FIP FRACTIONATION: THEORY

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Abstract. In this review, the main models of ion-neutral fractionation leading to an enhancement of the low FIP to high FIP abundance ratio in the corona or in the solar wind, are presented. Models based on diffusion parallel to the magnetic field are discussed; they are highly dependent on the boundary conditions. The magnetic field that naturally separates ions from neutrals moving perpendicular to the field lines direction, when the ion-neutral frequency becomes lower than the ion gyrofrequency, is expected to play an active role in the ion-neutral separation. It is then suggested that ion-neutral fractionation is linked to the formation of the solar chromosphere, i.e., in magnetic flux-tubes at a temperature between 4000 and 6000 K.

Key words: Element Abundances, FIP effect

1. Introduction

General reviews on the element abundances in the solar atmosphere have been published (Feldman, 1992; Saba, 1995; Meyer, 1993a; Meyer, 1993b; Fludra et al., 1998). Relative abundances were measured in the corona, transition region, and recently in the low chromosphere at the site(s) of solar flares, and compared to the mean photospheric abundances. Efforts have been made to determine variations of relative solar element abundances with specific solar features – quiet sun, active regions, sunspots, coronal holes, polar plumes and flares – showing variations between these structures.

On average, elemental abundances in the solar wind, and solar energetic particles abundances measured in situ, are in agreement with spectroscopic measurements of abundances in the upper solar atmosphere (Meyer, 1996a, 1996b). With respect to the photospheric composition, the low FIP elements are enriched relatively to the high FIP elements by a factor of about four. The discontinuity in abundances, allows to separate two classes of low FIP and high FIP elements and takes place between 10 and 11 eV.

2. Main Characteristics of the FIP Fractionation Models

Theoretical models of ion-neutral fractionation in the solar atmosphere have been built in order to explain the observed FIP dependence of the variation, from photosphere to corona, of the relative abundance of the solar atmosphere elements. They either consider a steady-state situation or follow the time evolution of the fractionation.

Most models assume element fractionation to take place in the chromospheric temperature plateau. They use parameters selected empirically to describe an atmosphere uniformly horizontally stratified. However, the great diversity of solar atmospheric magnetic structures, open, closed, quiet or active, which seems to be associated with various amplitudes of the fractionation effect, implies, that there is no need for a unique FIP fractionation model.

Models of fractionation have been suggested where the magnetic field does not play any role, except guiding the ions once they have been formed. In these models, fractionation results from diffusion along field lines, under the effect of collisions with vertically moving neutral hydrogen atoms and protons, of minor species irradiated by UV photons. The precise models, take into account the consecutive diffusion of the generated ions and hydrogen ionisation. They differ mainly by the boundary conditions used.

The observed magnetic structuration of the solar atmosphere, both in the very low chromosphere and in the corona, suggests that the magnetic field may play a key role in the FIP fractionation. At densities low enough for collisions not to couple ionized and neutral atoms, neutral high FIP elements can escape from a magnetic structure perpendicularly to the lines of force, which is not the case for ionized low FIP elements. For magnetic fields strong enough for this condition to be satisfied, these densities are chromospheric. Therefore, definite progress in understanding FIP fractionation may be linked to the understanding of the conditions of formation of the chromosphere.

3. Basic Equations

All models use the same basic equations, i.e. the continuity and momentum balance equations:

3.1. Continuity Equations

In 3D, the continuity equations (Burgers, 1960; Schunk, 1975) can be expressed as

$$\frac{\partial}{\partial t} n_j + \nabla \cdot (n_j u_j) = \frac{\delta}{\delta t} n_j$$

(1)

where the quantity on the right hand side of eqn. (1) is the rate of change of density as a result of collisions, and \(n_j\) and \(u_j\) are respectively the number density and velocity of the particle \(j\). Charge exchange does not modify the densities of the neutral and ionized fractions of a species. Consequently, and limiting ourself to the 1D case, writing respectively \(j^0\) and \(j^+\) the neutral and ionized species \(j\) (including in \(j^+\) all the states of ionization), the continuity equations can be rewritten as:

$$\frac{\partial}{\partial t} n_j^+ + \frac{\partial}{\partial \sigma} (n_j^+ u_j^+) = \gamma_j j^- j j^- n_j^- \quad \gamma_j j^- j^+ n_j^+$$

(2)