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Minor element abundances in the corona and solar wind

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Abstract

Using a time-dependent numerical model that spans the chromosphere, corona and solar wind, abundance variations resulting from gravitational settling in the chromosphere and corona have been studied.

Gravitational settling in the chromosphere may lead to a depletion in the abundances of minor elements in the solar wind relative to the photosphere. The observed overabundance (relative to the photosphere) of elements with a first ionization potential (FIP) lower than 10 eV in the solar wind, and the underabundance of high-FIP elements such as He and Ne is a long standing problem in solar physics. In Paper I and Paper II, we study the significance of the magnetic flux tube expansion factor on the abundances of high-FIP elements He, Ne and O in the solar wind. With a low expansion factor, of order 15-20, we can reproduce the observed fast solar wind He abundance, but a high expansion factor, of order 40-100, is required to reproduce the observed fast solar wind Ne abundance.

In the corona, gravitational settling leads to local abundance enhancements. The magnitude and location of a coronal abundance enhancement depends on the minor element heating rate and the background plasma parameters. Observations of minor element abundances in the corona, in combination with modelling, may place constraints on the minor element heating rates, thereby providing new constraints for models and theories on coronal heating.

In Paper I it is shown that, for proton-electron plasma parameters in accordance with observations from polar coronal holes, a coronal He abundance enhancement will occur in the region 1.2 - 2 $R_\odot$, where no observations of the He abundance exist. It can only be avoided by strong heating of the He ions, which leads to very high outflow velocities for both He and protons in the corona. In Paper II we show that such high outflow velocities in the corona causes O and Ne to be pushed far out of ionization equilibrium, and leads to ion fractions for O and Ne that are not in accordance with in-situ observations in the fast solar wind. The results from Paper I and Paper II suggest that He abundance enhancements are common in the region above 1.2 $R_\odot$. In Paper II we also investigate minor element abundance enhancements in the corona in a H-He background, using O as an example. We find that for O temperatures and outflow velocities in accordance with observations from coronal holes, coronal O abundance enhancements will occur at heights above 1.3 $R_\odot$.

In Paper III we study Fe elemental abundance enhancements in the slow solar wind. The results are compared to the observations of *Habbal et al.* (2007), who found evidence of coronal density enhancements of Fe^{+10} and Fe^{+12}, particularly along streamer edges. We show that the observations of *Habbal et al.* (2007) are consistent with an Fe elemental abundance enhancement, but owing to existing uncertainties about the plasma conditions in the source regions of the slow solar wind we cannot place any strong constraints on the coronal Fe heating rate. However, by comparing the modeled Fe ion fractions with in-situ observations in the slow solar wind we find that a background model with coronal hole-like densities and a high outflow velocity in the corona provides the best fit to observations.

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Contents

Chapter 1

Introduction

The work presented in this thesis is aimed at contributing to a better understanding of abundance variations in the solar corona and the solar wind. It is an interesting feature of the solar wind that the abundances of minor elements are generally not equal to the photospheric element abundances. The same is true for the solar corona, the outermost layer of the solar atmosphere. To fully understand the solar atmosphere, we must reach an understanding of the physical processes that determine the minor element abundances in the corona and solar wind. In this chapter, some concepts and questions that are important for the understanding of the dynamics of minor elements in the solar corona and wind will be introduced. In the next two chapters, the observational constraints (Chapter 2) and recent theoretical studies (Chapter 3) that have guided and inspired this work will be discussed. Finally, a brief summary of the results is given in Chapter 4. The three papers that make up this thesis are attached at the end, as an appendix.

1.1 The First Ionization Potential Effect

In the early 1980s it was realized that the abundances of minor elements with a First Ionization Potential (FIP) lower than 10 eV are enhanced in the corona and solar wind, relative to the photosphere, and that this effect must be explained by processes taking place in the chromosphere, where low-FIP elements are partly or fully ionized and high-FIP elements are almost entirely in the neutral state (*Meyer*, 1981; *Cook et al.*, 1984; *Geiss*, 1982). The FIP effect is most prominent in the slow solar wind and in coronal loops. In coronal holes and the fast solar wind the enhancement of low-FIP elements is usually thought to be weaker, although some authors argue that it may be entirely absent (see e.g. reviews by *Geiss*, 1998; *Feldman*, 1998; *Bochsler*, 2007). A similar, but related, problem is the observed underabundance of the two high-FIP elements He and Ne, which is clearly present in both high- and quiescent low speed streams (*von Steiger et al.*, 2000). In this thesis, focus has been on the abundances of the high-FIP elements He, Ne and O in the fast solar wind. Observations of minor element abundances, in combination with theoretical studies and modelling, can be used as a diagnostic tool to study the chromosphere in the sense that a realistic description of the chromosphere must be able to account for both the overabundance of the low-FIP elements and the underabundance of the high-FIP elements.

1.2 Ionization equilibrium and freezing-in

Observations of minor ions in the solar wind can also be used as a diagnostic tool to study the corona. Ionization and recombination in the corona is a result of ion-electron collisions, and depends sensitively on the electron temperature. In a steady state, the continuity equation for an ion species of charge i is

$$\nabla(n_i u_i) = n_e(n_{i-1}C_{i-1} - n_i(C_i + R_{i-1}) + n_{i+1}R_i), \tag{1.1}$$

where n_i is the density and u_i is the flow velocity of the ions, n_e is the electron density, C_i is the total ionization rate from charge i to $i+1$ and R_i is the recombination rate from charge $i+1$ to i. The electron temperature dependence is contained in the ionization and recombination rates. Assuming all ions of the same element flow radially outwards with the same flow velocity, u, Equation 1.1 can be written (*Hundhausen et al.*, 1968; *Ko et al.*, 1997)

$$u\frac{\partial y_i}{\partial r} = n_e(y_{i-1}C_{i-1} - y_i(C_i + R_{i-1}) + y_{i+1}R_i), \tag{1.2}$$

where

$$y_i \equiv \frac{n_i}{\sum_{i=0}^{Z} n_i} \tag{1.3}$$

is the ion fraction for the ions with charge i of an element with atomic number Z. If we assume a high electron density and a flow velocity close to zero, Equation 1.2 can be approximated by

$$y_{i-1}C_{i-1} - y_i(C_i + R_{i-1}) + y_{i+1}R_i = 0. \tag{1.4}$$

By solving the resulting set of $Z+1$ equations, one for each charge state of the element in question, we find that

$$\frac{y_{i+1}}{y_i} = \frac{C_i}{R_i}. \tag{1.5}$$

An ion population in this state, where the ion fractions of all charge states depend solely on the ratio of their ionization and recombination rates, and hence, solely on the electron temperature, is said to be in ionization equilibrium. As the electron density decreases with increasing distance from the solar surface, collisions between ions and electrons become increasingly rare and eventually the ion fractions will no longer adjust to the local electron temperature. For high flow velocities and low electron densities, ion fractions are "frozen-in", i.e.

$$\frac{\partial y_i}{\partial r} \rightarrow 0. \tag{1.6}$$

Whether the ion population is in the state of ionization equilibrium or is in the frozen-in state depends on the relative magnitude of the timescales for ionization, τ_i, and expansion, τ_e, given by

$$\tau_i \equiv \frac{1}{n_e(C_i + R_{i-1})}, \tag{1.7}$$

and,

$$\tau_e \equiv \left| \frac{u}{n_e} \frac{\partial n_e}{\partial r} \right|^{-1}. \tag{1.8}$$

When the outflow velocity is low and the electron density is high, the timescale for ionization is much smaller than the timescale for expansion and the ion population is in ionization equilibrium. When the outflow velocity is high and the density low, the timescale for ionization is much larger than the timescale for expansion and the ion fractions are frozen-in. We have so far discussed two possible states of the particle population, ionization equilibrium which implies zero or very low outflow velocities and high electron densities and the frozen-in state, which implies high outflow velocities and low densities. However, there is a third option which is relevant to the solar corona. For high outflow velocitries and high electron densities, the ion population will be neither in ionization equilibrium nor frozen-in. In this state, the ion fractions depend not only on the electron temperature, but also on the electron density and the outflow velocity of the individual ion species. If we assume that the transition from ionization equilibrium to the frozen-in state occurs very quickly, then the ion fractions measured in-situ, e.g. at earth orbit, will reflect the electron temperature at the point in the corona where freezing-in occured. With this assumption, the freeze-in temperature can be obtained. Since different ion species freeze-in at different distances from the sun, an estimate for the electron temperature gradient in the corona can be constructed from in-situ observations of ion fractions.

However, the assumption that the transition from ionization equilibrium to the frozen-in state occurs very quickly is not neccesarily valid. As noted above, the ions may go though a state, which can exist over an extended region in the corona, in which they are pushed out of ionization equilibrium without being frozen-in. This is reflected in the fact that freeze-in temperatures (*Ko et al.*, 1997) have proved to be consistently higher than electron temperatures derived from line ratios (*Habbal et al.*, 1993; *David et al.*, 1998; *Wilhelm*, 2006; *Landi*, 2008). To reconcile the different observations, it is necessary to simulate the ionization and recombination processes in a model which takes into account the flow velocity of the minor ions and the electron density of the corona. For some minor ions, the observed in-situ ion fractions can be reproduced in a model with a low coronal electron temperature, but for others this has proved difficult without the presence of a non-Maxwellian electron velocity distribution (*Esser and Edgar*, 2002).

Since the outflow velocity determines the degree of departure from ionization equilibrium, simulations of the ion fractions of minor ions in a model where the outflow velocity is taken into account can also place constraints on the minor ion outflow velocity in the region where freezing-in occurs. If the outflow velocity of the minor ions is close to that of the protons in the region where freezing-in occurs, then the in-situ ion fractions can also be used to place constraints on the proton outflow velocity in the corona.

1.3 Heating of minor ions in the corona

Observations of O^{+5} in coronal holes show temperatures of up to 200MK at 2 $R_\odot$ and outflow velocities that are significantly higher than the background proton-electron plasma (*Antonucci et al.*, 2000; *Kohl et al.*, 1999; *Esser et al.*, 1999; *Cranmer et al.*, 1999). Observations also indicate strong temperature anisotropies, where the temperature perpendicualar to the magnetic field is much higher than the temperature parallell to the field (*Cranmer et al.*, 1999, 2008). In combination with measurements that show proton temperatures to be much higher than electron temperatures in coronal holes, these observations have given rise to the notion that energy may be transferred to the ions through the ion cyclotron resonance and they have been interpreted as evidence for strong preferential heating of heavy ions in the corona (see e.g. review by *Cranmer*, 2009). *Lie-Svendsen and Esser* (2005) showed that if minor ions are not sufficiently heated in the corona, a local abundance enhancement will occur (see Chapter 3 for details). If the coronal O abundance could be determined with accuracy, it might be possible to combine observations and modelling to place further constraints on the coronal heating rate and heating mechanism(s) for O. However, the location and magnitude of the abundance enhancement will depend not only on the O heating rate, but also on the degree of collisional coupling to the background, and since the Coulomb collision frequency between minor ions and protons depends sensitively on the proton temperature, the accuracy of the constraints obtained using such an approach would depend on the accuracy of the observed coronal proton temperature. Clearly, this approach could be used also for other minor elements, given that their coronal abundance could be determined. Observations of minor element abundances in the corona, in combination with observations of the minor element temperature and outflow velocity, could therefore be useful for the development of the theories on coronal heating.

Chapter 2

Abundances & ion fractions

In this chapter, a summary of observations of element abundances and ion fractions that are relevant for the work presented in this thesis will be given. The Chapter is divided into three Sections describing abundances and ion fractions in the photosphere, corona and solar wind for four different elements: He, O, Ne and Fe.

2.1 Photosphere

The photospheric He abundance can be established with great accuracy through helioseismology. A recent review by *Asplund et al.* (2009) lists a value of $N_{He}/N_H = 0.085 \pm 0.002$. The photospheric O abundance can be estimated by observations of photospheric O emission lines. Analyses of photospheric O emission lines have yielded different values for the O abundance. A summary can be found in the review by *Asplund et al.* (2009), who recommends a value of $N_O/N_H = 4.9 \cdot 10^{-4}$. This is a relatively low value compared to older results. The photospheric Ne abundance is also debated. The value adopted by *Asplund et al.* (2009) is based on their calculations of the photospheric O abundance and a recent study of the Ne/O abundance ratio by *Young* (2005). *Young* (2005) uses observations of transition region lines in the quiet sun to arrive at $N_{Ne}/N_O = 0.17$, which gives $N_{Ne}/N_H = 0.85 \cdot 10^{-4}$ using the O abundance of *Asplund et al.* (2009), and suggests that this value should be used also for the photosphere. Taking into account that the process(es) responsible for the FIP effect and the observed underabundance of He and Ne in the solar wind are not well known, such extrapolations should be made with extreme caution. The recent revisions of photospheric abundances adopted in *Asplund et al.* (2009) have led to discrepancies between models of the solar interior and results from helioseismology. *Antia and Basu* (2005) suggested that the discrepancies might be resolved by increasing the photospheric Ne abundance. *Bahcall et al.* (2005) suggested a value of $N_{Ne}/N_H = 1.95 \cdot 10^{-4}$. We conclude that the photospheric Ne abundance is essentially unknown, and that the value suggested by *Bahcall et al.* (2005) should be taken as an upper limit.

The photospheric Fe abundance recommended by *Asplund et al.* (2009) is $N_{Fe}/N_H = 3.16 \cdot 10^{-5}$. Fe is a low-FIP element and its abundance is observed to be enhanced in the corona and solar wind relative to the photosphere (*von Steiger et al.*, 2000). As mentioned in Section 1.1, the FIP effect is believed to be caused by processes in the chromosphere. The modelling work on Fe presented in this thesis is concerned with observed density variations in the corona, and not with abundance variations between the photosphere and the corona/solar wind. Therefore, it was not necessary to take the FIP effect into account in this study, and since the Fe ions are treated as test particles in the model, the exact value of the Fe abundance assumed is not important.

2.2 Corona

Over the years, many attempts have been made to determine the coronal He abundance (e.g. *Gabriel et al.*, 1995; *Raymond et al.*, 1997; *Delaboudinière*, 1999; *Auchere*, 2000; *Laming and Feldman*, 2001, 2003), however this has proved difficult partly because of the low intensity of relevant emission lines in the corona, especially in polar coronal holes, and partly because of the complex nature of the exitation mechanisms of the emission lines (e.g. *Laming and Feldman*, 2001, 2003, and references therein). In the case of polar coronal holes, which are the focus of the studies in Paper I and Paper II on the coronal/solar wind He abundance, only two studies exist which determine the coronal He abundance: *Laming and Feldman* (2003) estimate the coronal He abundance by comparing the He II Baγ λ1085 emission line with emission lines from O VI, N V and C IV. To find an estimate for the He abundance from the observations, *Laming and Feldman* (2003) assume ionization equilibrium and photospheric abundances for O, N and C. They find that the He abundance on open field lines, in the region below 1.1 $R_\odot$, never exceeds 5%. In Paper II, we confirmed that the assumption of ionization equilibrium is valid, at least in the case of O VI, for outflow velocities in the region of interest (1.03-1.1 $R_\odot$) of order 10 km/s, which is in good accordance with observations of O VI Doppler shift by *Peter and Judge* (1999). The validity of the assumption of photospheric abundances is also discussed in Paper II, but remains uncertain.

Delaboudinière (1999) and *Auchere* (2000) compared observations and modelling of the coronal He II λ304 emission and found that, in the coronal holes, the falloff in the intensity of the line as a function of height above the limb was more rapid in the model compared with the observations. They interpreted this discrepancy as an indication that the He abundance in the polar coronal holes might be higher than the 8% assumed in the model. Furthermore, The HERSCHEL (Helium Resonant Scattering in the Corona and Heliosphere) sounding rocket mission observed coronal He and H emission lines out to 3 $R_\odot$ and a preliminary analysis of the data reveales the existence of regions with enhanced

He abundances (*Newmark et al.*, 2010). The coronagraph onboard HERSCHEL is a prototype of the coronagraph intended for the proposed Solar Orbiter mission (*Pancrazzi et al.*, 2010). The coronal O abundance has been measured in a polar coronal hole by *Antonucci and Giordano* (2001), who obtained a value of $N_O/N_H = 6 \cdot 10^{-4}$ at the average height of 1.64 $R_\odot$. However, as discussed in *Antonucci and Giordano* (2001), their results depend on the assumed plasma properties in the corona. Thus, the observations are consistent with an O abundance as high as 0.0014. There is also the possibility of contamination from plume plasma, which may have a different coronal O abundance compared to interplume plasma. The Fe abundance in the corona is not well known. However, recent solar eclipse observations by *Habbal et al.* (2007), of emission lines from Fe XI and Fe XIII, indicate that local density enhancements may be present at altitudes of $1.2 - 1.5R_\odot$.

2.3 Solar wind

The solar wind He abundance is highly variable. However, the fast wind streams from coronal holes have a relatively constant He abundance of between 3.5 and 5% (e.g. *Bame et al.*, 1977; *Wang*, 2008). It is not known what process(es) are responsible for lowering the He abundance from the photospheric value of 8.5% to the values typically observed in situ in the solar wind. In situ observations in the fast solar wind generally yield a higher O abundance than the value recummended for the solar photosphere by *Asplund et al.* (2009). *von Steiger et al.* (1995) found that typical O abundances in the fast wind range between 6 and $7 \cdot 10^{-4}$ and *von Steiger et al.* (2010) estimates a fast wind O abundance of $N_O/N_H = 6.6 \cdot 10^{-4}$. According to *Gloeckler and Geiss* (2007), typical ion fractions for O^{+6} and O^{+7} measured in situ in the high speed wind are approximately 0.98 and 0.015, respectively. *von Steiger et al.* (2000) found a value of $N_{Ne}/N_O = 0.083$ for the Ne abundance in the fast solar wind. If we adopt the fast wind O abundance of *von Steiger et al.* (2010), this yields a Ne abundance of $N_{Ne}/N_H = 0.55 \cdot 10^{-4}$. Typical ion fractions for Ne^{+7} and Ne^{+8} measured in situ in the high speed wind are approximately 0.015 and 0.98, respectively (*Gloeckler and Geiss*, 2007).

Table 2.1: Typical ion fractions for Fe in the slow solar wind (from *von Steiger et al.*, 2000).

Ion	Fe^{+8}	Fe^{+9}	Fe^{+10}	Fe^{+11}	Fe^{+12}
Ion fraction	0.15	0.2	0.2	0.15	0.1

Listed in Table 2.1 are typical ion fractions for Fe in the slow solar wind (from *von Steiger et al.*, 2000). Since the Fe simulations in Paper III are only concerned with the slow wind, the corresponding values for the fast wind are not listed. They can be found in *von Steiger et al.* (2000).

Chapter 3

Previous modelling efforts

In this chapter, some of the previous theoretical studies addressing the question of He and minor element abundances in polar coronal holes and the fast solar wind will be discussed. This is not intended as an extensive review, the purpose is simply to shed some light on the motivation for the studies that make up this thesis. Although these studies are concerned mainly with the fast solar wind from polar coronal holes, the physical mechanisms that are discussed in this Chapter do not depend on the asymptotic flow speed of the solar wind and may be as important for the understanding of low speed solar wind originating in open field regions, e.g. on the edges of streamers (*Abbo et al.*, 2010; *Antonucci et al.*, 2005, 2006), as for high speed solar wind from polar coronal holes.

3.1 Gravitational settling in the chromosphere

As we have seen in Chapter 2, it is well known that the He abundance in the fast solar wind is lower than the photospheric He abundance. This is a feature which a realistic model of the fast solar wind should be able to reproduce. However, previous theoretical studies of the fast solar wind have been faced with a very different, although related problem. When neglecting turbulent mixing processes in the upper chromosphere (which may or may not be important), and assuming radial expansion of the magnetic field or super-radial expansion with an expansion factor of about 5 (i.e. the area of the flow tube at 1 AU is assumed to be 5 times larger than it would be for a radially expanding field), it has proved difficult to explain how a sufficiently large He flux can be obtained in a fast solar wind (*Hansteen et al.*, 1997; *Lie-Svendsen et al.*, 2003).

By assuming mass conservation for H and He and equal flow velocities above the transition region, it is easy to show that if the He abundance at some height, $r = R_C$, in the chromosphere is equal to A, then the He abundance above the transition region is equal to

$$\frac{n_{He}}{n_H} = A \cdot \left(\frac{u_{He}}{u_H} \right)_{R_C} , \tag{3.1}$$

i.e. proportional to the velocity ratio at $r = R_C$. In a chromosphere where no mixing occurs (still assuming mass conservation and a nonzero He flow velocity), the flow velocity of He is determined by a force balance between gravity and friction. The flow velocity adjusts itself so that the friction force, which is proportional to $(u_H - u_{He}) \cdot \nu_{H,He}$ (where $\nu_{H,He}$ is the H-He collision frequency), together with the pressure gradient force can balance gravity. In the chromosphere, the collisional coupling results from neutral-neutral and neutral-ion collisions and is weak (i.e. the collision frequency, $\nu_{H,He}$, is low). Therefore, the flow speed difference between He and H must be large to reach the required magnitude of the friction force.

If the H flow speed is relatively low, i.e. close to the value of the flow speed difference, $u_H - u_{He}$, which is required to balance gravity, then u_{He} will be close to zero and $\frac{u_{He}}{u_H}$ will be very low, implying a very low solar wind He abundance. If the H flow speed in the chromosphere is lower than the flow speed difference which is required to balance gravity, then there will be a downflow of neutral He in the chromosphere, and the Ne density in the upper chromosphere will decrease until an upwardly directed pressure gradient force of sufficient magnitude has been set up which, together with the friction force, can balance gravity. In this case, the solar wind Ne flux in a steady state will be vanishingly small. If, on the other hand, the H flow velocity in the chromosphere is relatively large, i.e. much larger than the value of the flow speed difference, $u_H - u_{He}$, which is required to balance gravity, then u_{He} will also be large and $\frac{u_{He}}{u_H}$ will be close to 1, implying a near-photospheric solar wind He abundance.

Hansteen et al. (1997), who assumed a radially expanding flow tube, found it necessary to introduce an "artificially enhanced" collision frequency between neutral H and He in the chromosphere to ensure that the solar wind He abundance was kept at approximately the photospheric value. In the absence of the extra friction force on neutral He which is achieved by artificially increasing the H-He collision frequency, the He/H flow speed ratio in the chromosphere was very low and the solar wind was severely depleted of He. The introduction of such an "artificially enhanced" collision frequency was only an emergency measure, intended to make the study of coronal abundance variations feasible within the model, and *Hansteen et al.* (1997) suggested that "some process" was responsible for keeping H and He "well-mixed" in the chromosphere.

However, a study of the He abundance in a closed coronal loop, using a model very similar to that of *Hansteen et al.* (1997), shows that the assumption of a well-mixed chromosphere may have equally problematic consequences (*Killie et al.*, 2005). In a closed loop the net outflow in a steady state is zero, and the friction force on He, from collisions with neutral H and protons, is therefore also zero. Since the friction force on He is zero, gravity must be balanced by the pressure gradient force. This implies a rapid decrease in the He density as function of height.

In the transition region and corona there will be an upflow of neutral He, caused by the upwardly directed pressure gradient force on neutral He, which must be balanced by a downflow of ionized He. In the transition region, the upwardly directed "thermal" force on ionized He is very strong. To achieve a downflow of ionized He in the transition region, it is necessary to set up a pressure gradient force of equal magnitude and opposite direction which can balance the thermal force. This can only be acieved through a large accumulation of ionized He in the loop.

Killie et al. (2005) showed that in a coronal loop which is anchored in a well-mixed chromosphere, where some turbulent mixing process counteracts gravitational settling and keeps the He abundance in the upper chromosphere close to the photospheric He abundance, the coronal He density will become comparable to the H density after 1-3 days. If, on the other hand, the chromosphere is allowed to be stratified, ensuring a very low He abundance at the top of the chromosphere, they find that the coronal He abundance can be kept at lower values, in accordance with observations. Thus, the results of *Killie et al.* (2005) suggests that turbulent mixing processes are not important in the upper chromosphere.

To summarize, the results of *Hansteen et al.* (1997) and *Lie-Svendsen et al.* (2003), who modeled the solar wind on open flux tubes, suggest that turbulent mixing processes are important in the upper chromosphere, whereas the results of *Killie et al.* (2005), who modeled a quiescent coronal loop, suggest that turbulent mixing processes are not important in the upper chromosphere. One way to resolve this inconsistency is to allow for higher flow velocities in the chromosphere below open magnetic structures than what was obtained in *Hansteen et al.* (1997) and *Lie-Svendsen et al.* (2003).

As mentioned at the start of this Section, earlier models of the fast solar wind assumed either radial expansion of the magnetic field, or a super-radial expansion with an expansion factor of about 5 (*Hansteen et al.*, 1997; *Lie-Svendsen et al.*, 2003). In recent years it has become more common to assume a large super-radial expansion of the field. One consequence of a large magnetic field expansion factor is that the flow velocity in the chromosphere must be large to obtain the observed solar wind mass flux at 1 AU (*Esser et al.*, 2005). Using the neutral He momentum equation *Lie-Svendsen et al.* (2003) obtained an analytical expression for the largest possible He flux in the solar wind and found that an expansion factor of 15 or larger would be necessary to obtain a reasonable He flux in the solar wind.

The effect of a large expansion factor, of order 100, on the He abundance in the corona and solar wind was investigated by *Janse et al.* (2007). They concluded that in such a geometry the He abundance in the solar wind will be equal to the photospheric He abundance. Hence, an artificially enhanced collision frequency between neutral particle species in the chromosphere was no longer required to avoid a severely He-depleted fast solar wind. In other words, for a large magnetic field expansion factor it is not necessary to invoke turbulent mixing processes in the chromosphere to obtain a significant amount of He in the fast solar wind. In Paper I of this thesis it is shown that the observed solar wind He abundance can be reproduced with an expansion factor of order 10-20, in accordance with *Lie-Svendsen et al.* (2003).

The result obtained in Paper I leaves us with an important question. Will an expansion factor of order 20 also lead to solar wind abundances in accordance with observations for other high-FIP minor elements such as O and Ne? A clue to the answer can be found in *Pucci et al.* (2010), who modeled fractionation in the chromosphere due to gravitational settling for O, Ne and Fe. They find that the strongest constraint on the expansion factor is provided by the observed fast solar wind Ne abundance and that an expansion factor of at least 30-40 is required to produce a reasonable Ne flux in the solar wind. However, their model did not include He. In Paper II, we have therefore extended the study in Paper I to include O and Ne.

3.2 Gravitational settling in the corona

As mentioned in the discussion of the study of *Killie et al.* (2005), the steep temperature gradient in the transition region, which causes the strong "thermal" force acting on He ions, ensures that a large accumulation of ionized He in the corona is required to force a downflow of ionized He through the transition region. In open magnetic flux tubes, where the net outflow is nonzero, there is no need for a downflow of ionized He to cancel the upflow of neutral He in the transition region. In the case of an open flux tube the upflowing neutral, and subsequently ionized, He can be lost to the solar wind. In fact, once the He ions reach the corona, the energy required to escape the solar gravitational field is lower than the energy required to flow back down the temperature gradient to the chromosphere. Therefore, the He ions that flow into the corona in an open flux tube will be lost to the solar wind. Nevertheless, coronal He abundance enhancements may exist on open flux tubes as well.

In the low corona the collisional coupling between H and He (now in the form of protons and alpha particles) is strong, ensuring approximately equal flow velocities for the two species. As the proton and alpha particle temperatures increase and the density decreases further out in the corona the collisional coupling becomes weaker (i.e. the $p-\alpha$ collision frequency, $\nu_{p,\alpha}$ decreases). As in the chromosphere, the He flow velocity must adjust itself so that the friction force together with the pressure gradient force can balance gravity. When the $p-\alpha$ collision frequency decreases, the alpha particle flow velocity must then decrease relative to the proton flow velocity, to maintain the required magnitude of the friction force, which is proportional to $(u_p - u_\alpha) \cdot \nu_{p,\alpha}$. When the alpha particle velocity decreases relative to the proton velocity, mass conservation dictates that the alpha particle density must increase relative to the proton density, i.e. that a local He abundance enhancement must form. The He abundance enhancement results in an increased pressure gradient force, pushing the He ions away from the local density maximum, i.e. both towards the sun (although not with suffucient magnitude to force a downflow of He ions) and away from the sun and into the solar wind.

The slow moving He ions in the corona will act as a drag on the outflowing protons. The result is a reduction of the H flux, and thereby also a reduction of the He flux into the corona, since the He flux is proportional to the H flux. So there are two mechanisms working to limit the He abundance enhancement; the pressure gradient force, which is a direct result of the abundance enhancement, and the reduction in the He flux into the corona, which results from the drag on protons caused by the abundance enhancement. The abundance enhancement in the corona will grow until the He flux out of the corona matches the He flux into the corona.

As we saw in Chapter 2, the observations indicate that the He abundance in the low corona is never larger than 5%. In the region above 1.1 $R_\odot$ the coronal He abundance is essentially not known. Interestingly, all previous theoretical studies of the coronal He abundance in polar coronal holes, including the ones mentioned in Section 3.1, predict an abundance enhancement with a maximum at about 1.1 $R_\odot$, although the magnitude of the predicted abundance enhancement varies.

However, the coupling between He ions and protons depends sensitively on the proton temperature and in the studies of *Hansteen et al.* (1997); *Lie-Svendsen et al.* (2003) and *Janse et al.* (2007), the proton temperature reaches high values at low heights, typically about 3 MK or higher at 1.1 $R_\odot$. This is higher than what is reported in observational studies of the coronal proton temperature (*Cranmer et al.*, 1999; *Esser et al.*, 1999). In Paper I, we study coronal He abundance enhancements in a corona where the proton temperature is limited to lower values.

The possibility of abundance enhancements in the corona is, of course, not limited to He. As *Lie-Svendsen and Esser* (2005) showed, coronal abundance enhancements should be expected also for other minor elements, such as e.g. O and Si, if they are not heated sufficiently in the corona. In Paper II we study how variations in the location and magnitude of the coronal He abundance enhancement will affect the location and magnitude of a coronal O abundance enhancement. Nor is the possibility of coronal abundance enhancements limited to coronal holes. As stated in Section 2.2, the observations of *Habbal et al.* (2007) showed evidence of local density enhancements of Fe^{+10} and Fe^{+12}, with the most pronounced enhancements occurring along streamer edges.

As discussed in Section 1.3, knowledge of the coronal abundance of a minor element could be used to place constraints on the coronal heating rate for that element, given sufficient knowledge about the background proton-electron plasma parameters. However, the observations of *Habbal et al.* (2007) only provide evidence for local density enhancements of two specific charge states of Fe, which may or may not be associated with an elemental abundance enhancement. In addition, the density enhancements are in some regions seen only in one of the two

Fe ion species. Furthermore, reliable observations of the proton-electron plasma parameters in streamer-edge regions are difficult, since they can easily be contaminated by light from the plasma inside the streamer itself. In this context, two questions arise: 1) can Fe elemental abundance enhancements exist in the corona for the kind of proton-electron plasma conditions that are expected in streamer-edge regions? and 2) can coronal density enhancements exist only for specific charge states of Fe, depending on the heating rate for each individual charge state? In Paper III, we study elemental Fe abundance enhancements in the slow solar wind for different Fe heating rates and for different proton-electron plasma parameters.

Chapter 4

Summary of the results

In **Paper I** it is shown that for coronal proton-electron densities and temperatures in accordance with observations, coronal He abundance enhancements will occur in the region above 1.1 $R_{\odot}$. Since there are no measurements of the He abundance in this region, we cannot exclude the presence of He abundance enhancements in the corona. In fact, the results show that it is necessary to deposit large amounts of heat into the alpha particles in the corona to avoid a coronal He abundance enhancement. The study also confirms the results of *Lie-Svendsen et al.* (2003), who obtained an analytical expression for the largest possible He flux in the solar wind and found that an expansion factor of about 15 would be necessary to obtain a reasonable He flux in the solar wind. Assuming a He abundance in the mid-chromsophere of 8.5%, it is found that the observed solar wind He abundance can be reproduced with an expansion factor of about 20.

In **Paper II** we find that an expansion factor larger than 40 is required to obtain the observed Ne abundance in the fast solar wind. This is in good accordance with the results of *Pucci et al.* (2010). Since we cannot reproduce both the observed He abundance and the observed Ne abundance simultaneously in our present model, it is clear that a more complete model of the chromosphere is needed to understand why the He and other high-FIP element abundances change between the photosphere and the solar wind. Recent observations with the Hinode and Solar Dynamics Observatory spacecrafts (*De Pontieu et al.*, 2011) have revealed that fountainlike jets or spicules can accelerate plasma upwards from the chromosphere and into the corona. If these jets are responsible for a significant part of the mass supply to the corona, then the explanation for the abundance variations between the photosphere and the corona/solar wind should be sought within a theoretical framework and a model which is also capable of describing the physics of these plasma jets.

Although the degree of flux tube expansion cannot alone account for the variations in abundance between the photosphere and the solar wind, our results confirm that this effect, especially for Ne, is important and should be taken into account in models that aim to explain how the minor element abundances in the solar wind are determined. We also confirm another result from *Pucci et al.* (2010), that O may be fractionated with respect to H in the solar wind. Our results clearly show that to assume a constant abundance for any minor element in the whole region spanning the chromosphere, transition region and corona is problematic.

The effect of He on minor element abundance enhancements in the corona is also investigated in Paper II, using O as an example. As in the case of He, we find that an O abundance enhancement will be present in the corona, unless the O ions are heated considerably. The amount of heating which is required to avoid an abundance enhancement will result in an O^{+5} temperature which is higher than what is commonly observed in coronal holes. The magnitude and location of the O abundance enhancement depends mainly on the O heating parameters, but also weakly on the magnitude and location of the He abundance enhancement.

Furthermore, we find in Paper II that the high flow velocities that are associated with strong He heating causes the O and Ne ions to be pushed far out of ionization equilibrium, with the result that observed ion fractions for O and Ne in the solar wind cannot be reproduced. This result places constraints on the magnitude of the coronal He abundance enhancement (strong He heating means little or no enhancement of the coronal He abundance), as well as on the outflow velocity in the corona.

The results from both Paper I and Paper II strengthen the conclusion, drawn from many years of modelling the H-He solar wind (e.g. *Bürgi and Geiss*, 1986; *Hansteen et al.*, 1997; *Lie-Svendsen et al.*, 2003; *Janse et al.*, 2007), that He abundance enhancements should be a common feature in coronal holes. The results from the HERSCHEL sounding rocket mission should be able to confirm the presence of coronal He abundance enhancements, if indeed they exist (*Pancrazzi et al.*, 2010). The observed magnitude of the enhancements may give a clue to the partitioning of energy between protons and alpha particles in the corona, and if such observations could be made routinely it would provide insight into the variability of the coronal heating of protons and alpha particles. Such insight could in turn be helpful in the identification of the coronal heating mechanism(s).

In **Paper III** we show that the observed enhancements in the Fe XI line/continuum ratio in streamer edge regions (*Habbal et al.*, 2007) are consistent with Fe elemental abundance enhancements in the corona, caused by low heating rates for Fe. However, the exact heating rate required to obtain an elemental abundance enhancement in accordance with the observations depends sensitively on the proton-electron plasma parameters, and no strong constraint could be placed on the Fe heating rate based on the results presented in the paper. It was also found that by applying more heating to the Fe^{+12} ions compared to the Fe^{+10} ions, it is possible to avoid a density enhancement for Fe^{+12} while retaining the density enhancement for Fe^{+10}. These results show that if the background proton-electron plasma parameters can be determined with accuracy, observations of density enhancements of Fe charge states, in combination with modelling, could provide constraints on the coronal heating rates for Fe ions. The results from Paper II and Paper III, together with the observations of *Habbal et al.* (2007) suggest that coronal abundance enhancements on open field lines may be common for minor elements as well as for He.

Finally, we find that the proton-electron background solution with the lowest densities and the highest flow velocity comes closest to reproducing the observed in-situ ion fractions of Fe^{+10} and Fe^{+12}. Freezing-in occurs at large distances ($\sim 4 - 10$ $R_\odot$), where the electron temperature is considerably lower than at the electron temperature maximum. In the high-speed background, the Fe ions are pushed out of ionization equilibrium and the recombination of the high charge states, which would otherwise take place as the electron temperature drops, is inhibited. Thus, the results of Paper III support the idea that the slow solar wind is rooted in magnetic field structures with coronal hole-like densities in the low corona, as suggested by *Abbo et al.* (2010); *Antonucci et al.* (2005) and *Antonucci et al.* (2006).

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Appendix : Papers

Paper I

The helium abundance in polar coronal holes and the fast solar wind

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Paper II

O and Ne in a H-He fast solar wind

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Paper III

Modeling iron abundance enhancements in the slow solar wind

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