

## METEORIC IONS IN THE CORONA AND SOLAR WIND

J. LEMAIRE<sup>1</sup>

DESPA, Observatoire de Meudon, Meudon, France

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## ABSTRACT

The total mass of refractory material of interplanetary origin penetrating and evaporated in the “meltosphere” surrounding the Sun has been inferred from observations of meteoroids and fireballs falling in Earth’s atmosphere. The amount of iron atoms deposited this way in the solar corona is of the order of  $3000 \text{ t s}^{-1}$  or larger. The measured flux of outflowing solar wind iron ions is equal to  $2200 \text{ t s}^{-1}$ . The close agreement of both fluxes is evidence that a significant fraction of iron ions observed in the solar wind and in the corona must be of meteoric origin. A similar accord is also obtained for silicon ions. The mean velocity of meteoroid ions formed in the solar corona is equal to the free-fall velocity: i.e., independent of their atomic mass as the thermal speed of heavy ion measured in low-density solar wind streams at 1 AU. Furthermore, the heavy ions of meteoric origin escape out of the corona with a larger bulk velocity than the protons which are mainly of solar origin. These differences of heavy ion and proton bulk velocities are also observed in the solar wind.

*Subject headings:* abundances — meteors and meteorites — Sun: corona — Sun: solar wind

## I. INTRODUCTION

From coronal UV as well as infrared line emissions, it has been recognized for more than two decades that iron ions are a factor of 4 or 5 more abundant relative to oxygen ions in the solar corona than in the photosphere (Pottasch 1964, 1965; Seaton 1964; Byard and Kissell 1971). Solar wind (SW) particles and solar energetic particles (SEP) originating in the corona are also more abundant compared to oxygen ions in the photosphere by the same factor (Geiss 1982; Cook *et al.* 1979; Cook, Stone, and Vogt 1984; Geiss and Bochsler 1985, 1986; Breneman and Stone 1985; Meyer 1985*a, b*; Bochsler 1987; Schmid, Bochsler, and Geiss 1988). Silicon ions in the solar corona and SW show similar enrichments (Bochsler 1989). The same excess is observed for most elements with “first ionization potentials” (FIP) smaller than 9–11 eV (Meyer 1985*a, b*), or small “first ionization times” (FIT) (Geiss and Bochsler 1986). For a comprehensive review see Anders and Grevesse (1989).

As noted by Meyer (1985*a, b*) and Geiss and Bochsler (1986), many characteristics of an atom are directly or indirectly related to its FIP. A variety of processes can therefore lead to FIP-dependent separation and fractionation. For instance, elements with low FIP tend to be refractory, while elements with high FIP generally tend to be volatile. Therefore, a correlation with FIP may correspond to a correlation with volatility. Since interplanetary grains and asteroidal debris are predominantly refractory, the observed coronal, SW and SEP composition pattern could possibly originate from the products of meteoroids destruction in the solar corona. The aim of this paper is to check this hypothesis using recent fireball and SW observations.

Similar overabundances of iron and other metallic elements have been observed in Earth’s ionosphere (see, e.g., Zbinden *et al.* 1975). In this case there is no doubt that these overabundant ions are of meteoric origin (Nicolet 1955; Narcisi 1968). The hypothesis that the metallic ions, sodium, and potassium,

(forming layers observed at 80–110 km altitude) could be of terrestrial origin has been ruled out by Gadsden (1968, 1970) and Hunten (1981). Therefore, in this case, no vertical transport mechanism is assumed to lift these heavy elements from the troposphere upward into the mesosphere of Earth, as is sometimes assumed for the case of the solar atmosphere.

It is the purpose of this paper to show that there is now convincing experimental evidence for a similar meteoric origin of coronal and SW metallic ions. In § II we calculate the flux of refractory material vaporized into the inner part of the corona from the most recent estimates of the influx of sporadic meteoroids in Earth’s atmosphere. In § IV, the fraction of iron ions of meteoric origin deposited in the corona is estimated and compared with the observed average flux of iron ions carried out of the corona by the SW. Finally, in § V, we indicate why these heavy SW ions have a temperature approximately proportional to their mass, as it is observed at 1 AU; their outward bulk velocity is also larger than that of the SW protons, as generally found in low-density SW streams.

## II. THE FLUX OF METEORIC MATERIAL INTO THE MELTOSPHERE

According to the “interplanetary dust model” proposed by Grün *et al.* (1985), the total flux of solid grains falling down into Earth’s atmosphere, with a mass ranging between  $10^{-18} \text{ g}$  and  $1 \text{ g}$ , should be  $40 \text{ tons day}^{-1}$ , or  $14,600 \text{ tons yr}^{-1}$ . This corresponds to an interplanetary mass flux of  $9 \times 10^{-13} \text{ g m}^{-2} \text{ s}^{-1}$  at the heliocentric distance of Earth’s orbit. These results are based on in situ satellite measurements, zodiacal light observations, and hypervelocity impact microcrater studies of micrometeoroids whose masses are smaller than  $1 \text{ g}$ .

The range of masses sampled for this earlier study does not extend in the domain above  $100 \text{ g}$ , which however, is mainly under consideration here. Fortunately, photographic and television double and multistation observations of meteors and fireballs now provide these data for more than four orders of magnitudes higher; i.e; up to  $6 \text{ t}$ . Ceplecha (1988) determined the total number flux and mass flux of individual groups of sporadic (nonshower) meteors penetrating per year in Earth’s atmosphere (see also McCrosky 1968).

<sup>1</sup> On leave of absence from IASB, 3 Ave. Circulaire, B1180 Brussels.

The cumulative number ( $N$ ) of all objects of mass larger than  $m$  is shown by the solid line in Figure 1 derived from Ceplecha (1988). It is compared with the extrapolated values from the "interplanetary dust model" up to 100 g. Note that according to this most recent survey based on photographic and television data  $N$ , the cumulative number of events per year varies approximately as  $m^{-0.58}$ . According to Grün *et al.*'s model extrapolation beyond 1 g,  $\log N$  should have a steeper slope (dashed curve) corresponding to a  $m^{-1.34}$  mass dependence. But one could not rely on such kinds of extrapolations beyond the domain of full-sensitivity of the detectors, nor beyond the range of validity of the experimental methods used to establish any empirical model. Therefore, the dashed line in Figure 1 is likely to be an underestimate of the actual cumulative flux  $N$  in the mass range above 10 g.

From Table 3 in Ceplecha's survey the total mass flux of particles between 1 g and 6.3 t is  $5 \times 10^9$  g yr<sup>-1</sup> for the whole of Earth's surface. This corresponds to an influx of 13.7 t day<sup>-1</sup>, which is less by a factor of 3 than the value corresponding to the interplanetary flux model for  $10^{-18}$  g <  $m$  < 10<sup>2</sup> g.

Ceplecha's mass flux of  $5 \times 10^9$  g yr<sup>-1</sup> must be considered as a conservative minimum value, since from the trend of Ceplecha's model, one expects that objects with masses larger than 6.3 t contribute even more significantly to the total mass influx. However, since no good statistical data are available for

objects between 6 t and the much larger masses of comets and asteroids, a quantitative extrapolation beyond this limit remains uncertain. Thus, we will take 5 Gg yr<sup>-1</sup> as a conservative minimum value for the whole Earth's surface which is  $5.1 \times 10^{14}$  m<sup>2</sup>. The actual value for the total meteoroid mass influx on Earth, FME, will be a factor  $fm$  larger:

$$\begin{aligned} \text{FME} &= fm \ 5 \times 10^9 \text{ g yr}^{-1} \\ &= fm \ 158 \text{ g s}^{-1}, \end{aligned} \quad (1)$$

where the appropriate correction factor  $fm$  (larger than 1) takes into account the contribution of masses larger than 6.3 t as well as smaller than 100 g.

As a result of the gravitational focusing effect (Öpik 1951), the interplanetary flux of meteoroids at large distance from Earth is reduced by a factor  $\chi$  compared to the observed flux FME in Earth's atmosphere;  $\chi = 1 + (V_{\text{esc}}/v_{\text{inf}})^2$  depends on the ratio of the escape velocity ( $v_{\text{esc}} = 11$  km s<sup>-1</sup>) and the velocity of the impacting object at infinity:  $v_{\text{inf}} = 10\text{--}50$  km s<sup>-1</sup>. A simple derivation of this gravitational focusing effect is also given in Landau and Lifchitz (1960, p. 75). For the meteoroids reported by Ceplecha (1988) the value  $\chi$  ranges between 1.2 and 2.

Half of these objects moved toward the Sun and penetrate within the sphere of 1 AU centered on the Sun; almost the same amount of them move out of this sphere. If their distribution along the surface of this sphere would be independent of heliographic latitude, the flux of mass FMAU penetrating into this sphere would be equal to:  $5.10^9 (1 \text{ AU}/1 R_E)^2$  g yr<sup>-1</sup>, where  $R_E$  is the Earth radius; but since one suspects that there are fewer meteoroids orbiting at high heliographic latitudes than near the ecliptic, the actual value of FMAU is likely smaller by a correction factor  $f$  (smaller than 1) taking into account the reduction of flux due to its nonuniform latitudinal distribution:

$$\begin{aligned} \text{FMAU} &= f (fm/\chi) \ 2.75 \ 10^{18} \text{ g yr}^{-1} \\ &= f (fm/\chi) \ 8.74 \ 10^{10} \text{ g s}^{-1}, \end{aligned} \quad (2)$$

where  $f = \frac{1}{3}$  or  $\frac{1}{2}$ .

Slightly less than half of these objects move again out of this sphere. But, as for the unexpectedly large number of Sun-grazing comets observed during the SMM mission, some of these meteoroids are vaporized in the "meltosphere." The meltosphere is the region where the surface temperature of meteoroid exceeds the melting temperature ( $\sim 1500$  K for iron). Considering that solid grains moving toward the Sun radiate as spherical black bodies, and that they are in thermal equilibrium with solar radiation at all heliospheric distances, it can be calculated that these falling objects reach the melting temperature of 1500 K when they get at heliocentric distances smaller than 7.5 solar radii (see Russell 1929). Therefore, we will consider that the radius of the meltosphere is  $7.5 R_S$ .

The angle  $\theta_e$  between the radial direction and the direction of a meteoroid (originating in the asteroidal belt, at  $r_0 = 2.7$  AU) when it reaches  $r_e = 1$  AU can have any value between  $\theta_e = 180^\circ$  and  $90^\circ$ , depending on its orbital velocity  $v_0$  at aphelion. Indeed, from equations (A1) and (A2) in Appendix A, it can be seen that  $\sin \theta_e = r_0/r_e [1 + v_{\text{ff}}^2 (r_0/r_e - 1) v_0^2]^{1/2}$ , where  $r_0/r_e = 2.7$  and  $v_{\text{ff}}$  is the critical escape velocity at  $r_0$ . For  $v_0$  varying between  $v_0 = 0$  and  $0.52 v_{\text{ff}}$ , the value of  $\theta_e$  varies from  $180^\circ$  to  $90^\circ$ . However, only a fraction  $f_r$  of these Earth-crossing objects will penetrate the meltosphere with an angle  $\theta_m$  ranging between  $180^\circ$  and  $90^\circ$ . Only those grains which have at 1 AU

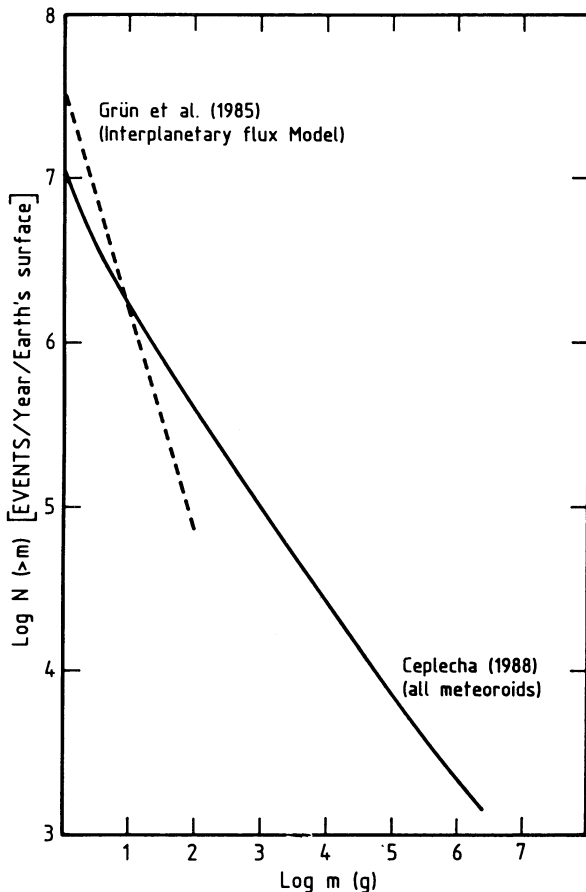


FIG. 1.—Cumulative distribution of large meteoroids and fireballs over the whole Earth, as determined by Ceplecha (1988) from photographic observations (solid line). For comparison an extrapolation of the "interplanetary flux model" of micrometeoroids obtained from other experimental techniques (dashed line).

an angle  $\theta_e$  between  $180^\circ$  and  $166^\circ$  will reach this innermost region of the heliosphere.

The fraction  $fr$  depends on the source of the meteoroids (that we assume to be asteroidal), on their velocity and mass distributions (that we assume to be isotropic and mass-independent, respectively), on the mean radial distances of the asteroidal belt, and on the radius of the meltosphere. The calculation of the ratio  $fr$  between the flux of asteroidal meteoroids penetrating the meltosphere,  $J(r_m)$ , and their flux at the distance of the Earth,  $J(r_e)$ , has been calculated in Appendix A, and reported in Table 1 for a wide range of values of these parameters. From the discussion presented there, we infer a likely value for this ratio:  $fr = 0.18$ . But larger (or smaller) values can well be possible. It would be interesting to initiate an independent study of fireball observations to determine more precisely the actual velocity distribution of these objects.

Assuming evenly distributed angles  $\theta_0$  implies that meteoric fragments are efficiently scattered by head-on collisions and gravitational accelerations in the asteroidal belt where most of the larger objects of Ceplecha's groups I and II have their origin. The gravitational field of the planets is also partly responsible for cumulative small angular deflections of these objects, as shown by Zimmerman and Wetherill (1973). To discuss injection mechanisms of these objects in highly eccentric Earth-crossing orbits is outside the scope of this paper. However, from meteorite and meteor observations one can deduce that asteroidal debris is indeed injected continuously by these mechanisms, into highly eccentric trajectories penetrating Earth's atmosphere as well as the meltosphere.

When meteor data are corrected to constant mass entering the atmosphere, the distribution of radiants shows considerable enhancements toward the Sun and anti-Sun directions, i.e., for  $\theta_e = 180^\circ$  and  $0^\circ$ , respectively (see Southworth and Sekanina 1973). This tends to indicate that the refilling process of highly eccentric orbits is indeed rather efficient.

To take into account this anisotropic distribution in angles  $\theta_e$  with peaks in the solar and antisolar directions, we allow for an additional correction factor  $f\theta$  (larger than 1, since  $0^\circ$  and  $180^\circ$  angles are more frequent than  $90^\circ$  angles); the net mass flux of meteoroids penetrating into the meltosphere is then given by

$$\begin{aligned} \text{FMMS} &= f\theta fr fl fm/\chi \ 9.0 \times 10^{10} \text{ g s}^{-1} \\ &= f\theta fl fm/\chi \ 1.6 \times 10^4 \text{ t s}^{-1}. \end{aligned} \quad (3)$$

Note that this is much larger than the estimated amount of micrometeoroids falling toward the Sun as a result of the Poynting-Robertson effect ( $0.26 \text{ t s}^{-1}$ ; Grün *et al.* 1985). Of course, when the mechanism of vaporization of meteoric material in the meltosphere is ignored (as it is in some earlier studies models of the "collisional balance of the meteoritic complex"), a mass flux of meteoroids almost equal to FMMS would move out again of the meltosphere; the difference between the inward and outward fluxes would then strictly be equal to the Poynting-Robertson flux quoted above. Although the Poynting-Robertson effect is negligible for the large objects, vaporization inside 7 solar radii increases considerably the sink of the meteoritic complex. Note that vaporization of small micrometeoroids inside the meltosphere will also contribute to an additional net mass inflow of meteoric material in the meltosphere larger than expected before.

Part of that material (FMMS) penetrating into the meltosphere can become fragmented. Most of these fragments are

vaporized, like the many Sun-grazing comets recently discovered during the *SMM* mission.

Since the large meteoroids of Ceplecha's groups I and II are the important contributors to this flux, it is reasonable to assume that they have a composition similar to the Orgueil meteorite reviewed by Anders and Grevesse (1989): i.e., 19% of iron (56 AMU), 10.6% of silicon (28 AMU); relatively lower (but nonnegligible) abundances of HCNO or volatile elements are also present in these meteorites. Therefore some amount of these elements is also deposited in the meltosphere in addition to the metallic ions mainly considered in this paper.

Note that a meteoric atom photoionized in the outer meltosphere will continue its fall toward the Sun because of its low charge-to-mass ratio until it reaches the inner solar corona. It is only in the denser region of the solar corona that these atoms are stripped to the very high ionization states which are observed. Once their charge-to-mass ratio has increased, they are picked up by the SW stream and accelerated outward by the interplanetary electric field.

The total number of iron and silicon atoms deposited at heliocentric distances smaller than  $7.5 R_S$  is estimated to be

$$\text{FNFe} = f\theta fl fm/\chi \ 3.3 \times 10^{31} \text{ Fe atoms s}^{-1}, \quad (4)$$

$$\text{FNSi} = f\theta fl fm/\chi \ 3.7 \times 10^{31} \text{ Si atoms s}^{-1}. \quad (5)$$

These fluxes will be compared in § IV with the average solar wind ion flux of these same elements as measured at 1 AU.

### III. IONIZATION OF METEORIC ATOMS IN THE SOLAR CORONA

The neutral atoms which are boiled off from the surface of the meteoroid are ionized by photoionization, by charge exchange, and eventually by inelastic collisions with the ambient coronal electrons. At the base of the corona where these ambient electrons have a temperature ( $T_e$ ) of  $1.0\text{--}1.4 \times 10^6 \text{ K}$ , and a number density ( $N_e$ ) of the order of  $10^8 \text{ cm}^{-3}$ , the characteristic time of ionization is  $300\text{--}1000 \text{ s}$  (Shklovskii 1965, p. 218). These ambient electrons have a nearly Maxwellian and isotropic velocity distribution with a mean thermal speed of  $6700 \text{ km s}^{-1}$ ; their mean thermal energy is  $130 \text{ eV}$ .

The larger the coronal electron temperature, the larger is the number of electrons which have energies exceeding the ionization potential of the newly injected meteoric atoms: the ionization potential of Si IV is  $45 \text{ eV}$ ;  $523 \text{ eV}$  for Si XII;  $130 \text{ eV}$  for Fe VII;  $489 \text{ eV}$  for Fe XVI (Allen 1963a). Thus, the energy of coronal electrons is high enough to strip off more than seven electrons from meteoric Fe atoms in about 100 minutes of time at the altitude of the coronal base, i.e., at  $70,000 \text{ km}$  above the photosphere.

The multiionized Fe or Si ions which are formed emit faint lines in the visible, infrared, and UV domains. From the relative intensities of these coronal emission lines, the relative abundances of ions in different ionization stages have been determined experimentally (Pottasch 1964, 1965; Seaton 1964; Byard and Kissel 1971). The comparison of these coronal abundances determined spectroscopically indicate that Fe, Si ions and other metallic ions are significantly more abundant relative to oxygen, carbon, or nitrogen ions in the corona than in the photosphere. Note that from these observations one could as well argue that the elements of the CNO group are more abundant in the photosphere than in the corona.

Solar wind measurements by Geiss and Bochsler (1985, 1986), Brenemann and Stone (1985), Bochsler (1987), Schmid, Bochsler, and Geiss (1988) confirm that Fe, Si, and other ref-

ractory elements with FIP smaller 9.5–11 eV are a factor 4.5 more abundant compared to oxygen ions in the SW than in the photosphere. In other words, elements with high FIP ( $> 11$  eV) like those of the CNO group are depleted by a factor of 4.5 compared to Fe, Si, and other metallic elements, when compared to their photospheric abundances. This trend is clearly illustrated in Figure 3 of the review article of Anders and Grevesse (1989).

This relative excess of low FIP elements in the solar corona and in SEP accelerated in the corona during flares can partly be due to an atom-ion separation process as suggested by Cook *et al.* (1979) and Geiss (1982). If FIP is the relevant physical parameter responsible for such an atom-ion separation, then the fractionation must take place in low-temperature material consisting of neutral and singly ionized atoms: i.e., in weakly ionized chromospheric gas where  $T < 10^4$  K (Meyer 1985a, b). Neutrals somehow diffuse away from the gas and enter the corona, whereas ions are prevented from doing so by the magnetic field. Two mechanisms based on this same idea have been investigated. Vauclair and Meyer (1985) proposed gravitational settling of heavy neutrals in a 6500 K "temperature plateau" of the middle chromosphere, with FIP as a key parameter. Geiss (1982) and von Steiger and Geiss (1989) have considered diffusive loss of neutrals across magnetic flux tubes during the fast rise of matter from the chromosphere to the corona; the driving force for the atoms being in this case a pressure gradient and the relevant parameter is the FIT, which is closely related to the FIP.

In both these theoretical mechanisms, there are a number of free parameters whose values can be chosen for the purpose of simulating the desired enhancement of low FIP or FIT elements in the solar corona; for instance, a flux tube or slab thickness of 10 km seems to give the best fit in the second type of model. Until now there has been no quantitative evaluation of the net flux of heavy and low FIP particles that these processes can uplift into the corona. Indeed, to be tenable these mechanisms should be able to account for the net average flux of heavy SW ions observed at 1 AU.

#### IV. IRON AND SILICON FLUXES IN THE SOLAR WIND

The mean flux of protons in the SW is  $3.8 \cdot 10^{12}$  protons  $m^{-2} s^{-1}$  at 1 AU (Feldman *et al.* 1979). This corresponds to a total mass outflow of  $1.7 \times 10^{12}$  g  $s^{-1}$ , assuming the SW flux is independent of heliographic latitude. This is a factor of 100 larger than the meteoric mass flux penetrating into the meltosphere (FMMS). This means that meteoric material does not enhance significantly the total mass content nor mass flux in the corona. Therefore, coronal and SW hydrogen ions are predominantly of solar origin; i.e., not of meteoric origin. This is not the case, however, for minor heavy ions more abundant in meteoric material.

From 45,000 spectra collected over a period of 4 yr near the maximum of solar cycle no. 21, Schmid, Bochsler, and Geiss (1988) have obtained a long-term average of  $2.6 \times 10^8$  Fe-ions  $m^{-2} s^{-1}$  at 1 AU. This corresponds to a total number flux of  $7.3 \times 10^{31}$  Fe-ions  $s^{-1}$  flowing out of the corona, provided this flux is uniform along Earth's orbit and independent of heliographic latitude. However, this is certainly an overestimated value. Indeed, the abundance of iron ions relative to hydrogen is known to be reduced in coronal hole associated streams by almost a factor of 3 as compared to the SW average (Schmid, Bochsler, and Geiss 1988; Gloeckler *et al.* 1989). For quiet and cool interstream SW flow regimes, iron fluxes have been

published by Bame *et al.* (1968; 1975). Iron ion flux determinations in high-speed SW have been obtained by Mitchell *et al.* (1983) and Ipavich *et al.* (1986). All these results tend to indicate that the Fe-ion flux is likely to be reduced at high heliocentric latitudes: i.e., that the value calculated above for a uniform distribution in latitude should be reduced by a factor  $fh$  of 2 or 3. Until we have out-of-ecliptic ion flux measurements from the future *Ulysses* mission, we only can make reasonable guesses for  $fh$ . Therefore, the total flux of Fe-ions carried by the three-dimensional SW is of the order of

$$FNFe_i = 7.3 \cdot 10^{31} / fh \text{ Fe-ions } s^{-1}. \quad (6)$$

The observed standard deviation of daily flux averages is fairly large:  $2 \times 10^8$  Fe ions  $m^{-2} s^{-1}$ , i.e., 30%. This shows the extreme inhomogeneities of the SW iron flux. The standard deviation of the monthly averages is a factor of 3.3 smaller. This large scatter in individual and daily measurements of the SW Fe flux can be the direct consequence of the patchiness of the sources of these ions which is concentrated along the meteor trails formed in the meltosphere.

Since the largest objects contribute most to the mass flux, while the number flux decreases with mass, one can expect a large variability (in time and in location) of meteoric material in the meltosphere and SW plasma. The large standard deviations of daily and monthly iron and silicon ion fluxes could possibly be the consequence of these combined effects.

The flux of small Sun-grazing comets may well contribute an even larger amount of mass to the meltosphere. However, since the mass of any of the Sun-grazing comets observed during the SMM mission is not determined, it is not possible to estimate how much mass these large bodies really contribute on average to the solar atmosphere. Therefore, at this stage one cannot exclude the possibility that small comets, which form a separate population of astronomical objects not of asteroidal origin, enhance, from time to time, the metallic ion abundances in the solar atmosphere and solar wind. The composition of these comets is not as well known as that of meteorites. If they would have retained enough nonrefractory material, these Sun-grazing comets (which are always seen moving toward the Sun and never outward) may contribute a supplementary amount of oxygen, hydrogen, and other elements to the corona. Of course, these more volatile elements are relatively less abundant in meteoroids of asteroidal origin. Note, however, that high FIP elements (like those of the CNO group) are present even in the latter meteoroids, but with a lower abundance. This means that a yet undetermined fraction of coronal and solar wind oxygen ions should not only be of cometary origin (in addition, of course, to those oxygen ions of photospheric origin), but some of them are of meteoritic origin as well.

Let us now compare  $FNFe_i (= 7.3 \times 10^{31} / fh \text{ Fe-ions } s^{-1})$  the total flux of iron ion in the SW and  $FNFe (= fh fl fm / \chi \cdot 3.34 \times 10^{31} \text{ Fe atoms } s^{-1})$ , the total iron atoms deposited in the meltosphere. From presumed values of  $fh$  (i.e., 2 to 3),  $f\theta$  (i.e., 1.2 to 2),  $fl$  (i.e.,  $\frac{1}{3}$  to  $\frac{1}{2}$ ),  $fm$  (i.e., 5 to 10),  $\chi$  (i.e., 1.2 to 2), one finds that the total correction factor  $ft = fh f\theta fl fm / \chi$  ranges between 2 and 25. The ratio

$$FNFe / FNFe_i = ft / (7.3 / 3.34) \quad (7)$$

can have any value between 0.9 and 10. This shows that within the degree of uncertainties of the measurements, the meteoric flux of Fe atoms into the meltosphere is equal and probably

larger than the flux of Fe ions carried out of the meltosphere by the SW.

If real, the excess of meteoric atoms deposited in the meltosphere could possibly diffuse down from the corona (where the expansion SW velocity has a very small subsonic value) into the photosphere through the chromosphere and transition region.

The most recent determination of average velocity and abundance of SW Si ions has been obtained from the *ISEE* ion composition instrument (ICI) by Bochsler (1989). From Figure 4 in that paper one can see that daily averages of Si ion flux at 1 AU vary between  $10^{7.8}$  and  $10^{8.8}$  Si ions  $\text{m}^{-2} \text{s}^{-1}$  (see also Bame *et al.* 1970, 1975). When the same correction factor are applied as for the Fe ions

$$\text{FNSii} = (1.8-18.0)10^{31}/f_h \text{ Si ions } \text{s}^{-1}. \quad (8)$$

Again this compares extremely well with the flux of Si atoms penetrating into the meltosphere; indeed the ratio

$$\text{FNSi}/\text{FNSii} = f_t/[3.72/(1.8-18)] \quad (9)$$

ranges then between the minimum and maximum values of 0.9 and 100. Since this ratio is most likely larger than unity, we suspect that a significant fraction of these meteoric Si atoms and ions diffuse downward into the photosphere, as meteoric elements do in Earth's atmosphere (Narcisi 1968; Gadsden 1968, 1970; Hunten 1981).

The remarkable agreement between the values of  $\text{FNFe}$  and  $\text{FNFei}$ , as well as between the values of  $\text{FNSi}$  and  $\text{FNSii}$ , are strong evidence that large meteoroids with masses ranging from 1 g to more than 1 t contribute significantly to enhance the coronal relative abundance of refractory (i.e., low FIP) elements in the solar corona.

Note that it can equally well be argued that this meteoric material is poor in volatiles (high FIP elements) or elements of the CNO group, and that observations quoted above show evidence of a smaller relative abundance of oxygen with respect to silicon (the element generally taken as a reference in meteoric abundance studies) in the solar corona as compared to the photosphere. Indeed, when silicon is taken as a reference, the solar corona and SW relative abundances of Fe and the other metallic ions compare well with those observed in chondrite meteorites (see Anders and Grevesse 1989).

The absence of enrichment of low FIP elements in fast speed streams originating from coronal holes, as recently found by Gloeckler *et al.* (1989) can also be explained in the framework of a meteoric source, either by a latitudinal or time variation of the inflow of meteoric material.

The large daily variability of the Fe and Si ion fluxes observed at 1 AU can indeed most naturally be explained as the consequence of the irregular nature of the injection of meteoroid showers into the meltosphere and deep solar corona.

#### V. HEAVY ION TEMPERATURES IN THE SOLAR WIND

When a neutral atom becomes ionized at a radial distance  $r$ , its velocity is equal or larger than the free-fall velocity:

$$v_{\text{ff}} = 617(R_{\text{S}}/r)^{1/2} \text{ km } \text{s}^{-1}. \quad (10)$$

As a consequence, the initial velocity of boiled-off meteoric atoms ranges between  $225 \text{ km } \text{s}^{-1}$  and  $600 \text{ km } \text{s}^{-1}$ , depending on the heliocentric distance where their first ionization took place within the meltosphere ( $r < 7.5 R_{\text{S}}$ ). This implies that the

initial velocities of meteoric ions are independent of their atomic mass,  $A$ ; their initial energies are then proportional to  $A$ . For instance, a proton of  $225 \text{ km } \text{s}^{-1}$  has an energy of 0.26 keV, while Si ions and Fe ions of the same velocity have energies equal to 7.4 keV and 15 keV, respectively. The deeper in the corona the first ionization of a meteoric atom occurs, the larger will be its initial velocity and its kinetic energy. As said above, a meteoric atom photoionized in the outer meltosphere has low  $Z/A$  and  $Z^2/A$  ratios so that it will continue to fall down toward the Sun, along the interplanetary magnetic field lines, until it gets highly ionized in the denser region of the solar corona.

This initial energy of meteoric ions is therefore significantly larger than the mean thermal energy of protons at typical coronal temperatures of  $1.0-1.6 \times 10^6 \text{ K}$  (i.e., 90–130 eV). Therefore, when a large flux of meteoric material showers into the solar corona, two different ion populations with different mean energies should be observed along a line of sight: (i) the hot meteoric ions which are almost monoenergetic and clustered along the new meteor trails, (ii) the thermalized heavy ions and ambient protons mainly of solar origin forming the background plasma.

The colder ions of solar chromospheric origin form the bulk of the coronal plasma and draw energy from the injected hotter meteoric ions diffusing through this colder coronal background. The double population of heavy ions should show up in Doppler profiles of faint coronal lines emitted by these ions. The hot ions should broaden the wings of the spectral emission lines as actually observed (see Billings 1963).

Along the cylindrical volume element surrounding the meteoroid trajectories in the meltosphere, the initial velocities of injected meteoric ions are nearly equal to that of the parent atoms; the angles of incidence of these trajectories are spread around the direction of the interplanetary magnetic field; at a given altitude, these initial velocities are almost all equal to the free-fall speed,  $v_{\text{ff}}$ : the dispersion of the initial velocities should be relatively narrow ( $\pm 20 \text{ km } \text{s}^{-1}$ ). The components of this initial velocity perpendicular and parallel to the local magnetic field direction determine (i) the Larmor gyroradii of the ions and (ii) their pitch angles.

The perpendicular components of the velocities of meteoric atoms and ions along a line of sight are spread between  $-v_{\text{ff}}$  and  $+v_{\text{ff}}$ , where  $v_{\text{ff}}$  is given by equation (10) for all radial distances,  $r$ , below the point of observation. When projected along the line of sight, the velocities of these particles have a distribution with a maximum at  $v_s = 0$ . The Doppler shifts of the photons emitted by these heavy ions have a distribution with a maximum corresponding to zero line-of-sight velocity and a dispersion corresponding to velocities proportional to  $v_{\text{ff}}$ . Furthermore, the half-width of these wings should vary with radial distance approximately as  $r^{-1/2}$ , i.e., like the variation with altitude of the free-fall velocity,  $v_{\text{ff}}$ , given in equation (10).

Since the velocity distribution of newly injected meteoric ions in the corona is characterized by a dispersion which is independent of their atomic masses,  $A$ , their characteristic temperature is proportional to  $A$ . Since their energy is rather high, their Coulomb collision cross section is significantly reduced compared to that of the colder thermalized ions. Therefore, their characteristic energy dispersion should be nearly preserved when they escape out of the solar corona. If the background SW density is not too large between the corona and 1 AU, these hot heavy ions of meteoric origin will not experience

significant energy transfer Coulomb collisions and should therefore have characteristic temperatures which are proportional to their atomic masses. This is precisely what is consistently observed (Feynman 1975; Neugebauer 1981; Schmidt *et al.* 1980; Ogilvie *et al.* 1980; Geiss and Bochsler 1986, and Bochsler, Geiss, and Joos 1985).

The expansion velocity of Fe and Si ions has also been found to be larger than that of the SW protons (Neugebauer 1976; Ipavich *et al.* 1986; Schmid, Bochsler, and Geiss 1987; Bochsler 1989). These observations are consistent with the meteoric origin of these ions. Indeed, as has been noted above their initial velocities in the solar corona is already larger than the quiet and cool SW flow velocity. There is a tendency for these hotter heavy ions of meteoric origin to run away into the interplanetary medium with larger average bulk speeds than the colder SW protons which are mainly of photospheric origin and less energetic.

But the observed differences between the bulk speed of hot heavy ions and the SW protons rarely exceeds  $+100 \text{ km s}^{-1}$ . Indeed, momentum transfer Coulomb collisions tend to slow down the outward stream of heavy ions and make it become equal to that of the background protons (the Coulomb cross section is proportional to the square of the charges of the interacting ions and inversely proportional to the square of their relative energy). Since the Coulomb cross section for momentum transfer is larger than for energy transfer, one expects the differences in bulk speeds between the heavy ion species and protons to be smaller than the differences between their temperatures (Neugebauer 1976).

Since the SW oxygen ions observed at 1 AU are also moving faster than the protons and since they also have a higher temperature than the hydrogen ions, it can be inferred that part of these ions are also of meteoric origin. Their smaller relative abundance being due (i) to their smaller abundance in meteoric material, (ii) to different mass-to-charge ratio and fractionation

rate, and (iii) differentiated drag forces in the coronal plasma. These effects will be discussed in a separate paper as well as the helium abundance in the corona and SW.

## VI. CONCLUSIONS

Coronal and SW observations can be accounted for by the fact that the solar corona contains a significant abundance of ions of meteoric origin in addition to plasma of photospheric and chromospheric origin.

The observed SW outflow of minor heavy ions is shown to be equal to (and probably even smaller than) the inflow of the meteoric material penetrating in the meltosphere of the Sun. The high temperatures of these heavy ions observed in the corona and SW are consistent with a meteoric source for these particles.

Furthermore, the observed differences of bulk velocities between the Fe or Si ions and SW protons may likely be explained by the meteoric origin of these heavy ions.

More detailed quantitative models are now being considered to test this explanation and its far-reaching consequences.

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## APPENDIX A

### FLUX OF ASTEROIDAL METEOROIDS AS A FUNCTION OF HELIOCENTRIC DISTANCE

Given the flux of meteoroids flowing into a sphere of a radius  $r_e = 1 \text{ AU}$ , we determine here what is the flux penetrating into a smaller sphere of radius  $r_m = 7.5 R_S$ , considering that most meteoroids observed at Earth originate in the asteroid belt where they have their apogee at a mean radial distance  $r_0 = 2.7 \text{ AU}$ .

From the equations of conservation of energy and angular momentum of particles moving along elliptic orbits in the gravitational field of the Sun, one obtains the following relationships between the velocities  $v_0$  and  $v$  respectively at  $r_0$  and  $r$ :

$$r_0 v_0 \sin \theta_0 = r v \sin \theta \quad (\text{A1})$$

$$v_0^2 = v^2 + v_{ff}^2(1 - r_0/r), \quad (\text{A2})$$

where  $\theta_0$  and  $\theta$  are, respectively, at  $r_0$  and  $r$ , the angles between the velocity vectors and the radial direction;  $v_{ff}$  is the free-fall velocity at radial distance  $r_0$ .

As in the exospheric theory developed by Lemaire and Scherer (1971, 1973) for the polar and solar winds, it is useful to introduce new dimensionless variables:  $y = r_0/r$ ,  $V_0 = v_0/v_{ff}$ , and  $V = v/v_{ff}$ . Any particle with a velocity corresponding to  $0 < V_0 < V_{0m}$  and whose angle  $\theta_0$  is in the interval  $[0, 180^\circ]$  will penetrate into the sphere of radius  $r$  or  $y$ , where

$$V_{0m} = 1/(1 + y)^{1/2} \quad (\text{A3})$$

For these particles  $\theta$  is smaller than  $\theta_0$ ; their contribution to the flux calculated below will be the dominant one.

Similarly, any particle with a velocity corresponding to  $V_{0m} < V_0 < 1$ , and whose angle  $\theta_0$  is in the intervals  $[0, \theta_{0m}]$   $[180^\circ - \theta_{0m}, 180^\circ]$ , will penetrate into the sphere of radius  $r$  or  $y$ , where

$$\theta_{0m} = \arcsin [(V_0^2 - 1 + y)^{1/2}/yV_0]. \quad (\text{A4})$$

Finally, any particle with a velocity corresponding to  $1 < V_0 < \infty$ , and whose angle  $\theta_0$  is in the interval  $[180^\circ - \theta_{0m}, 180^\circ]$  will penetrate into the sphere of radius  $r$  or  $y$ . All other inward or outward moving particles fail to enter the sphere of radius  $r$ .

TABLE 1  
RATIO BETWEEN THE ASTEROIDAL METEOROID FLUXES AT  
THE DISTANCE OF THE MELTOSPHERE<sup>a</sup> AND  
AT 1 AU

$r_0$ (AU)	$\Delta r_0$ (AU)	$\beta$	$fr = J(r_m)/J(r_e)$
2.0 .....	0.11	325	0.996
	0.52	15	0.22
	0.70	8	0.13
	2.00	1	0.04
	3.70	0.29	0.02
2.7 .....	0.11	590	0.9995
	0.52	27	0.30
	0.70	15	0.18
	2.00	1.7	0.05
	3.70	0.53	0.03
4.0 .....	0.11	1300	1.00
	0.52	60	0.40
	0.70	33	0.24
	2.00	4	0.06
	3.70	1.17	0.04

<sup>a</sup>  $r = 7.5 R_S$ .

For simplicity let us assume that  $f_0(V_0, \varphi_0, \theta_0; r_0)$ , the velocity distribution of the large meteoroids at  $r_0$  is independent of their mass. Although this assumption is uncertain, it is not essential for the following demonstration. Let us also consider that asteroidal fragments are continuously scattered in all possible directions by a mechanism similar to that described by Zimmerman and Wetherill (1973); note that other potential gravitation and collisional scattering mechanisms are possible, but it is out of scope to review and discuss them here.

For the sake of simplicity and in order to obtain a first-order approximation for the flux of meteoroids reaching a sphere of smaller radius  $r$ , the velocity distribution  $f_0(V_0, \varphi_0, \theta_0; r_0)$  will be taken isotropically with respect to the angle  $\theta_0$ , and Maxwellian with respect to  $V_0$ :

$$f_0(V_0) = C \exp[-\beta V_0^2], \quad (\text{A5})$$

where  $\beta$  characterizes the half-width of the velocity distribution. Considering that this half-width may be as narrow as the difference,  $\Delta V_0$ , between the orbital velocities at the inner and outer edges of the asteroid belt:  $\beta = 1/\Delta V_0^2 = (r_0/\Delta r_0)^2$ , one obtains for  $\Delta r_0 = 3.7$  AU, a value of  $\beta$  equal to 0.53. But since most of asteroids are confined in a much narrower region of 0.7 AU in radial extent, a more likely and conservative value for  $\beta$  is 15.

The flux of meteoroids originating in the asteroid belt and flowing into the sphere of radius  $r$  is then given by the sum of three integrals corresponding to the three classes of orbits described above:

$$J(r) = S \int dv_0 \int v_0^3 f_0(V_0) \cos \theta_0 d\theta_0 \int \sin \varphi_0 d\varphi_0, \quad (\text{A6})$$

where,  $S$  is the surface of the spherical zone intersecting the asteroid belt at  $r = r_0$ . These three integrals can be evaluated over the velocity ranges and angular intervals corresponding to all the classes of particles reaching  $r = r_e$  and  $r_m$ .

Replacing  $f_0(V_0)$  by equation (A4) in equation (A6), and using equation (A1) to equation (A4) one obtains the following expression for  $J(r)$ :

$$J(r) = \alpha \{1 - (1 - 1/y^2) \exp[-\beta/(1 + y)] - (1 + \beta y)/(2y^2) \exp(-\beta)\}, \quad (\text{A7})$$

where  $\alpha$  is a constant that contains  $S$ ,  $C$ , and other numerical constants that can be estimated from the observed flux  $J(r_e)$  at the orbit of Earth.

However, since we need only to calculate the ratio of the fluxes  $J(r_m)/J(r_e) = fr$ , the precise value of  $\alpha$  is not required here. This ratio  $fr$  depends only on the value of  $\beta$ , all other quantities being fixed by  $r_0$ ,  $r_e$ , and  $r_m$ :  $y_e = r_0/r_e$  and  $y_m = r_0/r_m$ .

Table 1 gives the values of  $fr$  for  $r_e = 1$  AU,  $r_m = 7.5 R_S$ , and three values for  $r_0 = 2.0, 2.7$ , and  $4$  AU; the value of  $fr$  is calculated from equation (A7) for a range of values of  $\beta$  corresponding to different values of  $\Delta r_0$ .

In this paper we use the value  $fr = 0.18$  as a conservative estimate corresponding to  $\beta = 15$ , i.e.,  $r_0 = 2.7$  AU and  $\Delta r_0 = 0.7$  AU (see Table 1). However, larger values of  $fr$  could be expected if  $\beta$  would be larger than 15. A more comprehensive study of fireball observations would be required to determine more precisely  $\beta$  and the actual velocity distribution of these objects.

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J. LEMAIRE: Institut D'Aeronomie Spatiale, 3, Ave Circulaire, B-1180 Brussels, Belgium