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Original Investigations

The Behaviour of Minor Species in the Solar Wind*

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Abstract. The flow of minor species in the solar wind is considered on the basis of a model in which all species are heated in an arbitrary manner as they leave the Sun and the minor species interact with the background proton-electron plasma through the radial electric field associated with the latter and by means of Coulomb collisions. In order to produce satisfactory results in which the ions all move at more or less the same speed at the orbit of the Earth, it is necessary to introduce heating functions such that each species is given energy in proportion to its mass. Coulomb collisions are found to be important as a means of removing energy from the heavier species close to the Sun and bringing all species closer to thermal equilibrium at great distances from the Sun. Substantial velocity differences can occur between species, especially close to the Sun. Furthermore it is not difficult to construct solutions in which the bulk velocity of the helium ions exceeds that of the solar wind, as is often observed.

Key words: Coronal Heating – Solar Wind – Minor Species.

1. Introduction

The solar wind is a fully ionized plasma comprised mainly of protons, electrons and alpha particles, but also containing small amounts (less than about 0.1% by mass) of hevier elements which in most cases are not fully ionized. The relative abundance of helium to hydrogen ions varies from <1% to >25% by number, being on the average about 4%, which is significantly different from the photospheric ratio (Neugebauer and Snyder, 1966; Wolfe *et al.*, 1966; Hundhausen *et al.*, 1967a; Bame *et al.*, 1968; Ogilvie and Wilkerson, 1969; Robbins *et al.*, 1970; Formisano *et al.*, 1970; Danziger, 1970; Formisano and Moreno, 1971; Bame, 1972; Hirshberg, 1972, 1973; Hirshberg *et al.*, 1972, 1974). The relative abundances of heavier ions are also variable and differ from the expected photospheric abundances (Bame *et al.*, 1968, 1970; Bühler *et al.*, 1969; Geiss *et al.*, 1970a; Hundhausen, 1970; Bame, 1972).

In the vicinity of the Earth's orbit the plasma is usually not in thermal equilibrium. For example the electron temperature is typically of the order of $1—2 \times 10^5$ °K whereas the proton temperature is typically $10^4—10^5$ °K and on the average is about 4×10^4 °K (Strong *et al.*, 1966; Neugebauer and Snyder, 1966; Hundhausen *et al.*, 1967abc, 1970; Coon, 1968). Furthermore the proton thermal distribution is usually anisotropic with the parallel temperature generally exceeding the perpendicular

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* Dedicated to Professor Georg Pfotzer with best wishes for his 65th anniversary.

temperature. There is evidence that the thermal velocities of different species are often comparable, so the temperatures of the species are then roughly proportional to their atomic mass (Neugebauer and Snyder, 1966; Wolfe *et al.*, 1966; Hundhausen *et al.*, 1967; Ogilvie and Wilkerson, 1969; Robbins *et al.*, 1970; Formisano *et al.*, 1970). Furthermore it has recently been confirmed that the bulk velocity of the helium component commonly exceeds that of the protons by as much as 5—10% (Formisano *et al.*, 1970; Bollea *et al.*, 1972; Asbridge *et al.*, 1973; Ogilvie and Zwally, 1972; Hirshberg *et al.*, 1974). There is no reason not to expect that similar velocity differences are prevalent in the case of other species.

In this paper we describe the results of calculations based on a model for a multi-fluid solar wind designed to elucidate some of the phenomena outlined above. The model differs in some essential aspects from previous models discussed by Jokipii (1966), Geiss *et al.* (1970b); Nakada (1970) and Alloucherie (1970). In contrast to the earlier work we make no assumptions concerning the temperatures of the different components of the solar wind, but instead use complete equations of motion for each species, including an energy equation. Heat sources are invoked as a means of simulating the presumed heating of the corona resulting from the damping of hydromagnetic or other waves (e.g. Konyukov, 1967; Holzer and Axford, 1969, 1970; Hartle and Barnes, 1970). We have also taken into account the effects of Coulomb collisions between protons and heavier ions which lead to an exchange of energy as well as momentum.

We have been forced to make several simplifying assumptions, which will need to be considered more carefully in future work. Firstly, we assume (as have most other workers) that the solar wind is essentially a proton-electron plasma and that the concentration of heavier ions is sufficiently small for them to have no significant effect on the flow of the protons. This approach is advisable in view of the complexity of the self-consistent multi-fluid problem (see for example, the three-fluid model considered by Yeh, 1970). Each species is therefore considered to be a separate fluid satisfying conservation equations for mass, momentum and energy, and interacting with the dominant proton-electron plasma only as a consequence of the electric field associated with the latter and of Coulomb collisions between protons and heavier ions. The fact that the treatment is not self-consistent may lead to substantial errors, although it is difficult to estimate these at the present time.

The effects of viscosity and of heat conduction by the protons and heavier ions are ignored, but these are probably not important. The state of ionization of heavier ions is assumed to be constant; however since this must depend on the electron temperature (which as a consequence of thermal conduction should be fairly uniform close to the Sun), the neglect of possible changes in the state of ionization of heavier ions should not be serious. We have neglected for the present the effects of a non-radial magnetic field and of solar rotation, although these may be important especially as far as the heavy ions are concerned. Our treatment of the process(es) by which hydromagnetic or other waves heat the solar wind is also rather arbitrary, and we have neglected to take into account the effects of momentum absorption which should in fact be related in a self-consistent way to the absorption of energy. Finally, although we have assumed that only Coulomb collisions and the large scale electric field couple the minor species with the dominant proton-electron plasma, it is certainly possible that turbulence generated by instabilities may play an important role in this respect.

2. *The Background Solar Wind*

In order to determine the behaviour of minor species, it is necessary to know the flow speed (u), the density (p) and the temperature (T) of the background proton-electron plasma and also the radial electric field (E). For convenience we make use of the simple solution for a single-fluid solar wind flow with heat addition discussed by Holzer and Axford (1970). [However it should be noted that a two-fluid treatment allowing for heat addition (e.g. Leer and Axford, 1972) would not be a great deal more difficult to handle.] The appropriate equations for steady, spherically-symmetric, radial flow are as follows:

$$\varrho u r^2 = F , \tag{1}$$

$$u \frac{du}{dr} + \frac{1}{\varrho} \frac{dp}{dr} + \frac{G\mu}{r^2} = 0 , \tag{2}$$

$$\frac{1}{r^2} \frac{d}{dr} \left[\varrho u r^2 \left(\frac{1}{2} u^2 + \frac{5}{2} \frac{p}{\varrho} - \frac{G\mu}{r} \right) \right] = Q(r) , \tag{3}$$

where r is the radial distance from the center of the sun, p is the plasma pressure, G is the gravitational constant, μ is the mass of the sun, F is the mass flux per steradian and $Q(r)$ is a term representing addition of energy to the flow resulting from the damping of hydromagnetic or other waves. The radial electric field $E(r)$, assuming the proton and electron temperatures are equal, is given by

$$E = \frac{m}{2e} \left(u \frac{du}{dr} + \frac{G\mu}{r^2} \right) , \tag{4}$$

where m is the mass and e the charge of a proton.

It is convenient to express these equations in terms of the Mach number $M = u / \sqrt{(5p/3\varrho)}$ and a dimensionless form of the radial distance $\xi = r/r_0$, where r_0 is the radius of the sun. By this means it is possible to reduce Eqs. (1), (2) and (3) to a single first order differential equation for M^2:

$$(M^2 - 1) \frac{dM^2}{d\xi} = \frac{2 M^2 (M^2 + 3)}{3 H(\xi)} \left\{ \frac{2 \mathscr{E}_0}{\xi} + \frac{2}{\xi} \int_1^\xi P(\xi')\, d\xi' - \frac{1}{6} (5 M^2 + 3) P(\xi) \right\} . \tag{5}$$

Here $P(\xi) = r_0^3 \xi^2 Q(\xi) / F$ and $H(\xi)$ is the stagnation enthalpy per unit mass:

$$H(\xi) = \frac{1}{2} u^2 + 5p/2\varrho = \mathscr{E}_0 + \int_1^\xi P(\xi')\, d\xi' + G\mu / r_0 \xi , \tag{6}$$

and $\mathscr{E}(\xi)$ is the total energy per unit mass:

$$\mathscr{E}(\xi) = \mathscr{E}_0 + \int_1^\xi P(\xi')\, d\xi' = \frac{1}{2} u_0^2 + 5p_0/2\varrho_0 - G\mu/r_0 + \int_1^\xi P(\xi')\, d\xi' . \tag{7}$$

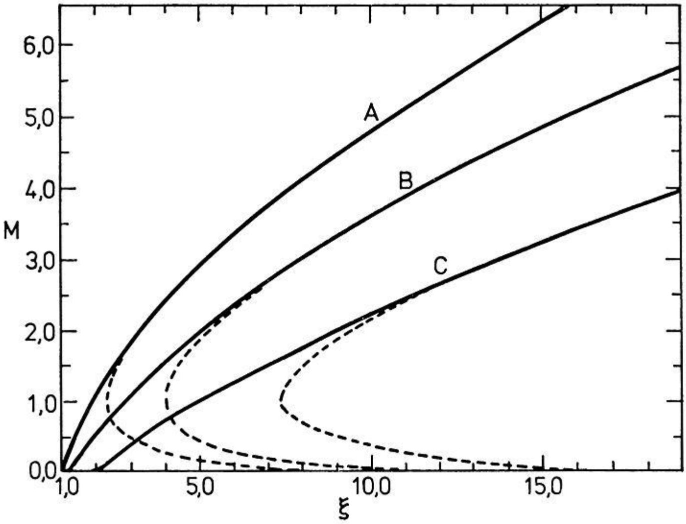

Fig. 1. Mach number versus radial distance for parameters representative of typical solar wind conditions. For curve A, $\mathscr{E}_o = -1.2 \times 10^{27}$ eV g^{-1}, $F = 1.6 \times 10^{11}$ g sec^{-1}, $Q = 1.23 \times 10^8$ eV cm^{-3}sec^{-1}, and $\beta = 4$. For curves B and C, $\mathscr{E}_o$ and F have the same values as for curve A, but Q has the values 5.41×10^6 eV cm^{-3}sec^{-1} and 4.51×10^5 eV cm^{-3}sec^{-1}, and β the values 2.0 and 1.0, respectively. The dashed curves represent solutions of the corresponding equations without heat addition but with total energies equal to the asymptotic energies obtained in the three cases considered. (See Holzer and Axford, 1970)

The subscript o refers to conditions at $r = r_o$ (i.e. $\xi = 1$). Eq. (5) has a singular point at $M^2 = 1$, $\xi = \xi_c$ where ξ_c is obtained from the condition that the term in braces on the right hand side should vanish:

$$\mathscr{E}_o + \int_1^{\xi_c} P(\xi')\, d\xi' + \frac{2}{3}\, \xi_c\, P(\xi_c) = 0\,. \tag{8}$$

We choose $Q = Q_o \exp(-\beta\,\xi)$ as a suitable form for the heating function, in which case it can be shown that the relation (8) defines a unique value $\xi = \xi_c > 1$ provided

$$\mathscr{E}(\infty) = \mathscr{E}_o + \int_1^{\infty} P(\xi')\, d\xi' > 0\,, \tag{9}$$

i.e. the total energy per unit mass at infinity is positive. It should be noted that under normal conditions in the solar corona $\mathscr{E}_o < 0$ and hence it is essential that energy should be given to the fluid by some means in order to permit it to escape from the Sun.

Examples of solutions of Eq. (5) are shown in Fig. 1 for various values of β and Q_o and with values of F and $\mathscr{E}_o$ corresponding to quiet solar conditions. These solutions pass through the singular point $M^2 = 1$, $\xi = \xi_c$ in each case, and are such that $M^2 = 0$ at $\xi = 1$ and $M^2 \to \infty$ as $\xi \to \infty$. They satisfy the requirement that $(p + \varrho u^2) \to 0$ as $r \to \infty$, which is appropriate to expansion of the solar corona into the relative vacuum of interstellar space. For the purpose of this paper, these solutions have been fitted by sixth degree polynomials, from which it is a simple matter to compute the speed, density and temperature of the proton-electron plasma and the electric field for use in treating the problem of the flow of minor species.

3. Equations of Motion for Minor Species

We treat each minor species as a separate fluid which interacts with the proton-electron plasma via Coulomb collisions and the radial electric field defined in Eq. (4), and which is heated as a result of wave damping in an arbitrary manner. With the same assumptions as made for the background solar wind flow and described in section 2 the equations governing the behaviour of a minor species (denoted by subscript i), having ionic charge Ze and mass Am are as follows:

$$\varrho_i u_i r^2 = F, \tag{10}$$

$$u_i \frac{du_i}{dr} + \frac{1}{\varrho_i} \frac{dp_i}{dr} + \frac{G\mu}{r^2} = \frac{Ze\,\mathrm{E}}{Am} + C_i, \tag{11}$$

$$\frac{1}{r^2} \frac{d}{dr} \left\{ \varrho_i u_i r^2 \left(\frac{1}{2} u_i^2 + \frac{5p_i}{2\varrho_i} - \frac{G\mu}{r} + \frac{Ze\,\phi}{Am} \right) \right\} = Q_i + Q_i' + \varrho_i u_i C_i, \tag{12}$$

where $\phi = -\int_{r_0}^{r} E(r')\, dr'$ and Q_i is the rate of heating of the i-species by wave damping.

The term C_i on the right of Eq. (11) represents the effects of friction (i.e. bulk momentum exchange) due to Coulomb interactions between the proton gas and the i-species. Q_i' is the corresponding rate at which energy is exchanged. According to Burgers (1969), for Maxwellian fluids

$$C_i = \left(\frac{8\pi e^4 \, ln\,\Lambda}{m^3} \right) \frac{Z^2}{A^2} (A+1)\, \varrho \, \frac{\Phi(v/\alpha)}{\alpha}, \tag{13}$$

$$Q_i' = \left(\frac{16\pi^{\frac{1}{2}} e^4 \, ln\,\Lambda}{m^4} \right) \frac{Z^2}{A^2} \varrho_i \varrho \, \frac{\exp(-v^2/\alpha^2)}{\alpha^3} \, k(T - T_i), \tag{14}$$

where $\alpha^2 = 2k(T_i/A + T_p)/m$, k is Boltzmann's constant, $v = (u - u_i)$, $\ln \Lambda \approx 22$ and $\Phi(\varkappa) = \{\psi(\varkappa) - \varkappa\psi'(\varkappa)\}/2\varkappa^2$ with $\psi(\varkappa)$ being the error function. T_p and T_i are the temperatures of the protons and the i-species ions, respectively.

As before, we express the equations of motion in terms of the Mach number for the species concerned, viz. $M_i = u_i/\sqrt{(5p_i/3\varrho_i)}$:

$$\begin{aligned}(M_i^2 - 1)\frac{dM_i^2}{d\xi} = \frac{2M_i^2(M_i^2+3)}{3H_i(\xi)} \Bigg[&\frac{2}{\xi} \left\{ \mathscr{E}_{oi} + \int_1^{\xi} (P_i(\xi') + P_i'(\xi') + C_i(\xi'))\, d\xi' \right. \\ &\left. - \frac{Ze\,\phi(\xi)}{Am} \right\} + 2r_o \left\{ \frac{Ze\,E(\xi)}{Am} + C_i(\xi) \right\} \\ &- \frac{1}{6}(5M_i^2 + 3)\{P_i(\xi) + P_i'(\xi)\} \Bigg],\end{aligned} \tag{15}$$

where

$$H_i(\xi) = \mathscr{E}_{oi} + \int_1^{\xi} (P_i(\xi') + P_i'(\xi') + C_i(\xi'))\, d\xi' - \frac{Ze\,\phi(\xi)}{Am} + \frac{G\mu}{r_o\,\xi}, \quad (16)$$

and $P_i(\xi) = r_o^3 \xi^2 Q_i(\xi)/F_i$, $P_i' = r_o^3 \xi^2 Q_i'(\xi)/F_i$. The quantity $\mathscr{E}_{oi}$ is the total energy per unit mass at $r = r_o$:

$$\mathscr{E}_{oi} = \frac{1}{2} u_{oi}^2 + \frac{5}{2} p_{oi}/\varrho_{oi} - G\mu(r_o)\,. \quad (17)$$

Eq. (15) has a singular point where $M_i^2 = 1$ and $\xi = \xi_{ci}$, ξ_{ci} being determined from the condition that the term on the right in square brackets should vanish:

$$\frac{2}{\xi_{ci}} \left\{ H_i(\xi_{ci}) - \frac{G\mu}{r_o\,\xi_{ci}} \right\} + 2 r_o \left\{ \frac{Ze\,E(\xi_{ci})}{Am} + C_i(\xi_{ci}) \right\} = \frac{4}{3} \{ P_i(\xi_{ci}) + P_i'(\xi_{ci}) \}\,. \quad (18)$$

This condition is effectively a relationship between the values of T_i and ξ at the point where $M_i = 1$ since $H_i(\xi) = \frac{5}{6} (M_i^2 + 3) k T_i$ and all the other quantities can be regarded as being functions of ξ, M_i^2 and T_i only. The relationship has the property that $dT_i/d\xi < 0$ for the simple exponential heating functions we have assumed, and its intersections with the actual temperature profiles are possible singular points. It is difficult to determine how many such singular points there are in general., however in the cases we have examined only one singular point (a saddle point permitting a subsonic-supersonic transition) appears to exist at relatively small values of ξ.

Solutions of Eq. (15) can be obtained by integrating towards $\xi = 1$ from a trial sonic point with the initial conditions determined from (18). It is found that in general a narrow range of values of ξ_c exists such that the integration proceeds smoothly towards $\xi = 1$, and for one value only, $\frac{1}{2} u^2 + 5p/2\varrho - G\mu/r \rightarrow \mathscr{E}_{oi}$ as $\xi \rightarrow 1$.

4. *Discussion of Solutions*

Our calculations have been limited to situations involving $^4He^{+2}$, $^{16}O^{+6}$, $^{20}Ne^{+8}$ and $^{56}Fe^{+12}$ as minor species. We have considered cases with $\beta = 1$ and $\beta = 2$, and with heat addition proportional to particle mass, to particle charge, and the same for all species. The proton flux at the orbit of Earth was usually taken to be 4.4×10^8 cm^{-2}sec^{-1}, corresponding to a number density of 10 cm^{-3} and a speed of 440 km sec^{-1}, but in addition some calculations were carried out with fluxes both larger and smaller than this value.

The results obtained were generally similar for $\beta = 1$ and $\beta = 2$, although in the latter case more solutions were "acceptable" in the sense that the speeds of all species were comparable to the speed of the background solar wind at large distances from

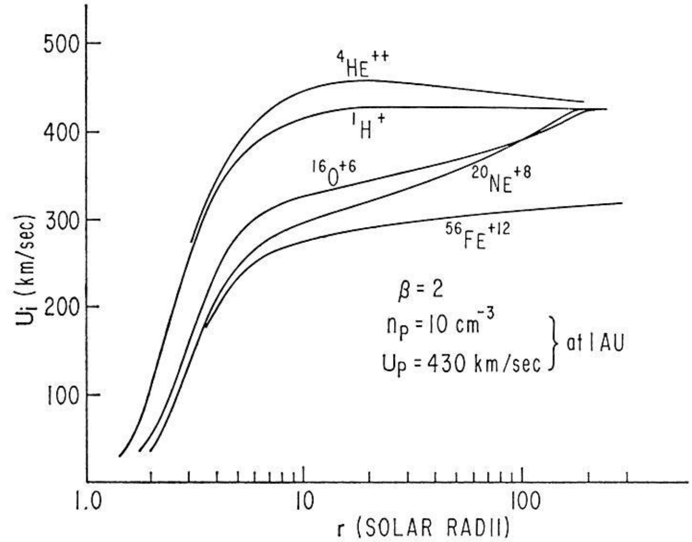

Fig. 2. Bulk speed of various species versus distance from the Sun for a case in which the solar wind flux is 4.3×10^8 cm^{-2}sec^{-1} and species are heated in proportion to their mass. Note that the bulk speed of the helium ions exceeds that of the background solar wind, whereas the $^{56}Fe^{+12}$ ions move considerably more slowly than the solar wind at 1 a.u. As a consequence of Coulomb collisions, $^{16}O^{+6}$ and $^{20}Ne^{+8}$ reach equilibrium with the background solar wind at the orbit of the Earth

the Sun. It is perhaps not surprising that the results are most sensitive to the form of the term representing heat addition. Indeed acceptable solutions were obtained only in cases where Q_i was taken to be proportional to A, so that if *all* interaction effects were neglected, each ion would behave more-or-less like an equivalent group of A protons moving together. Note however that the effect of the electric field is not the same for all species, and hence with $Q_i \propto Z$ it was found that the $^4He^{+2}$ gas attains a bulk speed of 360 km sec^{-1} at 1 a.u., while the speed of the $^{16}O^{+6}$ gas is 150 km sec^{-1} at the same distance. With $Q_i \propto A$, $\beta = 2$ and a proton flux of 4.4×10^8 cm^{-2} sec^{-1} at 1 a.u., the minor ions mostly move at about the same speed as the protons at 1 a.u., although the $^4He^{+2}$ speed is slightly greater and the $^{56}Fe^{+12}$ speed considerably smaller (see Fig. 2). The temperatures of the minor species are very large close to the sun in these circumstances (see Fig. 3), but except in the case of $^{56}Fe^{+12}$ they tend to approach the proton temperature at large distances from the Sun.

If the proton number density (and flux) is increased, thus increasing the importance of Coulomb collisions, it is found that the $^4He^{+2}$ speed no longer exceeds the proton speed at 1 a.u., and that the $^{56}Fe^{+12}$ speed is even further reduced (see Fig. 4). In contrast, if the proton flux is decreased, as shown in Fig. 5, the $^4He^{+2}$ gas moves considerably faster than the background solar wind at 1 a.u., while the heavier species (including $^{56}Fe^{+12}$) move essentially at the solar wind speed at 1 a.u. In general the temperatures of the minor species at 1 a.u. approach that of the protons if the speeds also approach the solar wind speed. Otherwise the minor species are much hotter than the protons.

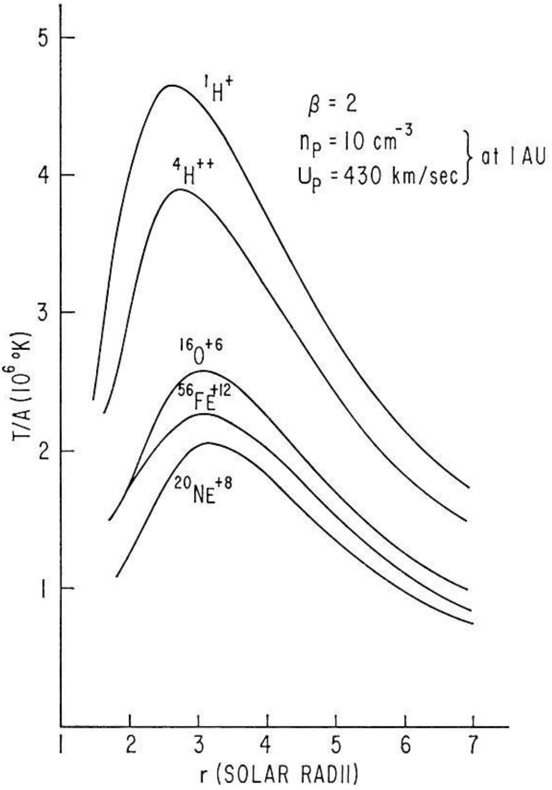

Fig. 3. Temperature distributions for various species as a function of distance from the Sun under the same conditions as described for Fig. 2

Unfortunately, due to the relative complexity of our model, we are unable to present any results in analytic form, as have Geiss *et al.* (1970b). However, as a consequence of our inclusion of (admittedly arbitrary) heat sources for minor species as well as protons and electrons, it must be expected that our results should differ from those obtained from a model in which the minor species escape from the Sun's gravitational field mainly as a result of friction due to Coulomb collisions (i.e. the term C_i on the right of Eq. (11)).

5. *Conclusions*

It is evident from the results described in the previous section that the nature of the heating mechanism is likely to play a very important role in determining the flow of minor species in the solar wind. Furthermore, in order to permit the heavier ions to escape from the Sun with reasonable speeds energy must be given preferentially to these species by whatever processes are involved in heating the corona. Our conclusion that the heating should be roughly proportional to particle mass is likely to remain valid even if we make more detailed calculations on the basis of refined models.

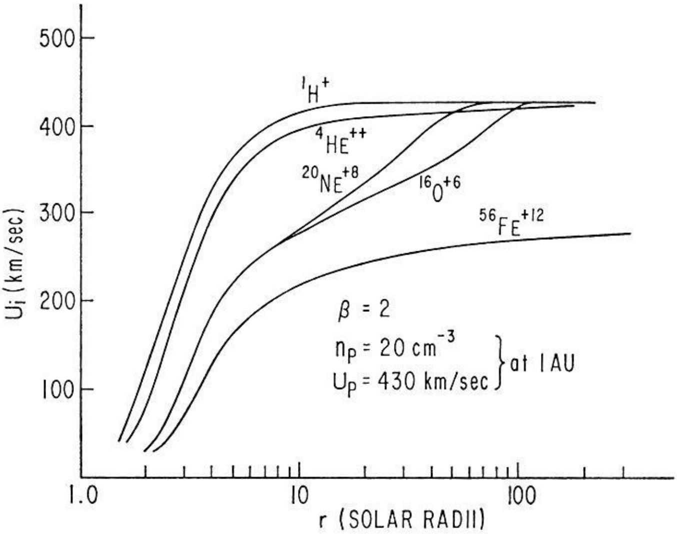

Fig. 4. Bulk speeds of various species versus distance from the Sun for a case in which the solar wind flux is 8.6×10^8 cm^{-2}sec^{-1}, and all ions are heated in proportion to their mass. In this case the bulk speed of the helium ions remains below that of the background solar wind but rapidly approaches it at the orbit of Earth and beyond. The bulk velocity of $^{56}Fe^{+12}$ is everywhere well below that of the background solar wind

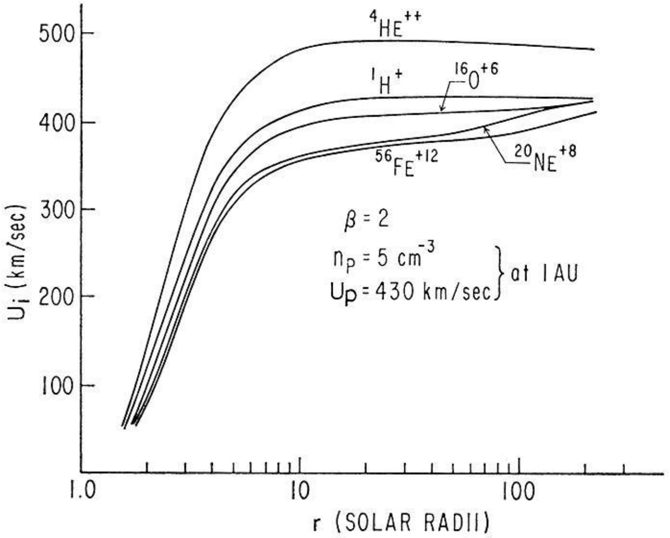

Fig. 5. Bulk speeds of various species versus distance from the Sun for a case in which the solar wind flux is 2.15×10^8 cm^{-2}sec^{-1} and all species are heated in proportion to their mass. In this case the bulk speed of the helium ions exceeds that of the background solar wind everywhere, being about 15% greater at the orbit of the Earth. As a consequence of reduced energy losses close to the Sun the $^{56}Fe^{+12}$ ions retain sufficient energy at large distances for their bulk velocity to remain close to that of the background solar wind; hence Coulomb collisions are sufficient to make the speeds approximately equal at a heliocentric distance of about 2 a.u.

As a consequence of preferential heating, the temperatures of heavy ions should in general exceed the solar wind proton temperature except perhaps at great distances from the Sun where Coulomb collisions may permit some species to come into thermal equilibrium with the protons.

In fact, it should be expected that different species should be heated differently although one cannot predict the nature of the differences without knowing the details of the mechanism(s) involved. For example, if heating results from the damping of hydromagnetic or other waves by resonant acceleration of particles, species with differing charge to mass ratios should certainly absorb different amounts of energy since they will resonate with different regions of the wave spectrum. The problem is extremely complicated however, since one must know, in addition to the wave spectrum, how each species moves relative to the background solar wind in order to determine which frequency range is important at any given location.

Our calculations serve to illustrate the effects of Coulomb collisions fairly clearly. The most important effect appears to be associated with heat transfer from heavy ions to the relatively cool proton gas close to the Sun. This is evident from the fact that the iron escapes more readily from the Sun when the proton flux is reduced (compare Fig. 2, 4 and 5). Secondly, it appears that species with velocities and temperatures that are not too different from those of the background protons approach thermal equilibrium and move together with the proton gas at large heliocentric distances purely as a result of Coulomb collisions. This is also evident in the Figures, especially with regard to the species $^{16}O^{+6}$ and $^{20}Ne^{+8}$.

The results described here suggest that there may be large velocity differences between minor ion species and the background solar wind, especially within a few tens of solar radii of the Sun. If this is indeed the case then it is essential that further calculations should take the presence of interplanetary electric and magnetic fields into account. Since all particles must move along magnetic field lines (considered to be co-rotating with the Sun), species which do not move at exactly the same speed as the protons cannot move radially (even if we neglect any tendency of the protons themselves to co-rotate). Accordingly, centrifugal effects must be important, especially for the heavier species. This should lead to some variation in the nature of the solar wind with heliolatitude as far as minor species are concerned.

Finally, we wish to draw attention to a basic shortcoming of the model we have used here, both with regard to the background solar wind and the minor species. If wave energy is absorbed as we have assumed, and if the source of the waves is the Sun, then the wave momentum which is absorbed must also be taken into account. That is, there should be terms in Eqs. (2) and (11) representing the wave momentum absorbed by the fluids, and having forms which are consistent with the energy absorption terms in Eqs. (3) and (12).

We intend to extend this work, taking into account the effects of the interplanetary magnetic field and of momentum absorption in addition to heating. However, we expect that our general conclusions with regard to the effects of Coulomb collisions and the need for differential heating for minor species will not be drastically changed.

It should be noted that although a model such as this can suggest reasons for differences of velocity and temperature between various species in the solar wind it contains no mechanism by which the ratios of particle fluxes can be made to differ from the equivalent concentration ratios in the photosphere. Such effects can be explained only by invoking processes such as mixing at the corona-chromosphere interface (e.g. Delache, 1967; Jokipii, 1966; Nakada, 1969).

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References

Alloucherie, Y.: Diffusion of heavy ions in the solar corona. J. Geophys. Res. *75*, 6899—6914, 1970

Asbridge, J. R., Bame S. J., Feldman, W. C.: Variations in the helium component in the solar wind. Trans. Am. Geophys. Union *54*, 440, 1973

Bame, S. J.: Spacecraft observations of the solar wind composition. Proc. Asilomar Solar Wind Conf., NASA SP-308, 535, 1972

Bame, S. J., Asbridge, J. R., Hundhausen, A. J., and Montgomery, M. D.: Solar wind ions: $^{56}Fe^{+8}$ to $^{56}Fe^{+12}$, $^{28}Si^{+7}$, $^{28}Si^{+8}$, $^{28}Si^{+9}$, and $^{16}O^{+6}$. J. Geophys. Res. *75*, 6360, 1970

Bame, S. J., Hundhausen, A. J., Asbridge, J. R., Strong, I. B.: Solar wind ion composition. Phys. Rev. Letters *20*, 393, 1968

Bollea, D., Formisano, V., Hedgecock, D. C., Moreno, G., Palmiotto, F.: HEOS-1 helium observations in the solar wind. Pro. Asilomar Solar Wind Conf. NASA SP-308, 588, 1972

Bühler, F., Eberhardt, P., Geiss, J., Meister, J.: Apollo-11 solar wind composition experiments: First results. Sci. *166*, 1502, 1969

Burgers, J. M.: Flow equations for composite gases. New York and London: Academic Press 1969

Coon, J. H.: Solar wind observations. In Earth's Particles and Fields, ed. B. M. McCormac, 359, New York: Reinhold 1968

Danziger, I. J.: The cosmic abundance of helium. Ann. Rev. Astron. Astrophys. *8*, 161, 1970

Delache, P.: Contribution à l'étude de la zone de transition chromosphère-couronne. Ann. Astrophys. *30*, 827—860, 1967

Formisano, V., Moreno, G.: Helium and heavy ions in the solar wind. Riv. Nuovo Cim. *1*, 365 ,1971

Formisano, V., Palmiotto, F., Moreno, G.: Particle observations in the solar wind. Solar Phys. *15*, 479, 1970

Geiss, J., Eberhardt, P., Bühler, F., Meister, J., and Signer, P.: Apollo-11 and 12 solar wind composition experiments: fluxes of He and Ne isotopes. J. Geophys. Res. *75*, 5972, 1970a

Geiss, J., Hirt, P., Leutwyler, H.: On acceleration and motion of ions in corona and solar wind. Solar Phys. *12*, 458—483, 1970b

Hartle, R. E., Barnes, A.: Nonthermal heating in the two-fluid solar wind model. J. Geophys. Res. *75*, 6915—6931, 1970

Hirshberg, J.: Solar wind helium enhancements following major solar flares. Proc. Asilomar Solar Wind Conf. NASA SP-308, 582, 1972

Hirshberg, J.: Helium abundance of the Sun. Rev. Geophys. Space Phys. *11*, 115, 1973

Hirshberg, J., Asbridge, J. R., Robbins, D. E.: Velocity and flux dependence of the solar wind helium abundance. J. Geophys. Res. *77*, 3583, 1972

Hirshberg, J., Asbridge, J. R., Robbins, D. E.: The helium component of solar wind velocity streams. J. Geophys. Res. *79*, 934—938, 1974

Holzer, T. E., Axford, W. I.: The theory of stellar winds and related flows. Ann. Rev. Astron. Astrophys. *8*, 31—60, 1970

Hundhausen, A. J.: Composition and dynamics of the solar wind plasma, Rev. Geophys. Space Phys. *8*, 729—812, 1970

Hundhausen, A. J., Asbridge, J. R., Bame, S. J., Gilbert, H. E., Strong, I. B.: Vela-3 satellite observations of solar wind ions: a preliminary report. J. Geophys. Res. *72*, 87, 1967a

Hundhausen, A. J., Asbridge, J. R., Bame, S. J., and Strong, I. B.: Vela satellite observations of solar wind ions. J. Geophys. Res. *72*, 1979, 1967b

Hundhausen, A. J., Bame, S. J., Ness, N. F.: Solar wind thermal anisotropies, Vela-3 and Imp-3. J. Geophys. Res. *72*, 5265, 1967c

Hundhausen, A. J., Bame, S. J., Asbridge, J. R., Sydoriak, S. J.: Solar wind proton properties: Vela-3 observations from July 1965 to June 1967. J. Geophys. Res. *75*, 4643, 1970a

Jokipii, J. R.: Effects of diffusion on the composition of the solar corona and the solar wind. In: The solar wind, ch. XIV, ed. R. J. Mackin and M. Neugebauer, 215—218, New York: Pergamon Press 1966

Konyukov, M. V.: Parker's solar wind theory, II. Flow with a heat source depending on a point. Geomagnetizm: Aeronomiya *7*, 469—475, 1967

Leer, E., Axford, W. I.: A two-fluid solar wind model with anisotropic proton temperatures. Solar Phys. *23*, 238—250, 1972

Nakada, M. P.: A study of the composition of the solar corona and solar wind. Solar Phys. *14*, 457—479, 1970

Neugebauer, M., Snyder, C. W.: Mariner-2 observations of the solar wind, average properties. J. Geophys. Res. *71*, 4469, 1966

Ogilvie, K. W., Wilkerson, T. D.: Helium abundance in the solar wind. Solar Phys. *8*, 435, 1969

Ogilvie, K. W., Zwally, H. J.: Hydrogen and helium velocities in the solar wind. Solar Phys. *24*, 236, 1972

Robbins, D. E., Hundhausen, A. J., Bame, S. J.: Helium in the solar wind. J. Geophys. Res. *75*, 1178, 1970

Strong, I. B., Asbridge, J. R., Bame, S. J., Heckman, H. H., Hundhausen, A. J.: Measurements of proton temperatures in the solar wind. Phys. Rev. Letters *16*, 628, 1966

Wolfe, J. H., Silva, R. W., McKibbin, D. D., Mason, R. H.: The compositional, anisotropic and non-radial flow characteristics of the solar wind. J. Geophys. Res. *71*, 3329, 1966

Yeh, T.: A three-fluid model of the solar wind. Planetary Space Sci. *18*, 199, 1970

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