DIFFUSION IN THE CHROMOSPHERE , AND THE COMPOSITION OF THE SOLAR CORONA AND ENERGETIC PARTICLES

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1. Introduction. Composition observations, (i) in the Solar Photosphere, and (ii) in the upper Transition Region (TR) and Corona (as well as in Solar Wind, SW, and Solar Energetic Particles, SEP) imply a change of composition of the solar atmosphere somewhere between the Photosphere and the upper TR ($T > 70000$ K) /7,8,25,26,46/. Heavy elements with First Ionization Potential (FIP) $>$ 9 eV (hereafter "high-FIP elements") are $\sim$4 times less abundant in the TR and Corona than in the Photosphere, as compared to both Hydrogen and heavy elements with lower FIP ("low-FIP elements").

These observations suggest a separation between neutral and ionized elements in a region where the high-FIP elements are mostly neutral, and the low-FIP elements ionized /25,26/. This occurs in the Chromosphere at altitudes above 600 km and below 2000 km above Photosphere (in the average quiet chromospheric model VAL C of /43/, used throughout this paper; fig. in /13/). Here we shall investigate whether diffusion processes can explain the observed change in composition.

2. The diffusion equation - Possible processes. When a gas mixture is subject to pressure, temperature or concentration gradients, or to selective forces, the gas components diffuse with respect to one another. This process, believed to be the reason for chemically peculiar A and B stars /e.g.28, 29,27,45/,has already been invoked to explain the He depletion in the Solar Wind /19,27,12,13/. Thermal diffusion in the TR has also been studied by /9,30,42,36,33,34,35,12,13/. The diffusion velocity for a gas with negligible abundance in a gas mixture may be written /6,10/

$$v_D = D \, (\nabla \ln c - k_p \nabla \ln p - k_T \nabla \ln T + F/kT)$$

where D is the diffusion coefficient, k_p the pressure diffusion factor (the $\nabla \ln p$ term is equivalent to the gravitational settling), k_T the thermal diffusion factor, F any selective forces (e.g. the radiative force), and c the concentration of the element.

In solar-type stars, the radiative acceleration is never large enough to compete with gravitational settling /28/ : the last term is negligible. In the chromospheric plateau, the temperature gradient is small, and the thermal term is also negligible. In the TR this term is large. However, all elements become 100 % ionized as T increases and the neutral-ionized element separation therefore cannot work there. As the concentration gradient is also generally small the diffusion velocity reduces to

$$v_D = D \, k_p \nabla \ln p \qquad \text{(gravitational settling term)}$$

In case of partial ionization of an element, the atoms spend part of their time in the various ionization states, and the resulting velocity may be written, in first approximation /29,1/, as $v_D = \eta_k \, v_{Dk}$, where η_k is the fraction of atoms in the ionization state k, and v_{Dk} the corresponding diffusion velocity.

If the elements have to diffuse across a magnetic field, the tansverse diffusion velocities of the ions are reduced by a factor of $(1+\omega^2 t_{col}^2)^{-1}$, where ω is the Larmor pulsation and t_{col} the characteristic time between two collisions /44,1/. If this factor is large, the transverse diffusion of ions is stopped, while the diffusion velocity of neutrals is unchanged. Thus the diffusion velocity of any element reduces to $v_D = \eta_n v_{Dn}$, where the index n refers to the neutral fraction.

Now, a large fraction of the solar surface is always covered with horizontal magnetic fields anchored in the network, from altitudes of $\sim$700 km /3,11,47,14,20,15/ up to above the Hα emitting region ($>$1500 km)/22,23/. Their typical intensity is $\sim$5 to 25 G. At a typical chromospheric temperature of $\sim$6000 K, the factor $\omega^2 t_{col}^2 \approx (4.6 \cdot 10^{13}/n_H)^2$ for ions becomes >1 for altitudes above $\sim$950 km , reaching values of $\sim$10 and $\sim$100 at $\sim$1100 and $\sim$1300 km. Above these altitudes, ions are effectively prevented from settling gravitationally, while neutrals are not.

3. The diffusion coefficient for neutral heavies. The diffusion coefficient D for neutral heavy nuclei of mass A on the dominant neutral H gas of the chromosphere can be expressed as /6,10/

$$D = 3\sqrt{2\pi}/16 \cdot 1/(n_H \cdot \sigma_{eff}) \cdot \sqrt{kT/m^*}$$

$$D = 4.287 \cdot 10^{18} \cdot 1/(n_H \cdot \sigma_{15}) \cdot \sqrt{T} \cdot \sqrt{1+1/A} \qquad (\mathrm{cm^2\ s^{-1}})$$

where n_H is the neutral H number density, T the temperature, $m^* = m_H A/(A+1) \approx m_H$ the effective mass of the interaction, σ_{eff} an "effective" collision cross section to be discussed below, and $\sigma_{15} = \sigma_{eff}$ in units of 10^{-15} cm^2. (The diffusion coefficient in ionized H is not very different; a small admixture of H^+ therefore does not affect the picture). The effective cross-section σ_{eff} can conveniently be expressed as $\sigma_{eff} = \pi r^{*2} \Omega^{(1,1)*}$, where r^* is some typical range of the interaction potential, and $\Omega^{(1,1)*}$ is the reduced collision integral describing the collision kinematics in the actual potential /6,10,32,41,31/.

The noble gas-H interaction potentials are characterized by a steep repulsive part and a tiny Van der Waals attractive well, whose depth $\epsilon \sim 10^{-3}$ eV is extremely small as compared to the mean thermal energy kT = 0.52 eV of the atoms in the $\sim$6000 K chromospheric gas (fig.1). So, only the repulsive part is important. The key information on these potentials comes from /5/, whose results have been by and large confirmed by more recent work /4,39, 40,17,38/. The repulsive part of the potential is most realistically fitted by a modified Buckingham-type potential /21,5,6,10/, and we have adopted the potential parameters of /5/. On this basis the collision integrals $\Omega^{(1,1)*}$ have been interpolated from the tables of /21/ (reproduced in /6,10/), yielding the effective cross-sections σ_{eff} given in Table 1 (or the effective collision radii r_{eff} such that $\sigma_{eff} = \pi r_{eff}^2$ shown in fig.1).

In reactive element-H potentials, the tiny Van der Waals minimum is completely swamped out by a$\sim$4 eV attractive well associated with the covalent bond (fig.1). The characteristics of these potentials have been derived from the data tabulated in /18/, using the formalism of /16/. They can be reasonably well fitted with Morse-type potentials /16,10/. The collision integrals $\Omega^{(1,1)*}$ have been interpolated from the tables of /37/ (reproduced in /10/), yielding the values of r_{eff} and σ_{eff} given in fig.1 and Table 1, the latter being $\sim$2.4 times as large as the σ_{eff}'s for noble gases.

Table 1

Interaction	He-H	Ne-H	Ar-H	C-H	N-H	O-H	S-H
σ_{eff} (10^{-15} cm^2)	0.89	1.05	1.45	2.84	2.17	2.35	3.27

4. The neutral element diffusion velocity and time scale. The diffusion velocity due to the gravitational force for neutral elements is /6,10/

$$v_D = D \cdot (A-1) \cdot \nabla(\ln p) \cdot \eta_n$$

$$v_D = 3.70 \cdot 10^{18} \cdot \sqrt{T} \cdot (A-1)\sqrt{1+1/A} / \sigma_{15} \cdot 1/n_H \cdot \nabla(\ln p) \cdot \eta_n \qquad (\mathrm{km/day})$$

where we have inserted D and n_H is in cm^{-3} and $\nabla(\ln p)$ in cm^{-1}. This velocity has been evaluated in the framework of model VAL C /43/. η_n is close to 1 for most high-FIP elements up to $x \approx 1900$ km (see fig. in /13/), except for C (and probably S) for which ionization reduces the diffusion velocity by factors up to $\sim$2.5 within the chromospheric plateau. Fig.2 shows the calculated v_D's vs.

altitude x, for the two extreme elements Ar and C. All other high-FIP elements have intermediate diffusion velocities.

From these velocities, we derive for each element A diffusion time scales $t_{D,A}(x) = N_H/(S_\odot v_{D,A}(x) \cdot n_H(x))$ /2/. This time is the time needed for a mass of N_H H-atoms above an altitude x, assumed completely mixed, to be depleted in atoms A by a factor of 1/e by downward diffusion at its base x ($S_\odot$ = solar surface area). These diffusion times t_D are plotted vs. altitude x in fig.3, for Ar and C.

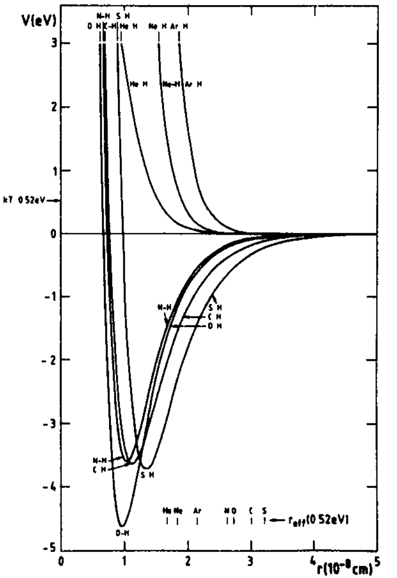


Fig.1

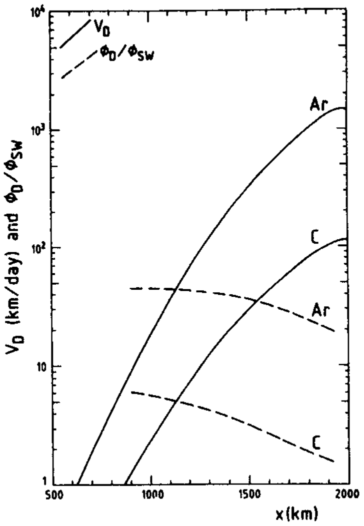


Fig.2

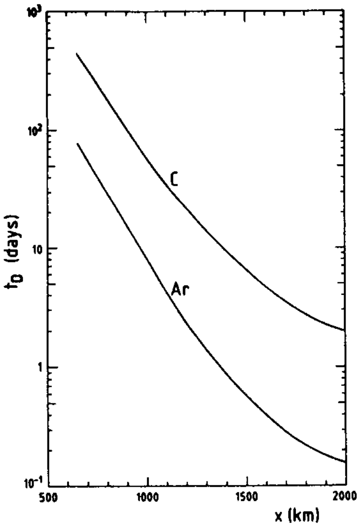
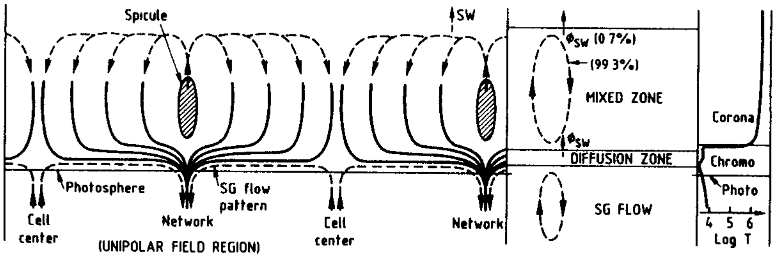


Fig.3

5. Discussion - A tentative scheme. The surface of the quiet Sun at altitudes of ~700 to 2000 km is believed to be largely covered, above the Supergranulation (SG) cells, by horizontal magnetic fields of intensity ~5 to 25 G, whose energy density exceeds that of the gas above ~1000 km (fig.4) /3,11,47, 14,20,15,22,23/. Above ~1000 km, the gas may therefore be stabilized by the field, and we may have in the chromospheric plateau a "diffusion region" with an horizontal field, which remains stable, isolated from lower lying material, over some unknown time scale τ. Gravitational settlement of heavy neutrals takes place there, but the horizontal field acts as a filter against ions. Starting in the upper Chromosphere above the network (SG boundaries), spicules are probably the major upward carrier of material from Chromosphere into Corona. Almost all the material they lift later falls back, either in the spicule itself, or as a rain along the more vertical configuration of the field at higher altitudes (fig.4). Only 0.7 % of it leaves the system in the form of SW /above ref./. Above the quiet "diffusion region" at altitude x, we therefore have an apparently fully "mixed region" comprizing the entire TR and Corona (fig.4). The material leaving the "mixed zone" as SW (flux $\phi_{SW,H}$) is treated as constantly replenished by fresh matter from the undelying "diffusion region" at an average effective velocity $U(x) = \phi_{SW,H}/n_H(x)$, in a steady state fashion lasting over the stability time τ of the "diffusion region".

By and large, the abundance of an element A in the "diffusion zone" (and hence in the "mixed zone") can be kept low if its downward diffusion velocity $v_{D,A}(x)$ relative to the bulk H gas is larger than the effective upward velocity U(x) of this bulk gas : $v_{D,A}(x)/U(x) = n_H(x) \cdot v_{D,A}(x)/\phi_{SW,H} = \phi_{D,A}(x)/\phi_{SW,A} \gtrsim 1$ (since n_A/n_H = cst throughout the "mixed zone"). Fig. 2 shows that this ratio is indeed >1 (~30 for Ar, and ~3 for C, our worst case), and does not depend much on the altitude x of the interface between the quiet and the mixed-up zones. This strong constraint is thus satisfied.

Fig.4



Other constraints lead to limits to the altitude x of the "diffusion region". An upper limit x $\lesssim$ 2000 km is imposed by the fact that the high-FIP elements must still be mostly neutral /43,13/. A lower limit x $\gtrsim$ 1000 km comes from the requirement that ions be prevented to diffuse by the horizontal magnetic fields ($\omega^2 t_{col}^2 \gg 1$). In addition the stability time of the required structure (i.e. the time during which the diffusion region is effectively isolated from the denser lower lying material, so that the zones above and below it remain unmixed) must be longer than the diffusion time t_D (fig.3). The higher the altitude, the more easily this constraint can be fulfilled. For our worst case, C , the required stability time decreases from ~ 60 days at 1000 km to 7 days at 1500 km and a minimum of ~ 2 days at 2000 km. These times are longer than the stability time of the low lying SG and network, which is of the order of 1 day /3/.

6. Conclusion.

The heavy element composition anomalies in the TR, Corona, SW and SEP can be explained in terms of gravitational settling of the heavy neutrals in the Chromosphere, provided that a large fraction of the solar surface is covered by quiet, presumably field stabilized, regions at high altitude in the chromospheric plateau (~ 1500 to 2000 km). These regions must effectively shield the coronal reservoir from the denser, lower chromospheric gas. They must be stable over at least a few days, and must therefore not be strongly perturbed by the daily changes of the SG pattern at lower altitude. Unless a different scheme is found to explain it, the odd coronal composition therefore permits to set stringent limits to the degree of chaos of the Chromosphere, to the turbulent exchange of matter between the lower and the upper chromospheric layers.

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