CHEMICAL FRACTIONATION AND ABUNDANCES IN CORONAL PLASMA

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ABSTRACT

Much of modern astrophysics is grounded on the observed chemical compositions of stars and the diffuse plasma that pervades the space between stars, galaxies and clusters of galaxies. X-ray and EUV spectra of the hot plasma in the outer atmospheres of stars have demonstrated that these environments are subject to chemical fractionation in which the abundances of elements can be enhanced and depleted by an order of magnitude or more. These coronal abundance anomalies are discussed and some of the physical mechanisms that might be responsible for producing them are examined. It is argued that coronal abundances can provide important new diagnostics on physical processes at work in solar and stellar coronae. It seems likely that other hot astrophysical plasmas will be subject to similar effects.

INTRODUCTION

It is difficult to think of an area of astrophysics today in which plasma chemical composition does not play a key part. Observations of the chemical compositions of stars provided the main initial observational impetus for the development of nuclear astrophysics. This is now used to interpret the observed abundance mixtures and evolution of stars and interstellar media of galaxies, and by extrapolation, in intergalactic space. Along with the theory of nucleosynthesis that revolutionised astrophysics are underlying assumptions that are still commonly built into models that use it. Two simple assumptions are: (i) the surface chemical composition of a main-sequence star reflects the initial chemical composition with which that star was born[1]; (ii) the initial composition of a star is representative of that of the interstellar medium from which it was formed.

In this context, to my mind coronal abundance anomalies are one of the more interesting observational developments in the field of stellar outer atmospheres in recent years. As element abundances can provide clues to astrophysical processes such as nucleosynthesis in stars, coronal abundances should provide us with powerful new diagnostics of processes occurring in coronal plasmas. Evidence for abundance anomalies in the solar corona can be traced back to some of the first analyses of UV and X-ray spectra to emerge in the 1960s and 1970s (see e.g. Meyer 1985 for a review). These apparent anomalies did not attract much attention at the time; lingering doubts remained as to whether or not the observed effects could be attributable to things other than compositional fractionation, such as a breakdown in the underlying assumptions of emitting regions comprising optically-thin plasma in a collision-dominated equilibrium. It was not until the 1990s that interest in the problem became more widespread. The reviews of Meyer (1985) were partly responsible for this, together with the advent of the X-ray spectrographs on *SMM*, *Yohkoh* and of the rocket-borne *SERTS* EUV spectrograph, in addition to solar wind experiments such as *Ulysses*. At the same time, analyses of *Skylab* spectroheliographs were providing convincing images of coronal abundance variations in the light of lines of different elements such as Mg and Ne (e.g. Feldman 1992).

Solar anomalies are still largely described in terms of the "FIP Effect"—the enhancement of elements with low first ionisation potentials (≤ 10 eV or so; e.g. Mg, Si, Fe) relative to those with high first ionisation potentials (≥ 10 eV; e.g. H, N, O, Ne). Departures from the simple single-step FIP pattern, such as

[1]This assumption is of course now modified to allow for the surface destruction of light elements such as Li, Be and B.

variations among the high FIP elements, have been observed: indeed, Schmelz et al. (1996) noted *"there is a growing body of evidence that a simple FIP-based formula is not the whole story for coronal abundances"*. As I outline below, element abundances in the coronae of other stars, and especially the more active stars, provide modern confirmation of these insightful remarks.

The example of stellar coronae demonstrates that magnetised plasmas are not necessarily homogeneous in composition, and that significant chemical separation can occur between regions of different density and temperature. As I discuss below, forces are indeed at work to enhance and deplete elements in coronae: rather than expecting coronae to share a homogeneous chemical composition with the underlying star, the issue is more whether or not the corona can mix itself sufficiently quickly to erase the natural tendency of the plasma to fractionate in composition. Whether FIP is really the underlying key parameter in all cases is not yet clear. Successful fractionation models must now have to explain the solar FIP effect as a special case of the general pattern of abundance anomalies that is emerging in the coronae of different types of stars. Similar physics could also be at work in other hot cosmic plasmas. Stellar coronae provide a means for studying these plasma effects and determining in what astrophysical scenarios some of our most basic assumptions concerning plasma composition might be incorrect.

THE FIRST STUDIES OF STELLAR CORONAL ABUNDANCE ANOMALIES: EUVE AND ASCA

The last decade ushered in the first detailed stellar coronal abundance studies, based on the low resolution X-ray CCD pulse height spectra from the *ASCA* satellite and higher resolution *EUVE* reflection grating spectra. These results have been reviewed recently by Drake (2002) and are only summarised briefly here.

EUVE studies showed that stars with activity levels similar to that of the Sun tend to exhibit a solar-like FIP effect (e.g. α Cen AB, ϵ Eri, ξ Boo A), with an enhancement of low FIP species over high FIP species compared to photospheric values. In contrast, active stars appeared considerably metal poor with Fe abundances apparently factors of 3-10 below expectations of their photospheric values. Schmitt et al. (1996), on finding a coronal Fe abundance for the RS CVn-type binary CF Tuc of 5-10 times lower than that of the solar photosphere dubbed the phenomenon the *Metal Abundance Deficiency (MAD) Syndrome*. At the same time, *ASCA* results were also indicating metal paucity in active stars, from the RS CVns down to active dMe flare stars (e.g. S.A. Drake 1996; Singh et al. 1999). This division between low-activity "FIP effect stars" and active MAD stars became apparent as early as 1995 (Drake et al. 1996). The general picture of the coronae of active stars being MAD appeared to be confirmed by analyses of *BeppoSAX* LECS spectra of late-type stars in the late 1990s (Pallavicini, Tagliaferri & Maggio 2000), though there was a tendency for the *BeppoSAX* metallicities to be slightly higher than those obtained from *ASCA* spectra (e.g. the case of II Peg; Covino et al. 2000 vs Mewe et al. 1997).

A body of evidence for *apparent* abundance differences between the plasma in large flares and the average quiescent corona of the parent star also now exists, based largely on *ASCA* and *BeppoSAX* observations, but stemming from earlier *GINGA* observations of active binaries (e.g. Stern et al. 1992). The interpretation in terms of abundances is likely to be correct (Drake 2002), and provides a tantalising hint that some large flares are comprised of material evaporated from the chromosphere, as the "standard" flare model (e.g. Martens & Kuin 1989) suggests (see also the contribution of M. Güdel in this volume for further discussion of large stellar flares in this context).

THE CHANDRA and XMM-NEWTON ERA

More recently, *Chandra* and *XMM-Newton* have been modifying this picture of coronal abundances anomalies. The first analyses of spectra of the active binary system HR 1099 confirmed the low Fe abundances, but uncovered overabundances relative to Fe of higher FIP elements and especially large enhancements of Ne (Brinkman et al. 2001; Drake et al. 2001). Drake et al. (2001) showed that evidence for the high Ne abundances was indeed present in earlier *ASCA* analyses of active stars in general but had been ignored. Brinkman et al. (2001) suggested the anomalies in HR 1099 followed an *inverse* FIP effect in which high FIP elements were enhanced relative to low FIP elements. Audard and co-workers (see contribution in

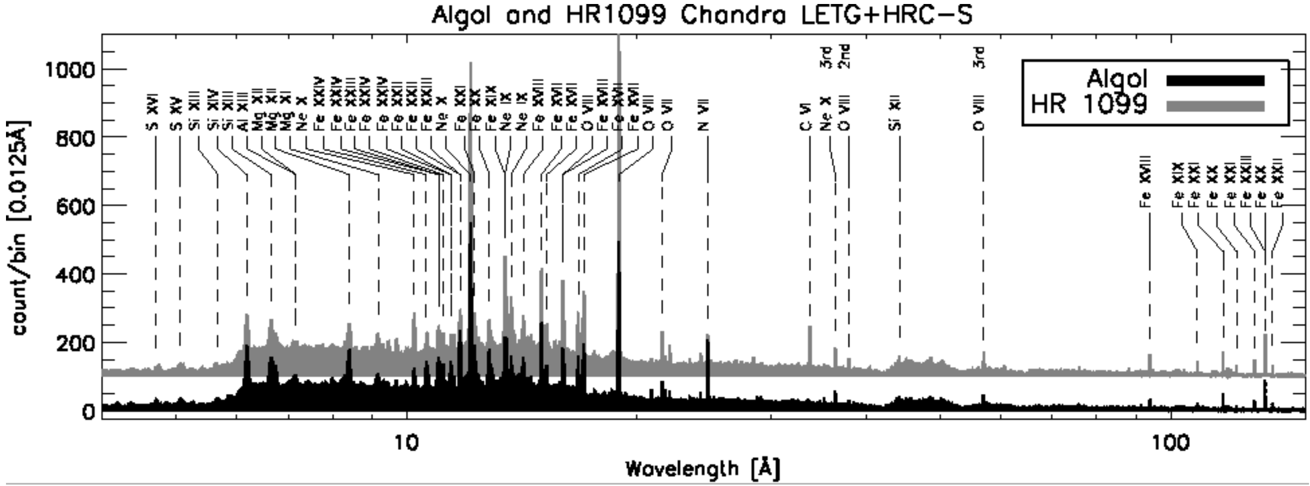

Fig. 1. Illustration of the remarkable similarity in the combined positive and negative order LETG+HRC-S spectra of Algol and HR1099 binned at 0.0125 Å intervals.

this volume) suggest, based on a more extensive analysis of XMM-Newton observations of stars of different activity level, that there is a continuum of behaviour from the FIP effect in relatively inactive stars like the Sun to the inverse FIP effect in the most active stars. However, the patterns do not all appear to be so simple to characterise: significant deviations from a FIP-based formula are present in the data both for HR 1099 (Brinkman et al. 2001; Drake et al. 2001), and from more recent analyses of the active binaries II Peg and AR Lac (Huenemoerder et al. 2002,2003). In particular, the abundances derived in the latter study of AR Lac indicate higher values for Al (FIP=5.99 eV) and Ca (FIP=6.11 eV) than for the elements Mg, Si, and Fe that all have a slightly higher FIP, opposite to the pattern expected for an inverse FIP effect. In HR 1099, Fe appears anomalously low compared to elements Si amd Mg with similar FIP, suggesting that the fractionation might not be completely mass-independent as is believed to be the case for the Sun.

The pattern of abundance anomalies across different star types and activity levels now appears much more rich and diverse than we realised. An important question is whether or not the anomalies are predictable based on observed stellar indices, or whether they depend so critically on coronal characteristics that in integrated starlight they can visibly change on short timescales on any given star, even outside of flares. The solar case does not provide a reliable guide here: observations indicate strong variations in abundances in different regions of the solar corona (e.g. Meyer 1996), and abundances that are seen to change on timescales of days in some coronal structures, such as emerging active regions (e.g. Sheely 1995). However, it is important to note that *there are no full-disk measurements of solar coronal abundances*, so it is difficult to estimate how the variations in abundances in the solar corona might translate to the integrated disk. In the stellar case, there are very few, if any, repeat observations of the same star made with the same instrument. Cross-comparison between different instruments can be difficult owing to the different uncertainties inherent in the analyses (e.g. Drake 2002).

That integrated disk abundances are in fact quite predictable is supported by a recent comparative study of the active binaries Algol and HR 1099 (Drake 2003). The dominant components of these systems at X-ray wavelengths (G8 III and K1 IV in Algol and HR1099, respectively) have very similar effective temperatures (4500 K, 4750 K), radii ($3.5R_\odot$, $3.7R_\odot$), masses ($0.8M_\odot$, $1.0M_\odot$) and rotation periods (2.87d, 2.84d); it might then be expected that they also share similar magnetic activity characteristics. The *Chandra* LETG spectra of these systems (Figure 1) are indeed remarkably similar over a broad range of charge states of Fe as well as in lines of and H- and He-like ions of O, Ne, Mg and Si. Both systems share a similar depletion of Fe by about a factor of 3, and strong enhancements of Ne.

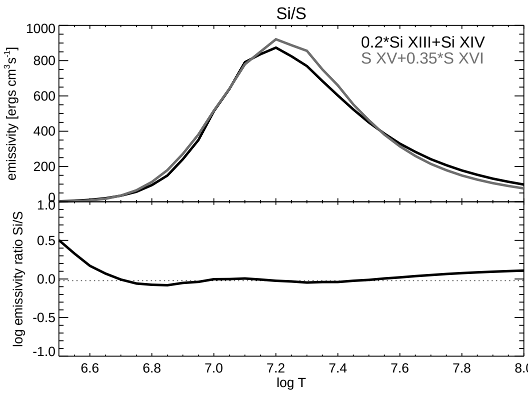

Fig. 2. Emissivities and their ratio vs temperature for a mixture of the Si and S H-like and He-like resonance lines. The ratio forms a temperature-insensitive abundance diagnostic.

Table 1. Abundance ratios for AU Mic based on temperature-insensitive H- and He-like line ratios, together with prominent lines of Fe (Drake et al. 2003). Quoted uncertainties are from Poisson statistics only; true uncertainties will be larger by typically 0.1 dex.

Diagnostic	Abundance Ratio[a]
N VII/(O VII+0.35*O VIII)	$[N/O]_\odot = 0.10 \pm 0.12$
O VII/(Ne IX+0.15*Ne X)	$[O/Ne]_\odot = -0.29 \pm 0.10$
(0.07*Ne IX+Ne X)/(Mg XI+0.17*Mg XII)	$[Ne/Mg]_\odot = 0.61 \pm 0.06$
(0.35*Ne IX+Ne X)/Fe XVII	$[Ne/Fe]_\odot = 0.77 \pm 0.04$
(0.15*Mg XI+Mg XII)/(Si XIII+0.2*Si XIV)	$[Mg/Si]_\odot = -0.29 \pm 0.06$
Mg XI/(0.5*Fe XVII+Fe XXI+2.0*Fe XVIII)	$[Mg/Fe]_\odot = 0.03 \pm 0.10$
(0.2*Si XIII+Si XIV)/(S XV+0.35*S XVI)	$[Si/S]_\odot = -0.07 \pm 0.17$
(0.4*Si XIII+ Si XIV)/ Cont. at 5.85 ± 0.5 Å	$[Si/H]_\odot = -0.43 \pm 0.10$

[a] Ratios are relative to solar values and are expressed in the standard logarithmic bracket notation.

"NEW" TECHNIQUES FOR HIGH RESOLUTION: TEMPERATURE-INSENSITIVE LINE RATIOS

Once spectral lines can be easily resolved, as exemplified by the *Chandra* grating spectra,[2] abundance analysis becomes at once both more obvious and more complex: while lines due to different elements can be discernible, making good use of the diagnostics usually requires a much more involved analysis than the relatively crude two-temperature parameter estimation methods used for low-resolution spectra. The source plasma is, instead, typically multi-thermal (e.g. Drake 1996), and the observed spectral lines containing the abundance information are formed over temperature ranges that can cover substantial variations in source plasma emission measure. Consequently, in the general case, abundances can only be derived if the source emission measure distribution is first determined (which is, in any case, notoriously difficult to determine if true uncertainties are to be accounted for—see Kashyap & Drake 1998 for a recent discussion). Such an analysis can be very time-consuming owing to the large number of lines that must be included from the different charge states present in the multi-thermal source.

One simplifying approach to analyses of solar EUV and X-ray spectra uses the ratios of spectral lines formed at similar temperatures. In the approximation that the ratio of the emissivities of two lines from different elements is constant over the temperature of formation of the lines involved, the ratio of the observed line fluxes yields directly the element abundance ratio. Such an approach can greatly simplify abundance analysis because the underlying emission measure distribution need not be know. However, as discussed by Drake et al. (2003), the ratios that have been used for solar X-ray spectra in the past are not so well suited to the stellar case because emissivity ratios depart significantly from a constant value over the range of temperatures seen in stellar X-ray spectra.

Due to the different temperature dependencies of spectral lines arising from different elements, it is obviously not possible to construct indices that are perfectly insensitive to temperature. However, within temperature intervals where the coronal emission measure is expected to be significant for active stars ($\sim 10^6$-10^7 K), Drake et al. (2003) have found that it is possible to find combinations of ratios of lines of different elements that are constant within reasonable uncertainties ($\lesssim 50\%$ or so) for their respective temperature ranges of formation. These ratios are constructed from, typically, two lines of each element, mixed such that the summed emissivity profiles in the numerator and denominator follow each other much more closely than ratios formed from single lines. An example for Si and S based on their He- and H-like resonance lines is illustrated in Figure 2.

This line ratio technique has been applied to the *Chandra* HETG spectrum of the active M0 dwarf AU Mic;

[2] This is strictly only partially true for *XMM-Newton* because a significant fraction of the flux in spectral lines observed with RGS remains unresolved in the broad wings of the instrumental profile.

the diagnostics and results are listed in Table 1. These results demonstrate immediately that AU Mic does share some similarities in coronal composition with the RS CVn-type binaries: enhanced Ne and depleted Fe relative to elements such as O, Mg and Si, for an assumed photospheric composition similar to that of the solar photosphere. The Si/S ratio for which the emissivity curves are illustrated in Figure 2 shows that both have essentially the same abundance, despite a difference in FIP (Si 8.15 vs S 10.36 eV). Uncertainties in these abundances tend to be dominated by the small residual temperature dependence of the emissivity ratios rather than by Poisson statistics in these bright lines, but still amount to less 50 % in general (Drake et al. 2003).

PROCESSES TENDING TO FRACTIONATE AND HOMOGENISE STELLAR OUTER ATMOSPHERES

Fractionation Forces

The solar corona is an inhomogeneous, dynamic, magnetised plasma. The source of coronal plasma is the underlying, weakly ionised chromosphere/photosphere. In the passage from the photosphere to the corona, and in the corona itself, forces are at play that do not act equally on all particles. The most relevant quantities dictating the different forces on a particle are its charge and mass. These forces will tend to segregate the plasma unless there are other processes at work to homogenise it. The principal forces at work are listed below.

$$\text{Gravitational settling} \qquad m_i g \tag{1}$$

$$\text{Thermal diffusion} \qquad -\frac{6}{5}\frac{\nu_{ie}\mu_{ie}}{kT}\frac{\rho_i}{\rho_e}\kappa_e T^{\frac{5}{2}}\,\frac{dT}{ds} \tag{2}$$

$$\text{Ambipolar electric field} \qquad E z_i \tag{3}$$

And when flows are involved,

$$\text{Frictional drag} \qquad m_i \nu_i \delta u_i \tag{4}$$

In these equations, subscripts e and i denote electrons and ions, respectively, m is the particle mass, μ is the reduced mass, g is the component of gravity parallel to the magnetic field that defines the coronal structure in question (such as a loop), s is the distance along the magnetic field, ρ is the species density, ν is the collision frequency, u is the flow speed, T is the temperature, z is the number of ionized electrons, E is the polarization electric field, κ is the coefficient of thermal conductivity and k is Boltzmann's constant.

Gravitational Settling

The pressure scale height for a given species is proportional to the particle mass. In order to prevent mass-dependent gravitational settling of metals, the corona must either be mixed, e.g. by turbulence, undergo bulk flow (including syphon flows) with a velocity larger than the gravitational settling velocity, or else gravity must be balanced with an outward-directed force.

Thermal Diffusion

Also known as the "thermal force", thermal diffusion refers to the tendency in regions of a plasma with a temperature gradient for heavier ions to diffuse toward higher temperature. This is essentially a kinetic effect caused by the effective non-Maxwellian velocity distribution of electrons in the region of the temperature gradient. Thermal diffusion was initially postulated as a possible explanation for the apparent excess of some metals in the corona found in early spectroscopic studies (e.g. Delache 1967; Nakada 1969; Tworkowski 1976).

However, thermal diffusion acting alone against gravity tends to enhance all metal abundances in the corona and does not easily produce a FIP bias. This can be seen by calculating the ratio of thermal to gravitational forces for H and different metals. I illustrate this ratio for H, Ne, Mg and Fe in Figure 3 for the VAL C model solar atmosphere (Vernazza et al. 1981). It can be seen that gravity dominates until

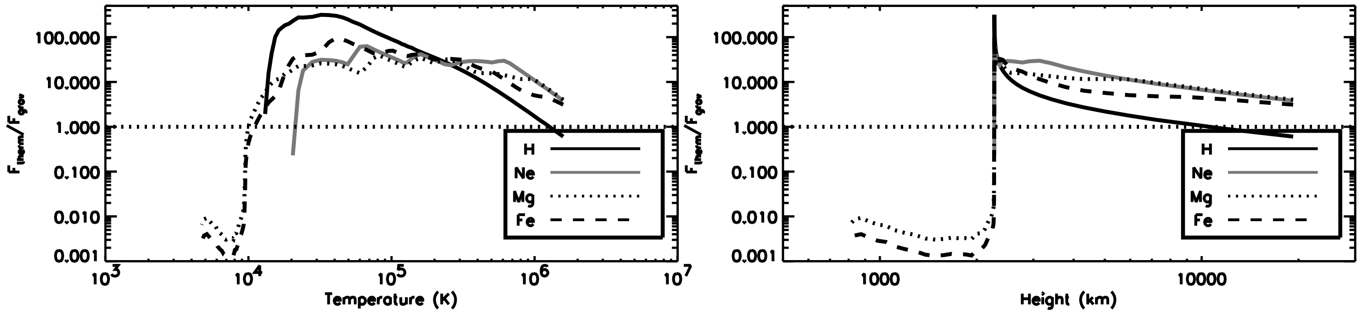

Fig. 3. Ratio of thermal to gravitational forces for H, Ne, Mg and Fe as a function of plasma temperature and altitude in the VALC solar model.

the onset of the strong temperature gradient at the base of the transition region. At this point, thermal diffusion is two orders of magnitude stronger than gravitational pull for H, and rises to more than an order of magnitude over gravity for metals. Based on these calculations, it appears unlikely that metals can be enhanced by thermal diffusion until the upper transition region at temperatures of a few 10^5 K, because at lower altitudes H is more strongly pulled into the corona—this would lead instead to a metal-poor plasma. At coronal temperatures, the thermal force does tend to select metals; however, there is another important force that acts on ions to further complicate the fractionation process.

Ambipolar Diffusion

The electric field, E, arises in response to the tendency of the plasma to differentially stratify through thermal diffusion and gravitational settling. To first order, the ambipolar field is due to the spatial distribution of protons and electrons. An obvious example of the significance of the ambipolar field is in holding down the electrons in the corona. The scale height for electrons is m_e/m_p times that for protons, but in large loops this tendency to separate is counterbalanced by the electric field thus generated. At the top of the corona, the ambipolar electric field is therefore directed outward. At lower altitudes the situation is more complicated because of the balance between the thermal force and gravity. In strong temperature gradients where the net force on protons is upward, then the expectation is for an electric field directed downward. These expectations are borne out by detailed calculations for the solar outer atmosphere by Fontenla (2002), and for multi-species loop models (Lenz 1999).

The net influence of the ambipolar field on a species i depends on the charge-to-mass ratio, q_i/m_i. Since the electric field arises to counterbalance other forces that tend to separate protons and electrons, the direction of the electric force on metals relative to H is given by their relative charge-to-mass ratios $q_i m_H/m_i q_H$. All metals in all ionisation stages have a lower q/m than ionised H, so their acceleration in the electric field is smaller. There are two important limits to the charge-to-mass ratio, q_i/m_i: (i) near the base of the transition region where low FIP light elements are likely to be twice ionised, but high FIP species only once ionised, q_i/m_i is higher for low FIP elements by a factor of ~ 2; (ii) at higher temperatures, q_i/m_i is more similar for both high and low FIP elements, and tends to ~ 2 when elements are fully ionised. At the top of the corona, where the ambipolar field is directed outward, all metals will therefore tend to sink relative to H. Note that this tendency is opposite that of thermal diffusion (Figure 3). In the transition region, where the ambipolar field is expected to be directed down toward the chromosphere, metals are drawn down to a lesser extent than H by the electric field (but more by gravity), and the net acceleration relative to H then depends on the balance between thermal, electric and gravitational forces.

Frictional Drag

The different forces described above can induce migrations of different species relative to each other. Such flows are subject to frictional forces that act, in general, to reduce relative flow. In a plasma dominated by hydrogen, friction for a given species arises through collisions with hydrogen atoms or protons. The frictional force depends on the collision frequency. Collision rates are much larger between protons and ions than that between protons and neutrals, or between hydrogen atoms and other neutrals or ions. These differences will be most crucial in the chromosphere and lower transition region where neutrals and ions co-exist with ionised hydrogen; upward drift of protons, as a result of mass-loss in a wind for example, will more easily carry ions with it than neutrals. In such a scenario, elements with FIP$>$ 13.6 eV can be left behind. This mechanism provides a basis for some models seeking to explain the FIP effect in the solar corona and wind (e.g. Marsch et al. 1995; Peter 1998) though McKenzie (2000) has shown that such 1-D models rely on spurious boundary conditions. Schwadron et al. (1999) present a detailed discussion of frictional effects and show that moderate flows of only a few km/s can be effective in eliminating compositional fractionation. These models included the ambipolar field due to hydrogen, though the thermal force was neglected.

Anti-Fractionation Processes

High resolution *TRACE* image sequences of the solar corona discussed elsewhere in this volume serve as a dramatic demonstration that coronae are dynamic systems characterised by (possibly ubiquitous) flows, and perhaps also by significant turbulence. Flows and turbulence are homogenising agents, acting against the processes discussed above that tend to chemically separate the plasma.

Turbulence

In the case of turbulence, on scales smaller than the particle mean-free path ("microturbulence") the turbulent velocity would need to be comparable to the thermal velocity to induce sufficient mixing. As noted by Schwadron et al. (1999), such turbulence can probably be ruled out. However, macroturbulent mixing on scales much larger than the particle mean-free path only need occur with velocities comparable to that of gravitational settling or ambipolar and thermal diffusion in order to prevent it.

Flows

Stellar coronae are in a state of flow because they are the source of mass loss in a wind—the slow wind in the case of closed, X-ray-bright magnetic structures on the Sun. As discussed above, flows could act to fractionate the plasma through differential frictional forces. However, once flows are significantly more rapid than migration caused by forces acting opposite to the flow—such as gravity in the case of upward flow—then all particles are carried along and the composition remains the same as that at the base of the flow (again, see the insightful discussion of Schwadron et al. 1999). The gravitational settling time for typical loops with densities of 10^9-10^{10} cm^{-3} in the solar corona is of order a day or so. Schwadron et al. (1999) estimate that flow speeds as low as ~ 100 ms^{-1} can be sufficient to prevent gravitational or mass-dependent settling. Interestingly for the case of enhanced Ne and other high FIP elements in the coronae of active stars, Schwadron et al. (1999) find that similar effects in their model can be produced by moderate syphon flows.

COMMENTS ON SOME FRACTIONATION MODELS

The advent of high resolution X-ray spectra of stellar coronae that allow the measurement of coronal abundances with greater accuracy and reliability than earlier generation instruments provides new challenges to fractionation models. Stellar observations show that the solar case is evidently only one particular example in the apparent continuum of abundance anomalies. Models proposed to date have been aimed at explaining the solar FIP Effect and enhancement of low FIP species. I refer to the nice summary of some of these models by Henoux (1995) for more detailed discussion. A successful model now has to be able to reproduce this range of anomalies. A full examination of the different models that have been proposed is beyond the page limit here; I comment instead on one or two models concerning fractionation that have appeared in the recent literature.

Neutral-ion separation in a magnetic field *e.g. Vauclair (1996); Steinitz & Kunoff (1999)*
Magnetic field-based separation acting in the chromosphere relies on ions being tied to the field but neutrals not. Vauclair (1996) proposed that rising magnetic field preferentially carried ions with it into the corona. Steinitz & Kunoff (1999) invoked the diamagnetic effect, or "magnetic mirror", whereby field lines diverging after emerging from the photosphere preferentially accelerate ionised species upward. Both models have problems if high FIP species are to be preferentially brought into the corona—the magnetic field instead needs to behave in the opposite fashion to retard ions. Doubtless it is possible to conceive a gradual change

in magnetic field behaviour from solar-like activity levels to the most active stars that might achieve this, though it does not seem straightforward.

Multi-species loop models *Lenz (1999)*
A nice discussion of the forces acting on different species in coronal loops has been presented by Lenz (1999), who investigated self-consistent loop models subject to different heating conditions. The abundance profiles of different elements in these quasi-static models was found to be sensitive to loop parameters, such as length, base pressure and heating rate, illustrating how plasma can fractionate in the absence of mixing processes. However, these models are static and the abundance profiles obtained can be substantially different in the presence of flows.

Flows and wave heating *Schwadron et al. (1999)*
Schwadron et al. (1999) studied the impact of flows and the resulting ambipolar field on species populations through a coronal loop. These effects alone do not produce a low FIP bias, though syphon flows could raise coronal abundances of high FIP elements—reminiscent of the situation in active stars. However, the same model could obtain enhancements of low FIP elements by applying MHD wave heating: ions are heated with respect to neutrals and so low FIP species can attain greater scale heights. Thus—by accident—this type of model is able to reproduce some of the aspects of coronal abundance anomalies in both low and high activity stars. While this warrants further study, it remains questionable whether coronae are too dynamic to be fractionated by these means, and, as argued by McKenzie (2000), whether time-dependent or spatially inhomogeneous processes are responsible.

CONCLUSIONS

Coronal plasma under the influence of gravity and/or with a temperature gradient will tend to chemically fractionate unless mixed or subject to flows. Magnetic fields might also play crucial roles in separating neutral and ionised species. Abundance peculiarities are then to be expected in coronal plasma, hopefully providing us with new diagnostics. Unfortunately, the interplay of the different forces and processes involved is complex, and the situation is likely complicated by the effects of flows and turbulence, and possibly by dynamic magnetic fields. Reading the observed chemical composition will require greater understanding of the controlling processes. Successful models describing coronal abundances are now need to satisfy the range of abundance anomalies being uncovered by stellar observations—enhancements of high FIP elements and apparent depletions of low FIP elements relative to photospheric abundances—in addition to the solar FIP effect.

However, despite the complicated physics and current lack of understanding of abundance anomalies, we are already in a position to make some useful statements.

Coronae are not hydrostatically stratified

The scale height for species in the solar corona is $\sim 30,000 T_6/m$ km where T_6 is the species temperature in units of 10^6 K and m is in amu. For protons at a typical temperature of 2×10^6 K, the scale height is then 60,000 km. As noted earlier, the scale height for Fe is 1/56 that of H, or about 1000 km for the same temperature, and so large long-lived coronal loops would therefore be essentially empty of Fe if gravitational settling were not counteracted by opposing forces or by mixing. An obvious conclusion that can then be drawn from the observation of iron at super-photospheric or photospheric abundance in large coronal loops is that the solar corona is not generally in hydrostatic equilibrium.

Mixing processes must be at work in low gravity active stars and in rapidly rotating stars

Typical giant stars can have surface gravities 100 times less than that of the Sun. Such low effective gravities can also be achieved on less evolved stars that are very rapidly rotating. These active stars tend to have coronae hotter than that of the Sun by an order of magnitude, with typical temperatures of 10^7 K. Upward thermal forces in these coronae will be much stronger than for the Sun, while the downward gravitational force can be much weaker. Since we do not see active coronae filled with metals (rather, they appear depleted in metals), their coronae must be significantly mixed by turbulence or homogenised by flows. The models of Lenz (1999) also support this conclusion for the solar corona since quite different abundance patterns that are not observed were produced for different loop lengths and base pressures. This indicates that something else is driving the observed composition.

Magnetic field fractionation mechanisms

If the magnetic field is indeed responsible for fractionation in the chromosphere, then coronal abundances provide will insights into changes in magnetic field topology as a function of stellar activity level.

Limits on flow velocities

If syphon-type flows are responsible for the high FIP biases seen in active stars, as hinted by the models of Schwadron et al. (1999) for solar loops, then we can place limits of a few km/s on the velocities of such flows since significantly larger velocities should erase the abundance pattern.

Wave heating and low FIP enhancements

The model of Schwadron et al. (1999) invokes preferential MHD wave heating of ionised species in the chromospheric region of partial ionisation to explain enhanced low FIP elements. It is unlikely that such heating mechanisms can be significant over the full range of activity levels observed for late-type stars (e.g. the most active stars have X-ray luminosities 10^4 times higher than the Sun). We might then expect a qualitative change in observed anomalies as such wave heating becomes insignificant, much as is observed.

These points provide only very simple examples of the insights abundances might provide for understanding the physics of coronal plasma. As noted in the introduction, similar fractionation processes are likely to be at work in other hot cosmic plasmas. Stellar coronae provide laboratories for studying these interesting and important effects.

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