Particle diffusion in atmospheres of CP stars

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Abstract. We give concisely the formulae governing diffusion of chemical elements and their isotopes in quiescent stellar atmospheres, due to electrostatic, gravitational and radiation fields and to impacts between particles. Isotope segregation of heavy elements due to light-induced drift is emphasized.

Key words: stars: chemically peculiar – diffusion

1. Introduction

The diffusive separation of chemical elements and their isotopes in stellar atmospheres can occur only in the case of lacking macroscopic motions, i.e. if the stellar wind and the meridional circulation are extremely weak and there is no convective turbulence. These conditions hold only for CP stars, and overabundances of heavy elements in their atmospheres can reach several orders of magnitude.

2. Diffusion equations of plasma components

The element diffusion is described with sufficient accuracy if we take into account the collisions between different atomic particles and the presence of external gravitation, radiation and electrostatic fields (Sapar & Aret, 1995). Momentum transfer from particles of types i to particles j is described by

$$\frac{\partial(\rho_j \boldsymbol{V}_j)}{\partial t} + \boldsymbol{\nabla} P_j = \rho_j \boldsymbol{a}_j + \sum_i \nu_{ij} \rho_i \boldsymbol{V}_i - \nu_j \rho_j \boldsymbol{V}_j \ . \tag{1}$$

Here the collision frequency of particle j with particles i and total collision frequency for particles j are to be found from expressions

$$\nu_{ji} = n_i \iint \sigma_{ji}(v_{ji}) v_{ji} f_j f_i d\boldsymbol{v}_i d\boldsymbol{v}_j \ , \quad \nu_j = \sum_i \nu_{ji} \ , \tag{2}$$

where n_i is the number density, v_{ji} the relative particle velocity and f_i the undisturbed velocity distribution. Indices indicate species of particles — all ions are treated separately and electrons are included as one of them.

In the time–independent approximation we obtain from Eq.(1) a system of algebraic linear equations for diffusion velocities V_j:

$$\nu_j \rho_j \boldsymbol{V}_j = \boldsymbol{F}_j + \sum_i \nu_{ij} \rho_i \boldsymbol{V}_i \ , \qquad \text{where} \quad \boldsymbol{F}_j = -\boldsymbol{\nabla} P_j + \rho_j \boldsymbol{a}_j \ . \tag{3}$$

Using a buffer-gas approximation we neglect interactions between heavy elements as small admixtures and take into account for each of them separately only interaction with buffer gas particles. Calculations showed, that adequate buffer gas mixture for modelling consists of H, He, C, N and O. The diffusion equations for a particular element can be derived from the continuity eqation

$$\frac{\partial \rho_\varepsilon}{\partial t} + \boldsymbol{\nabla}(\rho_\varepsilon \boldsymbol{V}_\varepsilon) = 0 \ , \qquad \text{where} \quad \rho_\varepsilon = \sum_{j \in \varepsilon} \rho_j \ , \quad \boldsymbol{V}_\varepsilon = \frac{1}{\rho_\varepsilon} \sum_{j \in \varepsilon} \rho_j \boldsymbol{V}_j \tag{4}$$

where summing is carried out over all particle species belonging to element ε. The electron density is to be found from the condition of gas electroneutrality.

The external acceleration of plasma particles due to gravity, electrostatic field, radiative acceleration both in spectral continua and lines and due to light–induced drift (Atutov & Shalagin, 1988; Nasyrov & Shalagin, 1993) has the form

$$a_j = \boldsymbol{g}_j + \frac{Z_j e}{m_j} \boldsymbol{E} + \boldsymbol{a}_{j,rad} \ . \tag{5}$$

Electrons, since they are much lighter than ions, tend to drift up in the atmosphere, generating an electrostatic field which blocks their escape. The electrostatic field has almost no influence on diffusion of heavy elements, but for light ions its lifting force can even prevail upon the opposite–directed gravity.

The electrostatic field can be found from the main system of linear equations for diffusion velocities and the condition of no electric current $\sum_i n_i Z_i \boldsymbol{V}_i = 0$.

In numerous studies (see Gonzalez et al., 1995; Michaud & Proffitt, 1993; Alecian et al., 1993; Ryabchikova, 1992 and references therein) the radiative expelling force for the majority of elements has been computed both for stellar atmospheres and for their envelopes. For line–rich metals the expelling force highly exceeds the gravity, thus being the dominant factor for the formation of observed metal overabundances in the CP stellar atmospheres..

Some essential discrepancies between the observations and theory have remained (Wahlgren et al., 1995). They can be partly removed when the light–induced drift is also taken into account (see also LeBlanc & Michaud, 1993).

In free–free and bound–free electron transitions the momentum of the photon is transferred to the generated ions. In bound–bound transitions it is transferred to particles in the upper state u and the radiation flux acts on them with a force:

$$\boldsymbol{f}^r_{ul} = \frac{\pi}{c} \int n_l \, \sigma_{ul}(\nu) \, \boldsymbol{F}_\nu \, d\nu \ , \qquad \sigma_{ul}(\nu) = \sigma^0_{ul} W(u_\nu, a) \ , \tag{6}$$

where n_l is the number density of particles in the lower state, $\boldsymbol{F}_\nu$ is the monochromatic flux, $\sigma_{ul}(\nu)$ is the photon absorption cross-section in the transition $l \rightarrow u$

which can be written using the Voigt function $W(u,a)$. The parameters of the Voigt function are $u = (\nu - \nu_0)/\Delta\nu_D$ and $a = \Gamma_{ul}/(4\pi\Delta\nu_D)$.

To find the radiative force acting on a particular ion, we need to summarize over all transitions. The effect of light–induced drift can be taken into account by substituting the Voigt function $W(u,a)$ in the radiative-force expression for spectral lines by

$$w(u,a) = W(u,a) - 2qD\frac{\partial W(u,a)}{\partial u}\,, \qquad \frac{\partial W(u,a)}{\partial u} = -\frac{\partial W(-u,a)}{\partial u}\,. \tag{7}$$

The expression $q = c\sqrt{2MkT}/h\nu$ is the ratio of the mean momentum of the ion species studied to the momentum of the absorbed light quantum, $h\nu/c$, being about 10^4. The light-induced drift is generated due to the lower mobility of atomic particles in the excited (upper) states resulting from larger impact cross-sections than in the ground (lower) state, yielding thus lower diffusion rates (particle mobilities) for excited states.

The uncompensated drift rate due to the difference of cross-sections σ is given by the expression $D_1 = 1 - \sigma_l/\sigma_u = \Delta\sigma/\sigma_u$. The spontaneous transitions which take place before collisions reduce the drift rate by factor $D_2 = 1 - A/(A+\nu_u) = \nu_u/(A+\nu_u)$, where A is the probability (frequency) of spontaneous transitions. Thus, the total reduction factor is $D = D_1 D_2 = \Delta\nu/(A+\nu_u)$. The effective value of $2Dq$ reduces to about 10^2 in the upper atmosphere and reaches to about 10^4 in the deeper layers.

The most effective case for light-induced drift is if in blends, the fluxes in the blue and red wing of a spectral line differ essentially, especially for isotope splitting of resonance spectral lines of heavy elements where the isotopic wavelength difference of spectral lines is of the order of the thermal Doppler width. In this case only the heaviest isotopes dominate in the atmospheres as observed, say, by HST for Hg, Tl and Pt in the spectrum of χ Lup (Wahlgren et al., 1995).

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