

ELEMENT SEPARATION BY UPWARD PROTON DRAG IN THE CHROMOSPHERE

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ABSTRACT

The extremely close collisional coupling between protons and heavy ions in the upper chromosphere suggests that proton drag is the main agent for ion-neutral separation there. We argue that a small upward drift of protons and electrons relative to the stationary neutral hydrogen component can explain the observed enrichment of elements with low first ionization potential (FIP) in the corona. The resulting abundances are determined by the ionization fractions of the different elements relative to that of hydrogen. We suggest that the required ambipolar flow may be induced by transient coronal heating leading to chromospheric evaporation. The model predicts that the FIP effect should be weak inside coronal holes, where most of the energy released in the corona is carried outward by the solar wind rather than being conducted downward as in closed magnetic regions and coronal plumes.

Subject headings: solar wind — Sun: abundances — Sun: chromosphere — Sun: corona — Sun: transition region

1. INTRODUCTION

Element abundances measured in the solar corona differ systematically from their photospheric values, depending on the susceptibility of each element to ionization. Whereas elements having high first ionization potential (FIP) retain their photospheric abundances relative to hydrogen, the easily ionized, low-FIP elements are enriched in the corona by a factor of order 4 (for observational reviews see Meyer 1985; Feldman 1992). The fractionation almost certainly takes place in the chromosphere, where the low-FIP elements are already ionized but the high-FIP ones are still neutral (Geiss 1982). Whatever process supplies plasma to the corona also appears to be extremely effective in separating ions from neutrals.

This Letter discusses the possible role of proton drag in the fractionation process. We suggest that the observed coronal abundances can be explained by the action of an upward ambipolar drift near the top of the chromosphere, such as might be induced by transient coronal heating.

2. PROTON DRAG IN THE CHROMOSPHERE

We consider a one-dimensional atmosphere in which the particle densities n , drift velocities v , partial pressures $p = nkT$, common temperature T , and vertical thermoelectric field E are functions of height z only. Subscripts s , p , and n will be used to denote the trace species (having charge number Z_s equal to 0 or 1), protons, and neutral hydrogen atoms, respectively. Neglecting inertial terms (since v_s is much less than the thermal speed), inelastic collisions, and interactions among the trace particles themselves, we may write the trace-species momentum equation in the form

$$v_s = \xi \left[C_{sp} v_p + C_{sn} v_n - C_{spn} (v_p - v_n) + \alpha_s n_s k \frac{dT}{dz} + Z_s e n_s E - \frac{dp_s}{dz} - \frac{GM_\odot m_s n_s}{R_\odot^2} \right] \quad (1)$$

(compare Fontenla & Avrett 1992), where the collisional coupling coefficients C_{sp} , C_{sn} , C_{spn} , and α_s are given in Geiss

& Bürgi (1986), and we define $\xi \equiv (C_{sp} + C_{sn})^{-1}$. An expression for the equilibrium electric field E in terms of the temperature and hydrogen ionization gradients may be found in Fontenla, Avrett, & Loeser (1993).

In evaluating the importance of the various contributions to the trace-species drift velocity, we note that the term involving C_{spn} (which corrects for the dependence of the collisional cross sections on the drift speeds) is negligible compared to the first-order momentum exchange terms proportional to C_{sp} and C_{sn} . Also, the thermoelectric field, which prevents a net flow of current, and the thermal force $\alpha_s n_s k (dT/dz)$, which drives ions to regions of higher temperature, will contribute significantly to v_s only in the steepest part of the transition region, where the temperature scale height becomes ~ 1 km.

In the upper chromosphere, where $T_4 \equiv T/(10^4 \text{ K}) \sim 1$ and $n_{p11} \equiv n_p/(10^{11} \text{ cm}^{-3}) \sim 1$, the dominant term in equation (1) will depend on whether the trace species is ionized ($s = i$) or neutral ($s = a$). For a singly ionized particle of atomic mass A , $C_{ip} \approx n_i m_i v_{ip}$, where $v_{ip} = 1.1 \times 10^5 \text{ s}^{-1} [A(A+1)]^{-1/2} T_4^{-3/2} n_{p11}$ (see Table A1 of Geiss & Bürgi 1986). Thus the drag exerted on the ion by protons exceeds the gravitational force, provided that

$$v_p > 0.25 \text{ cm s}^{-1} [A(A+1)]^{1/2} T_4^{3/2} / n_{p11}. \quad (2)$$

On the other hand, since $C_{in}/C_{ip} \approx 1.9 \times 10^{-3} T_4^{3/2} (n_n/n_p)$, the drag exerted on the ion by neutral H atoms can be neglected in comparison unless the hydrogen ionization fraction is very small.

For a neutral trace atom, $C_{ap} = n_a m_a v_{ap}$, where $v_{ap} = 2.6 \times 10^2 \text{ s}^{-1} \gamma_a^{1/2} [A(A+1)]^{-1/2} n_{p11}$ (see Table A1 of Geiss & Bürgi 1986; γ_a is the atomic polarizability in units of 10^{-24} cm^3). In this case, the proton drag on the neutral atom exceeds the gravitational force if

$$v_p > 1.1 \text{ m s}^{-1} [A(A+1)]^{1/2} / (\gamma_a^{1/2} n_{p11}). \quad (3)$$

In contrast to their overwhelming effect on heavy ions, the drag that protons exert on heavy neutrals is small and comparable to that exerted on the latter by neutral H: $C_{an}/C_{ap} \approx 0.23 r_{an}^2 \gamma_a^{-1/2} T_4^{1/2} (n_n/n_p)$, where $r_{an} \sim 2-3$ denotes the sum of

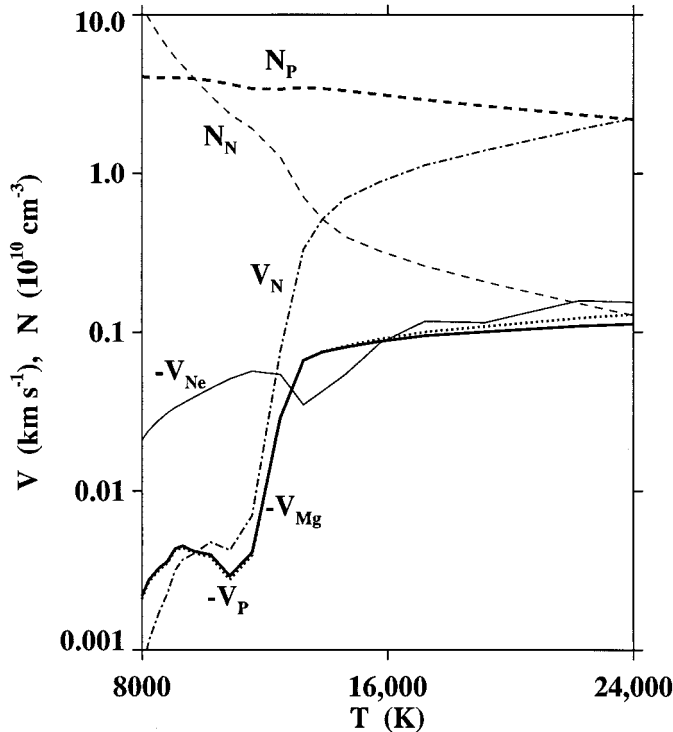


FIG. 1.—Downward drift velocities (in km s^{-1}) of Mg ions and Ne atoms at the base of a stationary transition region (model C of Fontenla et al. 1993). Also shown are the velocities and number densities (in units of 10^{10} cm^{-3}) of protons and neutral H atoms as a function of temperature $T(z)$. The downward-diffusing protons drag heavy ions with them; thus the Mg velocities (thick solid curve) practically coincide with the proton velocities (dotted curve). In contrast, the upward-diffusing H atoms (whose velocities are indicated by the dash-dotted curve) have essentially no effect on either of the trace species.

the radii of the colliding atoms in angstroms (see Table 1 of Marsch, von Steiger, & Bochsler 1995).

From the above estimates, it is apparent that even a very small proton drift velocity can act very efficiently to separate ions from neutrals in the upper chromosphere. It is instructive first to apply equation (1) to a hydrostatic model atmosphere of the kind developed by Fontenla, Avrett, & Loeser (1990, 1991, 1993; see also the discussion of Fontenla & Avrett 1992), in which the effect of ambipolar diffusion has been incorporated. In the Fontenla, Avrett, & Loeser (FAL) models, a downward flux of protons and electrons from the hot corona is balanced by an upward flux of neutral H atoms from the chromosphere; the ambipolar velocity is given in terms of the hydrogen ionization and temperature gradients by equations (3.1)–(3.3) in Fontenla et al. (1990). Figure 1 shows the drift velocities for singly ionized Mg (FIP = 7.6 eV) and neutral Ne (FIP = 21.6 eV) based on model C of Fontenla et al. (1993), where we have assumed that the Mg/H and Ne/H abundance ratios are independent of height. In the upper chromosphere and lower transition region, the Mg ions are dragged downward by the protons and $v_{\text{Mg}} \approx v_p < 0$. The Ne atoms drift downward as well, but mainly under the influence of gravity (last term in eq. [1]) rather than proton drag. In neither case does the thermal force contribute significantly to the drift velocity in the region $T \lesssim 24,000 \text{ K}$.

We conclude that stationary models which include the effect of ambipolar diffusion self-consistently cannot produce the observed enrichment of low-FIP elements in the corona,

because the protons that diffuse downward from the corona would prevent heavy ions from leaving the chromosphere. This result is perhaps not surprising, since such models do not address the question of how the bulk of the coronal material originates in the first place. It is apparent that an upward drift of protons and electrons would act very effectively to drag heavy ions out of the chromosphere. Such an ambipolar flow might develop in response to transient heating processes, in which energy is transferred preferentially to the ionized hydrogen component because of the dominance of proton-proton over proton-neutral H collisions. In hydrodynamic simulations in which a chromospheric gas is subjected to a flux of energetic electrons from the corona, upward velocities are found to develop throughout the heated upper chromosphere—where there is a buildup of excess pressure relative to that of the corona—unless the downward energy flux is extremely large (Fisher, Canfield, & McClymont 1985). Krall & Antiochos (1980) and Craig & McClymont (1981) have suggested that transient heating in coronal loops, followed by heat-flux-induced chromospheric evaporation, is the mechanism that supplies most of the coronal mass. Although the evaporation process has not, to our knowledge, been studied for a partially ionized chromospheric gas, it seems plausible to assume that the evaporating component should consist mainly of protons and electrons, leaving neutral H atoms behind.

In the remainder of this section we examine the consequences of an upward ambipolar flow in the chromosphere. To illustrate the effect of such a flow on the trace-species abundances, we suppose that the atmosphere is initially described by model P of Fontenla et al. (1993), but we arbitrarily set $v_n = 0$ and $v_p = 0.01v_{\text{th}}$, where $v_{\text{th}} \equiv (2kT/m_p)^{1/2}$ denotes the thermal velocity of the protons. We then allow the number densities of trace species and protons to evolve with time t according to the continuity equations

$$\frac{\partial n_s}{\partial t} = -\frac{\partial}{\partial z}(n_s v_s), \quad (4)$$

$$\frac{\partial n_p}{\partial t} = -\frac{\partial}{\partial z}(n_p v_p), \quad (5)$$

where v_s is given by equation (1). (For simplicity we neglect the small thermoelectric and thermal diffusion terms in eq. [1].) It is convenient to introduce a normalized abundance ratio or enrichment factor $a_s(z, t) \equiv (n_s/n_H)/(n_{s0}/n_{H0})$, where $n_H = n_p + n_n$ is the total hydrogen density, and photospheric values are labeled by a subscript zero. At $t = 0$, we require that $a_s(z, 0) = 1$, with $n_p(z, 0)$ given by model P. At the lower boundary $z = 0$ ($T \approx 7200 \text{ K}$), we impose the conditions $a_s(0, t) = 1$ (photospheric abundances) and $n_p(0, t) = n_p(0, 0)$ (constant proton flux); at the upper boundary $z = z_1 \approx 450 \text{ km}$ ($T \approx 100,000 \text{ K}$), we require that $\partial a_s/\partial z = 0$ for all t .

Figure 2 shows the Mg and Ne enrichment factors, a_{Mg} and a_{Ne} , plotted against temperature $T(z)$ at $t = 0, 5, 200,$ and 1000 s . Here we have assumed that magnesium is singly ionized whereas neon is neutral for $0 \leq z \leq z_1$. At the height where $T = 24,000 \text{ K}$, a_{Mg} jumps from 1 to 2.4 after only 5 s, and then increases slowly and almost linearly to a value of 4 over the next 1000 s. In contrast, a_{Ne} remains practically unchanged (although it falls slightly below 1). Because the chromospheric ions are so strongly coupled to the upward-drifting protons ($v_i \approx v_p$), these results depend only very weakly on the ion mass. Thus, for Fe ions ($A = 56$), we found

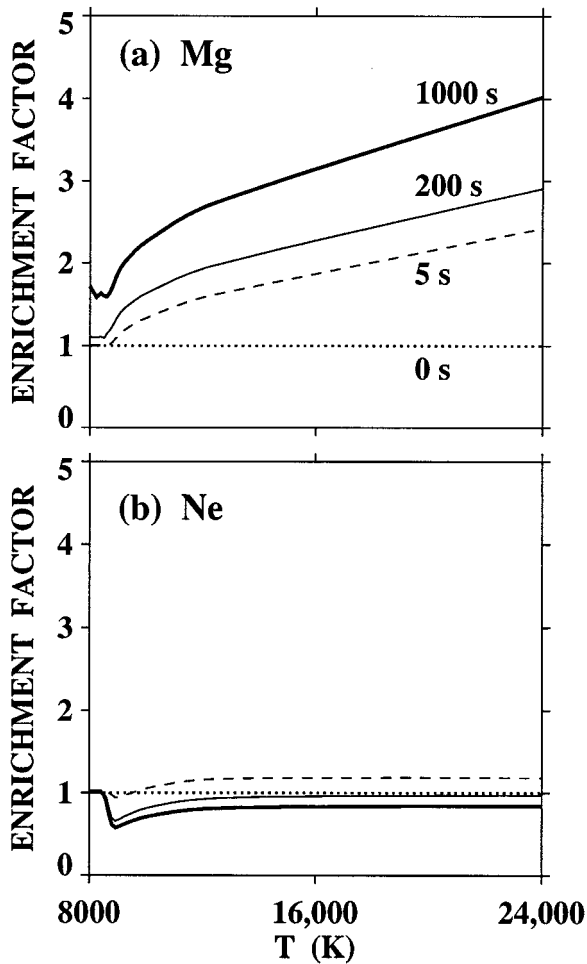


FIG. 2.—Time evolution of the normalized abundance distributions a_i of Mg ions and Ne atoms in the presence of an upward drift of protons, $v_p = 0.01v_{th}$ (where v_{th} is the proton thermal velocity).

that the time evolution of a_{Fe} was identical to that for a_{Mg} ($A = 24$). For neutral He atoms ($A = 4$), a_{He} fell to a value of 0.66 after 1000 s, as compared to 0.84 for Ne atoms ($A = 20$).

In the above illustrative example, the rate at which the enrichment factor for the ionized species, $a_i(z, t)$, increases at a given height is determined by the assumed proton velocity distribution, $v_p(z)$, and by the hydrogen ionization structure of the model atmosphere. The maximum enrichment is attained after a proton crossing time, $\tau_p \sim z_1/v_p \sim 4000$ s. However, it is evident that the calculation is not self-consistent, since the adopted flow field would modify the temperature and ionization structure of the atmosphere.

We can obtain a rough estimate of the net coronal enrichment factor for low-FIP elements by assuming that all protons—but no neutral H atoms—are evaporated from the upper chromosphere ($T \gtrsim 7000$ K) to fill the overlying coronal loop. Those elements that are fully singly ionized at these temperatures are then completely evacuated along with the protons, so that their normalized coronal abundances are given by

$$a_c \equiv \frac{n_{sc}/n_{Hc}}{n_{s0}/n_{H0}} = \frac{[\int_{z_1-h}^{z_1} n_s dz / \int_{z_1-h}^{z_1} n_p dz]}{[\int_{z_1-h}^{z_1} n_s dz / \int_{z_1-h}^{z_1} n_H dz]} = \frac{\int_{z_1-h}^{z_1} n_H dz}{\int_{z_1-h}^{z_1} n_p dz}, \quad (6)$$

where coronal values are indicated by the subscript c , and $h \sim v_{th}^2 R_{\odot}^2 / GM_{\odot} \sim 400$ km is a characteristic barometric scale height for the upper chromosphere. When applied to models A, C, F, and P of Fontenla et al. (1993), equation (6) yields $a_c \approx 5.1, 4.5, 5.3,$ and 9.5 , respectively. The variations in the derived enrichment factors reflect differences in the hydrogen ionization fractions in the different FAL models. In the case of model P, which has the highest densities at the base of the transition region, the rapid attenuation of the ionizing coronal radiation with depth leads to smaller values of n_p/n_H in the region $z_1 - h < z < z_1$, and thus to a relatively large value of a_c .

If proton drag is indeed the mechanism responsible for ion-neutral separation, those elements whose first ionization potentials are close to that of hydrogen should not be significantly enriched in the corona, since the proton drag affects only a fraction $n_i/(n_i + n_a) \approx n_p/n_H$ of these elements. Thus the coronal abundances are determined by the ionization fraction of each element relative to that of hydrogen, $[n_i/(n_i + n_a)]/(n_p/n_H)$, not by its absolute ionization fraction, $n_i/(n_i + n_a)$ (contrast the discussion in § IIIb of Meyer 1985).

3. SUMMARY AND DISCUSSION

We have argued that the action of a small ambipolar flow in the chromosphere, with the protons and electrons drifting upward with respect to the stationary neutral H component, can explain the observed enrichment of low-FIP elements in the corona. The resulting ion-neutral separation is extremely efficient because, at chromospheric temperatures, the cross section for proton-ion collisions is $\sim 10^3$ times larger than for proton-neutral collisions. The coronal abundance of each element depends on its FIP value relative to that of hydrogen (13.6 eV):

1. Low-FIP elements (e.g., Mg, Si, Ca, Fe) are fully singly ionized at temperatures where H is only partially ionized. These elements have drift velocities $v_i = v_p$ and are completely evacuated along with the protons. Their coronal abundance is independent of atomic mass and is determined by the inverse of the hydrogen ionization fraction within the upper ~ 400 km of the chromosphere.

2. Medium-FIP elements (e.g., C, N, O) have an ionization structure in the chromosphere similar to that of H. Because proton drag affects only a fraction n_p/n_H of these particles, their abundance relative to H remains unchanged between the photosphere and the corona.

3. High-FIP elements (e.g., He, Ne) are fully neutral at temperatures where H is partially ionized. Because the drag exerted by protons on neutral atoms is small and similar in magnitude to that exerted by neutral H, the presence of an ambipolar flow has relatively little effect on the abundance distribution of these elements.

The proton drag mechanism is thus consistent with the roughly bimodal or two-level structure of the observed abundances, where all elements having FIP $\lesssim 8$ eV show substantial coronal enrichment whereas those with FIP $\gtrsim 11$ eV show approximately the photospheric abundance (see, e.g., Fig. 2 in Feldman 1992).

As suggested in § 2, an upward ambipolar flow might be induced by transient coronal heating followed by evaporation of chromospheric gas. If all of the extra heat flux conducted down from the corona, $F_{c4} \equiv F_c / (10^4 \text{ ergs cm}^{-2} \text{ s}^{-1})$, were

converted into enthalpy, the resulting evaporative velocity v_{evap} would be given by

$$v_{\text{evap}}/v_{\text{th}} \sim (2F_c)/(5pv_{\text{th}}) \sim 0.01F_{c4}/(n_{p11}T_4^{3/2}) \quad (7)$$

(see Antiochos & Sturrock 1978). For a given heat flux, equation (7) gives an upper bound on the evaporative velocity, since it neglects the effect of radiative losses, which may be very significant in the case of “gentle” evaporation (Fisher et al. 1985). Our assumption in this Letter is that the evaporating gas consists mainly of protons and electrons, leaving behind a neutral hydrogen component in the chromosphere. A proper treatment of the separation process requires a self-consistent determination of the proton drift velocity and of the associated vertical electric fields, which we have not provided here.

It should be emphasized that the upward ambipolar flow and the accompanying ion-neutral separation are transient processes. Once the coronal densities become high enough for radiative losses to balance the increased heating rate, the evaporation stops and the coronal loop reaches a static equilibrium (Krall & Antiochos 1980; Craig & McClymont 1981), such as might be described by the FAL models. At this point, the coronal plasma is strongly enriched in low-FIP elements; subsequent evolution of the abundances would occur only on the very long diffusive timescales within the loop.

While a large heat flux into the chromosphere may be

induced by transient heating along *closed* magnetic loops, most of the energy deposited within *open* magnetic regions will be carried outward by the solar wind rather than being conducted downward (see, e.g., Withbroe 1988). The resulting absence of an upward ambipolar flow in the chromosphere may explain why the FIP effect is observed to be weak in high-speed streams (Geiss et al. 1995). An interesting exception is provided by polar plumes, which are magnetically open but appear to be unusually enriched in low-FIP elements like Mg ($a_{\text{Mg}} \sim 10$, according to Widing & Feldman 1992). To maintain the high gas densities observed in plumes, a large amount of energy must be dissipated very near the base of the plume (Wang 1994), perhaps as a result of magnetic reconnection between small bipoles and unipolar flux concentrations within coronal holes (see Wang & Sheeley 1995). Coronal plumes may thus provide an ideal illustration of chromospheric evaporation and the resulting ion-neutral separation.

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