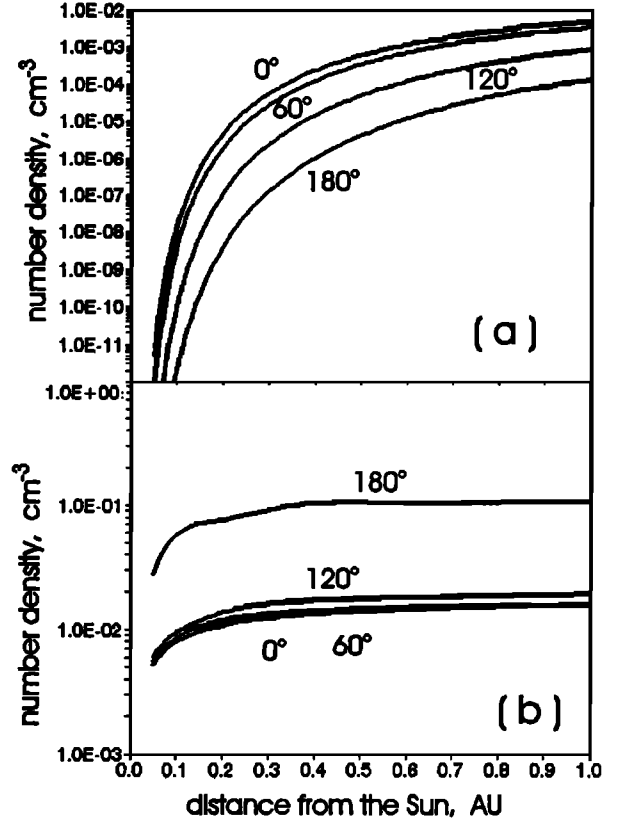

Figure 2. Radial dependence ($0 < R < 1$ AU) of the number density of interstellar (a) hydrogen and (b) helium for $\Theta = 0$, 60°, 120°, and 180°. Read 1.0e-02 as 1.0×10^2.

exchange cross sections and higher hydrogen atom number densities.

3.2. Outgassing of Interplanetary Dust

Interplanetary space is filled with a population of dust which tends to congregate toward the Sun and is largely restricted to within 15° of the ecliptic plane [*Banks*, 1971; *Holzer*, 1977; *Fahr et al.*, 1981]. The surface layer (< 500 Å) of the dust grains is quickly saturated by bombarding solar wind ions followed by desorption of neutral particles, atoms and molecules, from the surface in order to maintain equilibrium. The saturation time does not exceed few years which is much less than the corresponding Poynting-Robertson residence time [e.g., *Fahr et al.*, 1981]. *Banks* [1971] considered this process in detail and calculated number densities of hydrogen and helium atoms due to dust outgassing. Neutral particle number density is scaled by an interplanetary dust geometrical factor $\Gamma(R)$, which is the inverse of the solar wind ion free path against interception by interplanetary dust grains. The uncertainty of this parameter, as discussed by *Banks* [*1971*], is 4 orders of magnitude $\Gamma(1 \text{ AU}) = 10^{-21} - 10^{-17} \text{ cm}^{-1}$. *Holzer* [1977] favored the value $\Gamma(1 \text{ AU}) = 2 \times 10^{-19} \text{ cm}^{-1}$ which was later adopted by *Fahr et al.* [1981].

While helium desorbs from grains in atomic form, the physics and chemistry of hydrogen desorption are poorly understood. *Banks* [1971] initially assumed that dust emitted hydrogen is in atomic form. Later *Fahr et al.* [1981] reconsidered hydrogen desorption and concluded that most of hydrogen is desorbed in molecular form. An improved

model of dust distribution was also used in the latter calculations, and we will assume here (with some modifications introduced below) dust-generated number density distributions of hydrogen and helium as given by *Fahr et al.* [1981].

The helium number density, as calculated by *Fahr et al.* [1981] (their Figure 5) and adopted as basis in this work, can be approximated as

$$n_{He}(R) = 2.32 \times 10^{-5} \times R^{-1} \text{ cm}^{-3} \qquad (5)$$
$$0.0232 \text{ AU} < R < 0.232 \text{ AU}$$

$$n_{He}(R) = 10^{-4} \text{ cm}^{-3} \qquad (6)$$
$$0.232 \text{ AU} < R < 0.464 \text{ AU}$$

$$n_{He}(R) = 2.77 \times 10^{-5} \times R^{-1.67} \text{ cm}^{-3} \qquad (7)$$
$$0.464 \text{ AU} < R < 1 \text{ AU}$$

where R is in AU.

The hydrogen number density can be approximated as

$$n_H(R) = 4.13 \times 10^{-6} \times R^{-1.15} \text{ cm}^{-3} \qquad (8)$$

for 0.0232 AU $< R <$ 1 AU, where R is in AU. The distribution of molecular hydrogen can be easily derived from that of atomic hydrogen. The loss of H_2 occurs mostly in two processes: photodissociation with probability κ, and photoionization with the probability $(1-\kappa)$. The former process,

$$H_2 \longrightarrow H + H, \qquad (9)$$
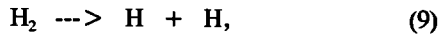
is assumed to be the only source of atomic hydrogen. In equilibrium the production rate of hydrogen atoms is equal to their loss rate,

$$n_{H2} \times \beta_{H2} \times 2 \times \kappa = n_H \times \beta_H \qquad (10)$$

and consequently,

$$n_{H2} = n_H \times \beta_H / (\beta_{H2} \times 2 \times \kappa), \qquad (11)$$

where n_{H2} and β_{H2} are molecular hydrogen number density and loss rate, respectively.

The hydrogen number density distribution (8) can be easily modified on the basis of updated rates and cross sections. *Fahr et al.* [1981] used the molecular hydrogen photodissociation rate (at 1 AU), $0.34 \times 10^{-7} \text{ s}^{-1}$, and total ionization rate, $\beta_{H2} = 6.3 \times 10^{-7} \text{ s}^{-1}$; the latter rate was suggested by *Siscoe and Mukherjee* [1972]. These rates determined the photodissociation branch probability, $\kappa = 0.05$.

The photodissociation rate, however, should be higher since, as pointed out by *Dalgarno and Allison* [1969], contributions from photon absorption into discreet states that predissociate were apparently ignored. D.E.Shemansky (unpublished manuscript, 1991) thoroughly investigated these additional branches and recommended the photodissociation rate, $3.1 \times 10^{-7} \text{ s}^{-1}$ at 1 AU [*Shemansky and Hall*, 1992].

For assumed solar wind parameters and updated cross sections [*Barnett et al.*, 1990], the H_2 ionization rates at 1 AU are $0.001 \times 10^{-7} \text{ s}^{-1}$ and $1.2 \times 10^{-7} \text{ s}^{-1}$ for solar wind proton impact and proton charge exchange correspondingly. Assuming the same H_2 photoionization and electron impact

ionization rates, as those adopted by *Siscoe and Mukherjee* [1972], the total molecular hydrogen ionization rate is 2.85 $\times 10^{-7} \text{ s}^{-1}$ at 1 AU. The total molecular hydrogen loss rate, due to photodissociation and ionization, is $5.95 \times 10^{7} \text{ s}^{-1}$, as compared to $6.6 \times 10^{7} \text{ s}^{-1}$ used by *Fahr et al.* [1981]. The probability κ^* of the photodissociation branch is now $\kappa^* = 0.52$ as compared to the $\kappa = 0.05$ given by *Fahr et al.* [1981].

These new rates are used here to modify the hydrogen number densities of *Fahr et al.* [1981] in the following manner. If we assume the production rate of molecular hydrogen of *Fahr et al.* [1981], then the H_2 number density would be a factor (ratio of loss rates) $6.6/5.95 = 1.11$ higher than the number density obtained by *Fahr et al.* [1981] as can be derived from (9). Assuming the same loss rate of atomic hydrogen, the atomic hydrogen number density would be a factor $\kappa^*/\kappa = 10.4$ higher than the one given by *Fahr et al.* [1981]. Such corrections are obviously only approximate (within 10-15 % accuracy which is acceptable for the purpose of the present work) since accurate calculations require a detailed and complicated model as used by *Fahr et al.* [1981].

The corrected dust-generated number densities of atomic and molecular hydrogen, assumed in this work, are

$$n_H(R) = 4.3 \times 10^{-5} \times R^{-1.15} \text{ cm}^{-3} \qquad (12)$$

$$n_{H2}(R) = 3.9 \times 10^{-5} \times R^{-1.15} \text{ cm}^{-3} \qquad (13)$$

where R is in AU. The radial dependence of dust-produced neutrals, n_H, n_{H2}, and n_{He}, is given in Figures 3a-3d where they can be compared with the interstellar neutral atom distribution at different angles Θ. Obviously, the dust-produced neutral particle distributions are independent of the angle Θ and are identical on these four figures (Figures 3a-3d).

One can see that interstellar helium is much more abundant than dust-produced helium, and the latter can be safely neglected. Dust-produced hydrogen atoms are more numerous in the Sun's vicinity while interstellar hydrogen becomes much more abundant at 1 AU from the Sun. The point at which contributions from these two sources are equal depends on the angle Θ and varies from 0.35 AU for $\Theta = 0$ to 0.8 AU for $\Theta = 180°$. Dust-produced molecular hydrogen is concentrated in the region close to the Sun. Incidentally, its presence should be manifested by a molecular hydrogen component in solar wind pickup ions. Measurement of molecular hydrogen pickup ions should allow the indirect determination of the amount of interplanetary dust in the Sun's vicinity.

No direct experimental data of dust-produced neutrals are available, and the uncertainty of their number density estimates remains high. Optical detection of dust-generated neutral particles is difficult because the light scattering region is very close (only 5°-10° offset angle) to the Sun. The experimental concept to optically (584 and 1216 Å) measure such neutrals was developed by *Fahr et al.* [1980]. Two sounding rocket (Skylark 12) launches were attempted in 1985 and 1989 from the range "Barreira do Inferno" in Natal, Brazil. The first launch failed due to the problems with the separation of the third rocket stage. Experimental data obtained during the second launch in 1989 were inconclusive because of a malfunctioning on-board computer
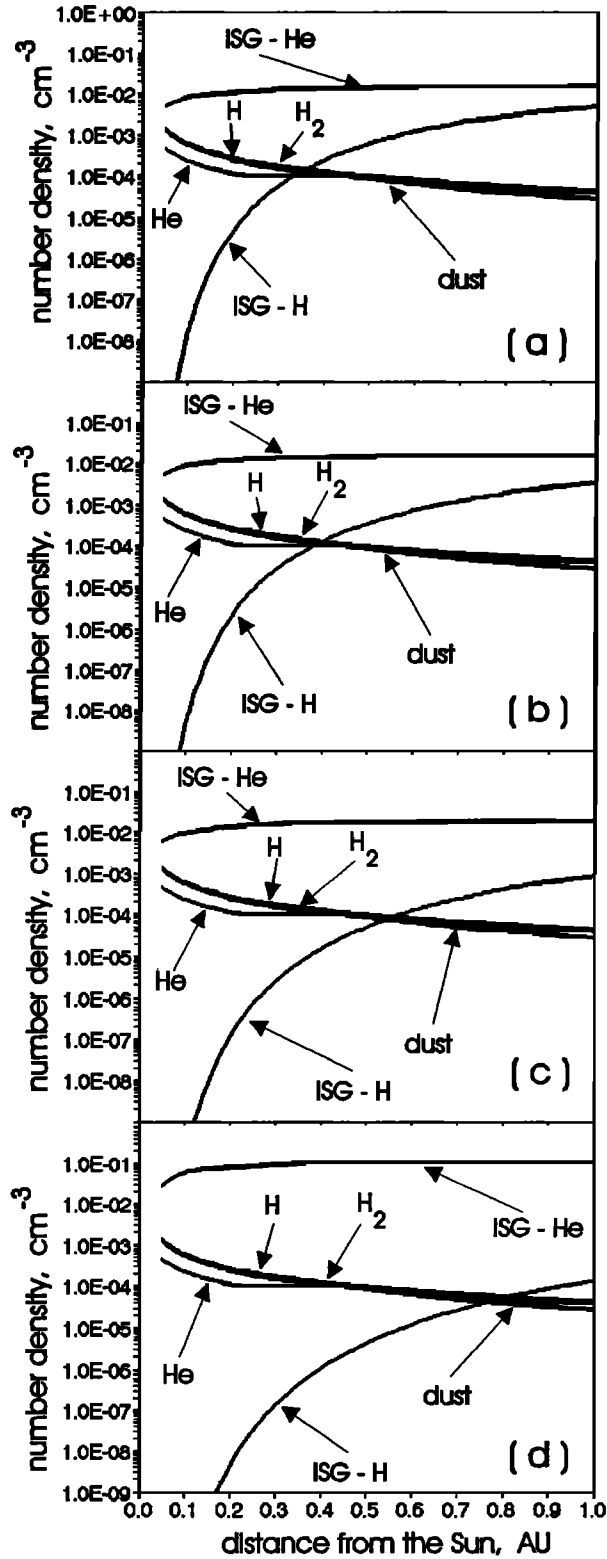
Figure 3. Number density radial dependence $(0 < R < 1$ AU) of dust-produced ("dust") helium and atomic and molecular hydrogen. Dust-produced neutral particle distributions are independent of the angle Θ. Interstellar hydrogen (ISG-H) and helium (ISG-He) number densities are shown for angles (a) $\Theta = 0$; (b) $\Theta = 60°$; (c) $\Theta = 120°$; (d) $\Theta = 180°$.

and unexpectedly strong signal contamination by high-energy particles [*Lay et al.*, 1989, 1991]. The feasibility of a direct, in situ measurement of dust-produced neutral particles on the future Solar Probe mission is unclear due to spacecraft protective shield sputtering and ablation [*Gruntman*, 1993].

3.3. ENAs From the Heliospheric Interface

The solar wind is a highly supersonic plasma flow into the LISM, which is characterized by a certain finite pressure. It is believed that this supersonic plasma flow terminates at a solar wind termination shock front, beyond which its kinetic energy is largely converted into thermal energy in subsonic plasma. As neutral ISG atoms pass through the interface region, there is a certain probability for solar wind protons to charge exchange with interstellar gas and give rise to heliospheric ENAs (HELENAs). This process was first invoked by *Patterson et al.* [1963]. A detailed HELENA flux simulation was performed recently by *Gruntman* [1992]. The expected HELENA flux at 1 AU is highly anisotropic with an intensity of about 200 cm^{-2} s^{-1} sr^{-1} at its maximum in the upwind direction, $\Theta = 0$. The kinetic energy of the hydrogen atoms is in the range 200-1000 eV. The upper limit of the HELENA number density within 1 AU is 10^{-5} cm^{-3}. This value is comparable with the dust contribution and much smaller than the ISG contribution for $R > 0.5$ AU. For $R < 0.5$ AU the HELENA contribution is much smaller than that of interplanetary dust. Consequently, the contribution of HELENAs can be neglected in this work.

4. Stationary Neutral Solar Wind

Two different processes contributing to the production of a neutral component in the solar wind are recombination in the expanding plasma, and charge exchange of the solar wind ions on neutral particles in interplanetary space. Not all NSW atoms would reach the Earth because of the ionization loss on their way from the place of their "birth" to 1 AU.

4.1. Probability to Reach 1 AU

When a neutral atom is born in the solar wind it is moving in outward direction with the local velocity of the solar wind. An atom is a subject to loss processes, and it may not survive its travel to the Earth. The probability for an atom born at a distance R_0 from the Sun to reach Earth's orbit R_E is

$$P(R_0, V_A) = \exp \left[- \int_{R_0}^{R_E} \frac{\beta_A(R)}{V_A(R)} \, dR \right] \tag{14}$$

where ionization rate β_A and atom velocity V_A depend on the distance from the Sun, R. Assuming that atom velocity is constant and $\beta_A = \beta_A(R_E) (R_E/R)^2$, one can transform (14) as

$$P_A(R_0, V_A) = \exp \left[- \frac{\beta_A(R_E) R_E}{V_A} (\frac{R_E}{R_0} - 1) \right] \tag{15}$$

The ionization rate of atomic hydrogen that is used in the (15) is determined by photoionization only. Charge ex-

change, which is the main ionization loss process for atomic hydrogen in interplanetary space, does not contribute to the loss of the NSW atoms. When charge exchange occurs, it results in a replacement of one neutral atom moving with the solar wind velocity by another one moving with the same velocity and in the same direction. Some momentum exchange that may happen in such a collision could contribute to the angular broadening of the NSW flux.

The effect of scattering in charge exchange collisions can be easily estimated if one notes that the scattering angle (for small angle elastic scattering) depends on the collision impact parameter b approximately as $\approx 2\ U(b)/E_P$, where $U(b)$ is the interaction energy of collision partners at the distance b and E_P is the projectile energy. For resonance charge exchange ($H^+ + H \longrightarrow H + H^+$ and $He^{++} + He \longrightarrow He + He^{++}$), typical interaction energy is few eV (impact parameters 1 - 2.5 Å) resulting in scattering angles of few milliradian (few tenths of a degree). The scattering is much more important for proton charge exchange on helium atoms ($H^+ + He \longrightarrow H + He^+$) when typical interaction energy is 10-15 eV resulting in scattering angles $1°-2°$. The scattering effect is disregarded in this work.

The probabilities $P_{H,He}$ for NSW hydrogen and helium atoms to reach 1 AU without loss are shown in Figure 4 as a function of the distance R_0 of the place of their birth from the Sun; the solar wind velocity is $V_{SW} = 500$ km/s. The radial dependence is strong at the Sun's vicinity while the probabilities change only slightly at larger R_0. For atoms born at $R_0 > 0.1$ AU the probability to reach 1 AU is higher than 80% for helium atoms and 55% for hydrogen atoms. The higher atom velocity V_A the smaller is ENA ionization loss. The solar wind electron impact ionization [*Rucinski and Fahr*, 1989] would contribute to the NSW atom loss rate in a way similar to the ionization of interstellar and dust-generated neutrals. The situation is different for two-step photoionization [*Gruntman*, 1990]. As a result of their high-velocity, NSW atoms are Doppler-shifted and two-step photoionization is negligible.

4.2. Recombination

The number of neutral hydrogen atoms born in the recombination process in a unit volume during time interval dt at the distance R from the Sun is $\alpha(T_e)\ N_e^2(R)\ dt$,
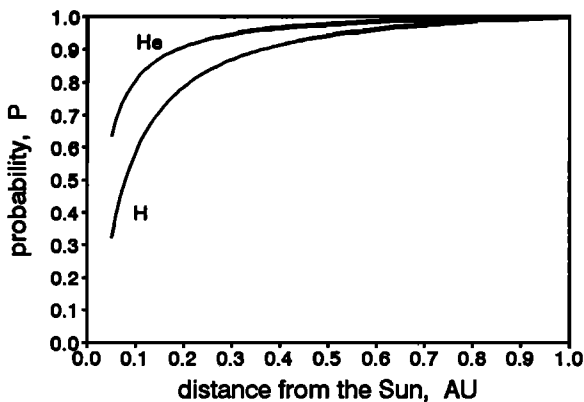

Figure 4. Probability for neutral hydrogen and helium atoms to reach 1 AU as a function of the atom's birthplace; atom velocity is 500 km/s.

where $N_e(R) = N_{H+}^E\ (R_E/R)^2$ is the local solar wind electron number density. For our purposes, the solar wind can be assumed to be fully ionized plasma with equal electron and proton number densities. The recombination rate coefficient α depends on the electron temperature T_e, which in turn is a function of the distance from the Sun. Only hydrogen atoms are born in the recombination process. The recombination-produced hydrogen ENA flux at R_E is equal to an integral, over the distance from the Sun to Earth, of the production rate multiplied by the probability P_H to reach R_E without ionization and reduced by the factor $(R/R_E)^2$ allowing for the divergence of the NSW flux. The stationary NSW flux (cm^{-2} s^{-1}) at R_E is

$$F_{NSW,recom}^E = (N_{H+}^E)^2 \int_{R_{min}}^{R_E} \alpha(T_e)\ (R_E/R)^2\ P_H(R,V_{SW})\ dR \quad (16)$$

where the electron temperature depends on the distance from the Sun, $T_e = T_e(R)$.

We will use a typical radial dependence of the electron temperature as given by *Holzer* [1977] (his Figure 1b), which can be approximated by

$$T = 1.32 \times 10^6\ K \quad (17)$$
$$R < 0.056\ AU$$

$$T = 1.23 \times 10^5 \times R^{-0.82}\ K \quad (18)$$
$$0.056\ AU < R < 1\ AU$$

where R is in AU. The hydrogen radiative recombination rate coefficient in the temperature range of interest can be approximated by

$$\alpha = 7.9 \times 10^{-8} \times T_e^{-1.2}\ cm^3\ s^{-1} \quad (19)$$
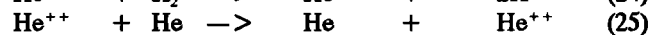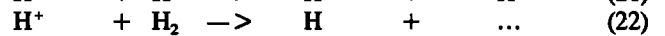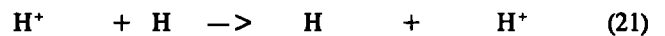$$10^5 < T_e < 3 \times 10^6\ K$$

$$\alpha = 7.9 \times 10^{-10} \times T_e^{-0.8}\ cm^3\ s^{-1} \quad (20)$$
$$10^4 < T_e < 10^5\ K$$

where T_e is in Kelvin. For solar wind parameters and ionization rates given above, the hydrogen ENA flux in the solar wind due to recombination would be $F_{NSW,recom}^E = 54$ cm^{-2}s^{-1} at the Earth's orbit. In terms of a number density fraction the recombination produced neutrals constitute 2×10^{-7} of the quiescent solar wind at 1 AU from the Sun.

4.3. Charge Exchange

The two most important solar wind ion components are protons and doubly charged helium ions (alpha particles). Major components of the neutral gas participating in charge exchange collisions are hydrogen atoms, hydrogen molecules, and helium atoms. The charge exchange processes contributing to the NSW production are

H^+	+	H	$\longrightarrow$	H	+	H^+	(21)
H^+	+	H_2	$\longrightarrow$	H	+	$\ldots$	(22)
H^+	+	He	$\longrightarrow$	H	+	He^+	(23)
He^{++}	+	H_2	$\longrightarrow$	He	+	$2H^+$	(24)
He^{++}	+	He	$\longrightarrow$	He	+	He^{++}	(25)

The cross sections for processes (21)-(25) are well known [e.g., *Barnett et al.*, 1990], and they are shown in Figure 5 for collision velocity range from 300 to 1400 km/s. Several branches are possible in the processes (22) and the total cross section for charge transfer to a proton in a collision with a hydrogen molecule is given here. For a collision velocity of 500 km/s the charge exchange cross sections are

$q_{H+,H}$	=	15.8	$\times 10^{-16}$ cm^2
$q_{H+,H2}$	=	4.9	$\times 10^{-16}$ cm^2
$q_{H+,He}$	=	0.01	$\times 10^{-16}$ cm^2
$q_{He++,H2}$	=	0.27	$\times 10^{-16}$ cm^2
$q_{He++,He}$	=	2.4	$\times 10^{-16}$ cm^2

for processes (21)-(25) correspondingly.

We assume that the solar wind spherically expands with the constant velocity V_{SW}; its neutral component is much smaller than the ion component, and the effect of the Sun's gravitational field is negligible. Let us consider a solar wind element at the distance, R ($0 < R < R_E$), from the Sun. The probability dp_I for a selected ion I (H$^+$ or He^{++}), to charge exchange while moving from R to ($R+dR$) is

$$dp_I = dR \times \sum_k n_k(R) \, q_{I,k}(V_{SW}) \qquad (26)$$

where n_k are the number densities of neutral species and $q_{I,k}$ are corresponding charge exchange cross sections, and the summation is performed over all present neutral particle species, k (H, H$_2$, and He). It is also assumed here that the velocity of neutral atoms is much smaller than that of the solar wind, and hence the collision velocity between particles is equal to V_{SW}. A contribution of the charge exchange between R and ($R+dR$) to the NSW flux (cm^{-2} s^{-1}) at the Earth's orbit would be a product of the local solar wind ion flux, $F_{SW,I}(R)$, probability of charge exchange, dp_I, probability for neutral atoms to reach the Earth's orbit without ionization, $P_{H,He}(R,V_{SW})$, and factor $(R/R_E)^2$ allowing for the divergence of the spherically expanding

Figure 5. Velocity dependence of the charge exchange cross section (10^{-16} cm^2). (1) H$^+$ + H $-\!\!>$ H + H$^+$; (2) H$^+$ + H$_2$ $-\!\!>$ H + ... ; (3) H$^+$ + He $-\!\!>$ H + He$^+$; (4) He^{++} + H$_2$ $-\!\!>$ He + 2H$^+$; (5) He^{++} + He $-\!\!>$ He + He^{++}

NSW flux. The total flux (cm^{-2} s^{-1}) of hydrogen and helium atoms at 1 AU from the Sun, $F^E_{NSW,H,He}$, is an integral over the distance from the Sun to Earth

$$F^E_{NSW,H}$$

$$= N^E_{H+} \, V_{SW} \int_{R_{min}}^{R_E} P_H(R,V_{SW}) \sum_k n_k(R) \, q_{H+,k}(V_{SW}) \, dR \qquad (27)$$

$$F^E_{NSW,He}$$

$$= N^E_{He++} \, V_{SW} \int_{R_{min}}^{R_E} P_{He}(R,V_{SW}) \sum_k n_k(R) q_{He++,k}(V_{SW}) \, dR \qquad (28)$$

The lower integration limit used by us is $R_{min} = 0.05$ AU. Actually, the results of calculations are only slightly sensitive to the value of R_{min} since the probability, $P_{H,He}(R,V)$, decreases rapidly with the approach to the Sun (Figure 4). In case of the NSW hydrogen component, $F_{NSW,H}$, charge exchange occurs on interplanetary H, H$_2$, and He, while in case of the NSW helium component, $F_{NSW,He}$, neutral particles involved are H$_2$ and He only. The alpha particle component of the solar wind is assumed to be $\xi = N^E_{He++}/N^E_{H+} = 0.05$ and abundance of singly charged helium ions He$^+$ is negligibly small.

The angular dependence of stationary NSW hydrogen and helium components, $F^E_{NSW,H}(\Theta)$ and $F^E_{NSW,He}(\Theta)$, is shown in Figure 6. Also shown are contributions to the NSW hydrogen component due to charge exchange on interstellar hydrogen (ISG - H) and helium (ISG - He) atoms as well as their sum $F^E_{NSW,H}(ISG)$. For parameters accepted in this work most of the contribution to the NSW hydrogen component is due to charge exchange on interstellar neutrals: charge exchange on interstellar hydrogen dominates everywhere except the downwind region where charge exchange on interstellar helium becomes more important.

The NSW hydrogen component due to charge exchange on dust generated neutrals does not depend on angle Θ, constitutes 9.2 $\times$ 10^2 cm^{-2} s^{-1} and its relative contribution becomes substantial in the downwind region. Most of the charge exchange occurs on dust-generated atomic hydrogen (approximately three fourths) and some on molecular hydrogen (one fourth) with negligible contribution of dust-generated helium. The NSW helium component $F^E_{NSW,He}$ is generated almost exclusively by charge exchange on interstellar helium atoms. A contribution of charge exchange on dust-generated neutrals is less then 4 cm^{-2} s^{-1} and can be disregarded.

Most of the expected stationary NSW hydrogen atom flux, with the exception of the downwind region, is produced by the interaction of the solar wind ions with interstellar neutrals. One has to note, however, that characteristics of interplanetary dust in the Sun's vicinity are not known with high accuracy. If the dust population is more numerous than adopted in this work, then the situation may change, and the dust contribution could become the most important contributing factor determining the properties of the NSW at 1 AU from the Sun.
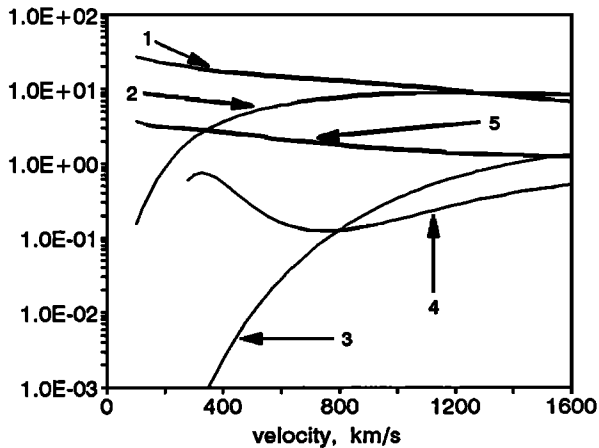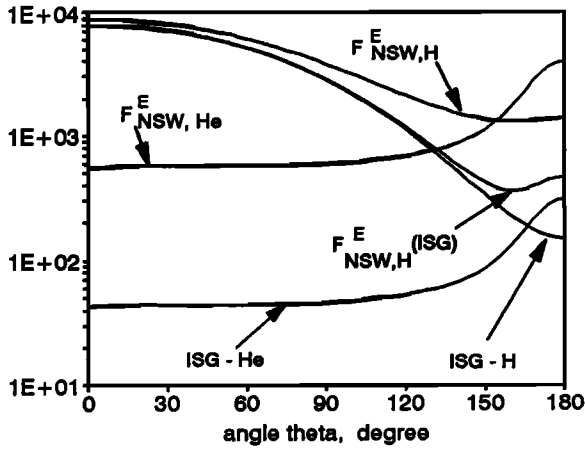
Figure 6. Angular dependence of the stationary neutral solar wind (NSW) hydrogen and helium flux $(cm^{-2}s^{-1})$ components at the Earth's orbit; $F^E_{NSW,H}$ and $F^E_{NSW,He}$ are the total fluxes; $F^E_{NSW,H}(ISG)$ is the total contribution of the ISG consisting of charge exchange on interstellar hydrogen (ISG-H) and helium (ISG-He).

5. ENAs due to CME

Many typical features of CMEs were described recently in detail by *Hildner* [1992], *Gosling* [1992, 1993a, b], and *Hundhausen* [1993]. For our modeling it is important that a large nonrecurrent geomagnetic storm can be produced by a strong CME with the leading edge velocity > 1000 km/s near the Sun. CMEs often spread more than 45° in heliocentric longitude and latitude, and they are characterized by increased abundance of helium (He^{++}/H^+) and depression of plasma ion and electron temperatures. Consideration of the effects of shocks preceding CMEs as well as plasma between the shocks and CMEs are beyond the scope of the present work. We assume here that a storm starts when CME plasma impinges on the magnetosphere.

The model of CME propagation chosen here uses an approach close to that of *Hsieh et al.* [1992], the latter based on results of the computer simulation by *Han et al.* [1988]. Several substantial modifications are, however, introduced by us to facilitate the computation.

It is assumed that at the moment of time, $t_0 = 0$, all parts of the CME has the same velocity V_0, the CME's leading edge is located at ρ_1, its trailing edge is at ρ_2, and its size in a radial direction is $\Delta_1 = \rho_1 - \rho_2$ (Figure 7). Each CME element moves with a certain constant deceleration, $a(\rho) < 0$, which is a linear function of the initial position of this element, $\rho(t_0)$. The CME leading edge is moving faster than the trailing edge, that is $|a(\rho_1)| <$

Figure 7. A model for coronal mass ejection (CME) propagation toward the Earth.

$|a(\rho_2)|$. As a CME moves toward the Earth, its radial size grows, it decelerates, and different parts of the CME move with different velocities. The CME leading edge reaches the Earth (at the time moment t_1) and then after some time (at the time moment t_2) the trailing edge passes the Earth. At this moment, t_2, the trailing edge is at $\rho_4 = 1$ AU, the leading edge is at ρ_3, and the CME radial size is $\Delta_2 = \rho_3 - \rho_4$ (Figure 7). An advantage of such a model, which significantly simplifies the computation, is that at any given moment of time ions at a given point in the CME have only one radial velocity and conversely the ions with a given velocity can be found only at one point of the CME.

We will assume here that $\rho_1 = 0.1$ AU, $\rho_2 = 0.05$ AU, $\rho_3 = 1.1$ AU, and $\rho_4 = 1.0$ AU. The radial size of the CME changes from $\Delta_1 = \rho_1 - \rho_2 = 0.05$ AU to $\Delta_2 = \rho_3 - \rho_4 = 0.1$ AU. The initial velocity is assumed to be $V_0 = 1200$ km/s and the deceleration of the leading edge, $a_1 = a(\rho_1) = -2.3 \times 10^{-3}$ km s^{-2}, the value adopted by *Hsieh et al.* [1992]. The propagation time required for the leading edge to reach $\rho_3 = 1.1$ AU and the trailing edge to reach 1 AU, $t_2 - t_0 = t_2$, can be obtained from

$$a_1 \, t_2^2 / 2 \; + \; V_0 \, t_2 - (\rho_3 - \rho_1) = 0 \qquad (29)$$

which gives $t_2 = 1.45 \times 10^5$ s. The acceleration of the trailing edge element can then be obtained from

$$a_2 = a(\rho_2) = 2\,[(\rho_4 - \rho_2) - V_0 t_2]\,/\,t_2^2 = -3.01 \text{ km/s}^2 \qquad (30)$$

In our model the acceleration of any given CME element depends linearly on the initial position of this element, ρ ($\rho_2 < \rho < \rho_1$), that is,

$$a(\rho) = a_2 + (\rho - \rho_2)(a_1 - a_2)/(\rho_1 - \rho_2) \qquad (31)$$

Time t_2 corresponds to the moment when the CME trailing edge reaches the Earth. The magnetic storm starts earlier at time, t_1, when the leading edge reaches the Earth. This time moment t_1 can be found from

$$a_1 \, t_1^2 / 2 \; + \; V_0 \, t_1 - (\rho_4 - \rho_1) = 0 \qquad (32)$$

which gives $t_1 = 1.28 \times 10^5$ s. CME/ENAs born at ρ_1 at the moment t_0 would be the first to reach the Earth at the moment, t_3, and are the earliest possible CME/ENA precursor of the approaching CME. This moment is in our case

$$t_3 = (\rho_3 - \rho_1)\,/\,V_0 = 1.12 \times 10^5 \text{ s} \qquad (33)$$

The maximum possible time delay between the CME/ENA advance warning and the onset of the storm is consequently $t_1 - t_3 = 1.6 \times 10^4$ s $\approx$ 4.4 hours.

For assumed initial CME velocity, $V_0 = 1200$ km/s, the CME leading edge impinges on the Earth with the velocity, $V_1 = V_0 + a_1 t_1 = 905$ km/s, and the trailing edge has the velocity, $V_2 = V_0 + a_2 t_2 = 763$ km/s at 1 AU.

The calculation of the probability for a hydrogen CME/-ENA to reach 1 AU without ionization is more complicated than in case of the stationary NSW hydrogen atoms. A CME/ENA is a subject of photoionization in the same way as NSW hydrogen. However, a contribution of the charge exchange cannot be neglected anymore. An ENA moves
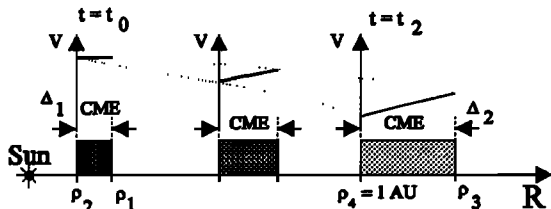
relative the gradually decelerating CME plasma and at some moment of time crosses the CME's leading edge and continues its flight in the stationary unperturbed solar wind. We assume here that no ionization due to charge exchange occurs when an ENA is inside the CME. This assumption is reasonable, since if the charge exchange does occur, a new ENA would have velocity close to that of the original ENA. Outside the CME, an ENA is a subject of charge exchange as a neutral atom moving relative the solar wind plasma with the velocity, $V_A - V_{SW}$, where V_A is the atom velocity relative the Sun.

If an ENA is born with the velocity V_A at the distance R_1 from the Sun and crosses the CME's leading edge at the distance, R_2, then the probability to reach the Earth (at R_E) without ionization is

$$P(R_1,R_2,V_A) = P_{PH}(R_1,V_A) \times P_{CX}(R_2,V_A) \qquad (34)$$

where

$$P_{PH}(R_1,V_A)$$

$$= \exp\left[\frac{\beta_A^{PH}(R_E) R_E}{V_A}\left(1 - \frac{R_E}{R_1}\right)\right] \qquad (35)$$

$$P_{CH}(R_2,V_A)$$

$$= \exp\left[\frac{N_{H+}^E (V_A - V_{SW}) q_{H+,H} R_E}{V_A}\left(1 - \frac{R_E}{R_2}\right)\right] \qquad (36)$$

where $q_{H+,H} = q_{H+,H}(V_A - V_{SW})$. The distance R_2 can be easily found from considering the ENA motion with the constant velocity V_A and the decelerating motion of the CME's leading edge.

As in case of the stationary NSW, there are two processes that contribute to the CME/ENA flux: recombination and charge exchange on interplanetary neutrals. The CME/ENA flux will be characterized by a changing in time velocity distribution function. The flux due to charge exchange, $G_{H,He}^{CX}$ (cm^{-2} s^{-1}), with velocity V at 1 AU at a time moment t is

$$G_{H,He}^{CX}(V,t)$$

$$\qquad (37)$$

$$= \int_{R_{min}}^{R_E} N_i\left(R,V,t - \frac{R_E-R}{V}\right) V(R,t) \, P(R,V,t)(R/R_E)^2 \sum_k q_{i,k} n_k(R) \, dR$$

where $N_i[R,V,t-(R_E - R)/V]$ is the radial and velocity distribution of the CME's ions at the time moment $[t - (R_E - R)/V]$. The CME/ENA flux due to recombination would consist of atomic hydrogen component only and is equal to

$$G_H^{REC}(V,t)$$

$$\qquad (38)$$

$$= \int_{R_{min}}^{R_E} \left[N_i\left(R,V,t - \frac{R_E - R}{V}\right)\right]^2 \alpha(T_e) \, P(R,V,t) \, (R/R_E)^2 \, dR$$

From a computational point of view it is convenient to evaluate integrals (37) and (38) by selecting an element in the CME at $t_0 = 0$ and considering the contribution of this element to the NSW flux during its propagation toward 1 AU. The sum of contributions of all elements initially constituting the CME would give the CME/ENA flux. The neutral particle radial number density distributions are known. The number density radial dependence of the CME ions and electrons is different from that of the stationary solar wind. At 1 AU the CME number density is not particularly higher than that of the stationary solar wind [e.g., Gosling, 1992]. To keep the model simple, we assume here that the CME's number density is $N_{H+}^E = 10$ cm^{-3} at 1 AU and a solid angle subtended by the CME does not change with the propagation from the Sun. Such an assumption leads to a simple relation between plasma number density at 1 AU and number density at arbitrary R, taking into account the radial expansion of the CME's size, Δ. The CME number density would be approximately factor 2 larger at 0.1 AU than it would be for a stationary expansion case.

In reality, one can expect higher enhancement of the CME plasma density closer to the Sun since CMEs experience greater expansion in transit to the Earth than the stationary solar wind [e.g., Gosling, 1992]. The correction allowing for this effect will result in higher CME/ENA fluxes, especially for the early arriving neutral particles, than obtained from the present model. Therefore our estimates of the CME/ENA flux can be considered as conservative.

The alpha particle component in a CME is assumed to be $\xi = N_{He++}^E/N_{H+}^E = 0.10$, a factor 2 higher than in the quiescent solar wind. There are indications that the ratio He^+/He^{++} may increase in CMEs up to such high values as > 0.1 [e.g., Schwenn et al., 1980]. The charge exchange cross sections of helium ions and atoms are approximately factor 3 higher for singly charged ions than for doubly charged ions in the energy range of interest. Therefore the contribution of singly charged helium ions to the helium CME/ENA flux may constitute up to 30 % of the total helium ENA flux. We further disregard this contribution.

The electron temperature is known to be depressed in CMEs, and we adopt here the temperature radial dependence

$$T_e = 5 \times 10^4 \, R^{-1} \, \text{K} \qquad (39)$$

where R is in AU. The recombination rate coefficient α is approximated by (19) and (20).

As an example, the calculated time dependence of the CME/ENA fluxes, G_H and G_{He}, is shown in Figures 8a and 8b for $\Theta = 0°$ and $180°$, correspondingly. The CME plasma impinges on the Earth (i.e., the geomagnetic storm starts) at the time moment $t = 62$ (one time unit, or time step, is 300 s = 5 min; $t = 0$ does not coincide with the moment t_0). The CME's trailing edge passes the Earth at $t = 120$. The CME/ENA hydrogen flux (Figures 8a and 8b) consists of contributions of recombination ("recom") and charge exchange on interstellar ("isg") and dust-generated ("dust") neutrals.

We are interested mostly in ENA flux preceding the beginning of the storm ($t < 62$). One can see that the dust-generated neutrals account for the major part of the hydro-
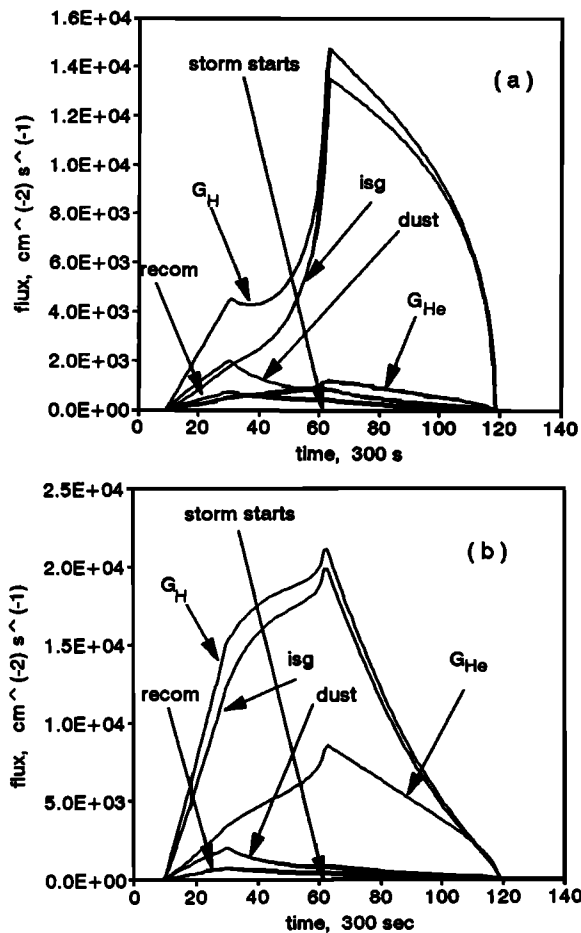
Figure 8. The CME/energetic neutral atom (ENA) flux time dependence at 1 AU from the Sun for (a) $\Theta = 0$ and (b) $\Theta = 180°$; 1 time step is equal to 300 s. G_H and G_{He} are the total fluxes of hydrogen and helium CME/ENAs. Contributions of different processes are shown for the hydrogen component of the CME/ENA, G_H: "recom," recombination; "isg," charge exchange on interstellar neutrals; "dust," charge exchange on dust-produced neutrals. The start of the geomagnetic storm is marked by the arrow.

gen CME/ENA flux for $\Theta = 0$ at the initial stage ($t < 30$) of the ENA flux enhancement. The NSW/CME flux due to charge exchange on the ISG becomes more important later ($t > 30$). For $\Theta = 180°$ the ISG contribution dominates from the very beginning due to enhanced number density of interstellar helium in the downwind region. Charge exchange on interstellar helium is especially important for early coming CME/ENAs. Obviously, the first to arrive are ENAs born close to the Sun and characterized by higher velocity (energy), and charge exchange cross sections of protons on helium atoms rapidly increases with velocity (Figure 5). The gravitational focusing of helium explains also the large signal of the helium CME/ENA component for $\Theta = 180°$. A contribution of the recombination in the expanding CME plasma remains relatively small.

Energy distributions of hydrogen CME/ENAs are shown in Figures 9a and 9b for $\Theta = 0°$ and $180°$ for time moments $t = 20, 30, 40, 50,$ and 60. The energy of the particles arriving at $t = 20$ and 30 is higher than the energy of ENAs at $t = 50$ and 60. Curve shapes in

Figures 9a and 9b reflect the difference in relative contributions of charge exchange on interplanetary helium and hydrogen atoms. The energy distributions of helium atoms are similar to those of hydrogen and are shown in Figure 10.

Until the CME impinges on the Earth, the CME/ENA flux arrives simultaneously with the quiescent NSW ENAs. Although the CME/ENA flux is slightly smaller than that of the quiescent NSW, energies of CME/ENAs are significantly higher. This energy dependence on ENA origin allows one to easily distinguish between the NSW and CME ENA fluxes.

The results of the CME/ENA simulation are model sensitive. They show, however, the major characteristic CME/ENA features (Figures 8, 9, and 10) as well as demonstrate the relative importance of the processes involved. For higher CME number density and lower electron temperature the relative contribution of recombination would be larger, although it is unlikely that it may become the dominating process. The major source of uncertainty in estimates remains interplanetary dust. For example if dust geometrical factor, $\Gamma(R)$, is higher than adopted in this paper, then it will result in higher ENA flux preceding the storm, the latter being important for storm's advance warning.
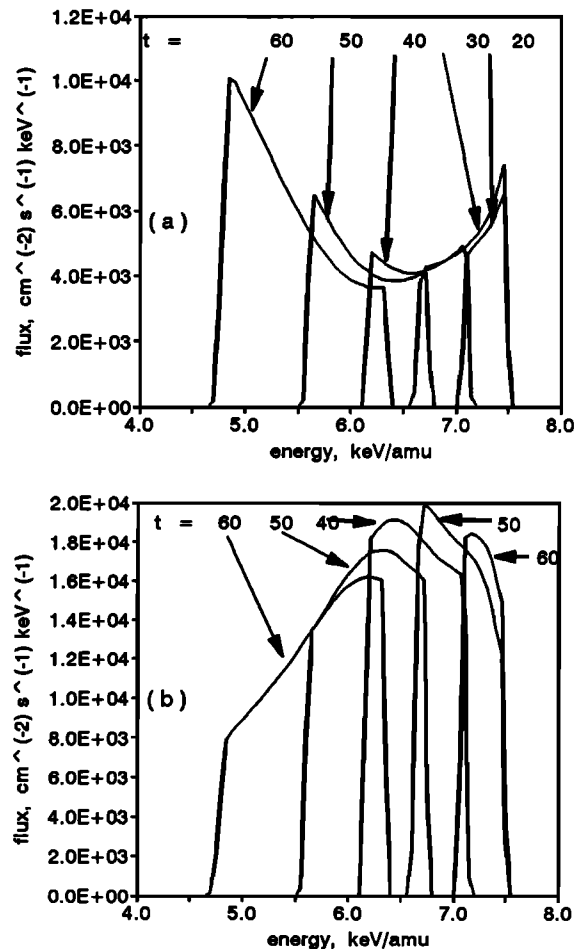

Figure 9. Energy distributions of hydrogen CME/ENAs at 1 AU at times $20, 30, 40, 50,$ and 60 for (a) $\Theta = 0$ and (b) $\Theta = 180°$; 1 time step is 300 s. Energy of quiescent NSW atoms is 1.3 keV.

Figure 10. Energy distributions of helium CME/ENAs at 1 AU at times 20, 30, 40, 50, and 60 for (a) $\Theta = 0$ and (b) $\Theta = 180°$; 1 time step is 300 s. Energy of quiescent NSW atoms is 1.3 keV.
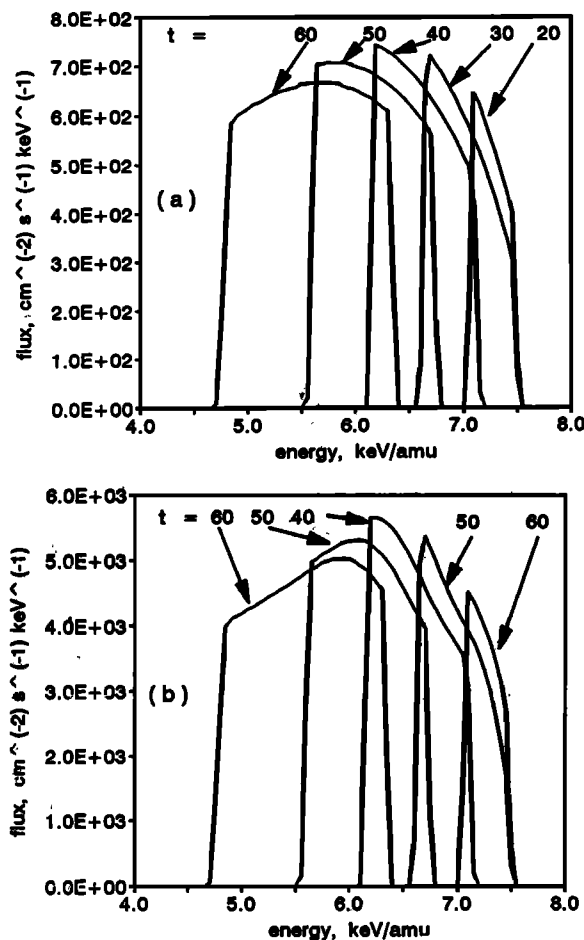
6. Advance Storm Warning

The significant "high-energy" ($E > 3$ keV/amu) CME/ENA flux is expected 2.5 - 3 hours before the arrival of the CME (Figure 8). The advance warning instrumental package could be deployed at a spacecraft either inside or outside the magnetosphere (say at the Lagrangian point L1) and it should include ENA, plasma, and magnetic field instruments. A detection of the high-energy ENA flux triggers a preliminary alert signal and starts the procedure to assess recently accumulated and current plasma and magnetic field measurements.

It was pointed out [e.g., Tsurutani et al., 1992a; Gosling, 1993a] that favorable conditions for development of a large geomagnetic storm include high differential velocity between the CME and surrounding solar wind and long-duration (as long as days prior the current moment) precursor southward interplanetary magnetic field. If the evaluation of the available plasma and magnetic field measurements outside the magnetosphere shows that these conditions are met, then an alert signal, as well as an estimate of the expected storm's magnitude, are sent to concerned parties (electric power grids, communications, satellite operations, etc.) that triggers execution of protective actions by users.

The advance warning of the approaching CMEs discussed here is based on the ability to measure weak ENA fluxes in space. This is a challenging task and consideration of the available techniques is out of scope of this paper as well as of this journal. As we mentioned earlier, experimental techniques to measure ENAs in the energy range of interest (0.5 keV $< E <$ 20 keV) were under gradual development since late 1960s [e.g., Wax and Bernstein, 1967; Bernstein et al., 1969; Gruntman and Morozov, 1982; McEntire and Mitchell, 1989; McComas et al., 1989; Hsieh et al., 1992; Gruntman, 1993; Funsten et al. 1993] with recently increased interest and attention due to prospects of their applications for global magnetosphere imaging [e.g., Williams et al., 1992].

Two major approaches for ENA detection are based on (1) ENA stripping in thin foils and (2) direct detection using coincidence requirements. The latter approach implemented in the NSW experiment [Gruntman and Morozov, 1982; Gruntman and Leonas, 1983; Gruntman et al., 1990] is optimized for conditions of the quiescent NSW characterized by relatively low ENA velocities (~ 1 keV/amu). Such velocities result correspondingly in a relatively large aberration angle (for an observer moving with the Earth around the Sun) and allows one to achieve satisfactory suppression of the direct solar light by a careful design of the instrument's baffle. The CME/ENA flux has much higher velocity (3-8 keV/amu) and correspondingly much smaller aberration angle, which makes it virtually impossible to build an adequate baffle to protect the sensor from the solar light. The technique based on the ENA stripping in thin foil [e.g., Bernstein et al., 1969; McComas et al., 1991] is preferable under such conditions. The stripping efficiency of high-energy CME/ENAs would be rather high (~ 0.1 for hydrogen atoms and 0.05-0.08 for helium atoms). The ions (stripped ENAs) with energies less than 2-3 keV/amu (corresponding to the quiescent solar wind preceding the CME) can be easily rejected by retarding potential filter, and the remaining higher-energy ions can be conveniently deflected (to suppress the effect of the background EUV/UV light), energy analyzed (required energy resolution E/ΔE = 10-15), and reliably detected. Development of efficient diffraction filters [Gruntman, 1991; Scime et al., 1993] can facilitate the EUV radiation suppression.

To conclude, the progress in development of ENA measurement technique suggests that both the quiescent NSW and CME/ENAs can be reliably measured at 1 AU from the Sun. Such measurements, performed continuously, can provide a basis for advance warning of large geomagnetic storms and prediction of their magnitude as well as for remote study of the dynamics of CME propagation outward from the Sun.

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