Element Stratification in Stars: 40 Years of Atomic Diffusion
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THE ROLE OF LIGHT-INDUCED DRIFT IN DIFFUSION OF HEAVY METALS AND THEIR ISOTOPES IN CP STARS: AN EXAMPLE OF MERCURY

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Abstract. Main theoretical formulae and some computational results of evolutionary segregation of Hg isotopes due to light-induced drift in the atmospheres of chemically peculiar stars have been represented.

1 Introduction

The important role of light-induced drift (LID) in diffusive separation of chemical elements and their isotopes in the atmospheres of CP stars has been brought up by Atutov & Shalagin (1988) and later studied by Nasyrov & Shalagin (1993), LeBlanc & Michaud (1993), Sapar & Aret(1995) and Aret & Sapar (2002). On the example of mercury we show that LID gives an essential contribution to diffusion of heavy elements and their isotopes in the atmospheres of CP stars, causing sedimentation of lighter isotopes and levitation of the heavier ones. The computations of the evolutionary model atmosphere sequences have been made using a FORTRAN program SMART, composed by the authors.

2 Segregational evolution of heavy metal isotope abundances

Diffusional segregation of isotopes is based on the equations of continuity and of the diffusion velocity V_i. Using the ratio C_i of abundance (concentration) to its initial value for isotope i of the chemical element studied, we get for the plane-parallel stellar atmosphere the equations in the form suitable for the model computations:

$$\frac{d\ln C_i}{dt} = \nu_i + \left(\frac{d\ln\mu}{dn}\right)^{-1}\left(\frac{d\nu_i}{dn} + \nu_i\frac{d\ln C_i}{dn}\right), \quad \nu_i = \frac{\rho V_i}{\mu}, \quad V_i = a_i t_i - \Delta_i\frac{d\ln\rho C_i}{dr},$$

where ρ is the total density, μ is the total column density of the stellar atmosphere and n is the number of the current atmospheric layer. We used the simplest

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expression for the diffusion velocity ignoring thermal diffusion. Here a_i is the total acceleration due to gravity, light pressure and LID. Free flight time between collisions t_i has been estimated from formula $\Delta_i = kTt_i/M_i$, where the diffusion coefficients Δ_i were taken from the paper by J.-F. Gonzalez *et al.* (1995) and averaged duly over the ionization stages. Thus

$$\frac{d\ln\rho C_i}{dn} = -\frac{M_i a_i \mu}{kT\rho}\,\frac{d\ln\mu}{dn}.$$

Equivalent acceleration due to LID for transitions from a lower quantum state l to the upper state u can be found as (Aret & Sapar 2002):

$$a^d_{ul} = qD\frac{\pi}{c}\int\limits_0^\infty \sigma^0_{ul}\frac{\partial W(u_\nu,a)}{\partial u_\nu}F_\nu d\nu\ ,$$

where σ^0_{ul} is the total transition cross-section per gram, $W(u_\nu,a)$ is the Voigt function, $q = Mv_Tc/2h\nu$ and the efficiency of LID $D = (C_u - C_l)/(A_u + C_u)$, where C_u and C_l are the collision frequencies of particles in upper and lower states and A_u is the frequency of spontaneous transitions.

Collision frequencies were found using Coulomb interaction model for ions and hard-sphere collision model for neutrals as in Gonzalez *et al.* (1995). We accepted that the interaction force due to atomic polarisability is proportional to r^{-5} and thus the integral contribution of the core is proportional to r^{-4}. We assumed that the contribution of the core to the collision cross-section of ions is characterized by the factor $\phi_j = (1-\delta_{0j})D_0^2/D_j^2$, where D_j is the diffusion coefficient of the particle in the ionization stage j. The radius of the core in the hard-sphere model has been taken to correspond to the effective main quantum number in the hydrogenic approximation. Thus the total diffusion coefficient of the LID for the sum of ions j is $\Delta_i = \sum_j(D_0\phi_j + D_j)X_j$, where X_j is the ionization rate of ions j.

The influence of microturbulence on the diffusion can be expressed via an additional turbulent diffusion coefficient D_T in the expression of the diffusion velocity (Schatzman 1969), namely in this case

$$V_i = a_it_i - (\Delta_i + D_T)\frac{d\ln\rho C_i}{dr}, \quad \text{where}\ \ D_T \sim \left(\frac{kT}{M}\right)^{3/2}\frac{1}{g}\ .$$

We obtained the expression for D_T assuming that the characteristic microturbulence velocity is of the order of the mean thermal velocity of heavy metals with mass M and the characteristic height is of the order $H = kT/Mg$. Consequently $D_T \gg \Delta_i$ and as a result the equilibrium gradient of $|\ln C_i|$ is essentially smaller and the diffusive evolution is many dex slower than in the case of ideally quiescent stellar atmosphere.

3 Input data and results of evolution modelling

Model computations including LID demand high-precision input physics. Since the overlap of spectral lines is crucial for the LID generation, precise isotopic and

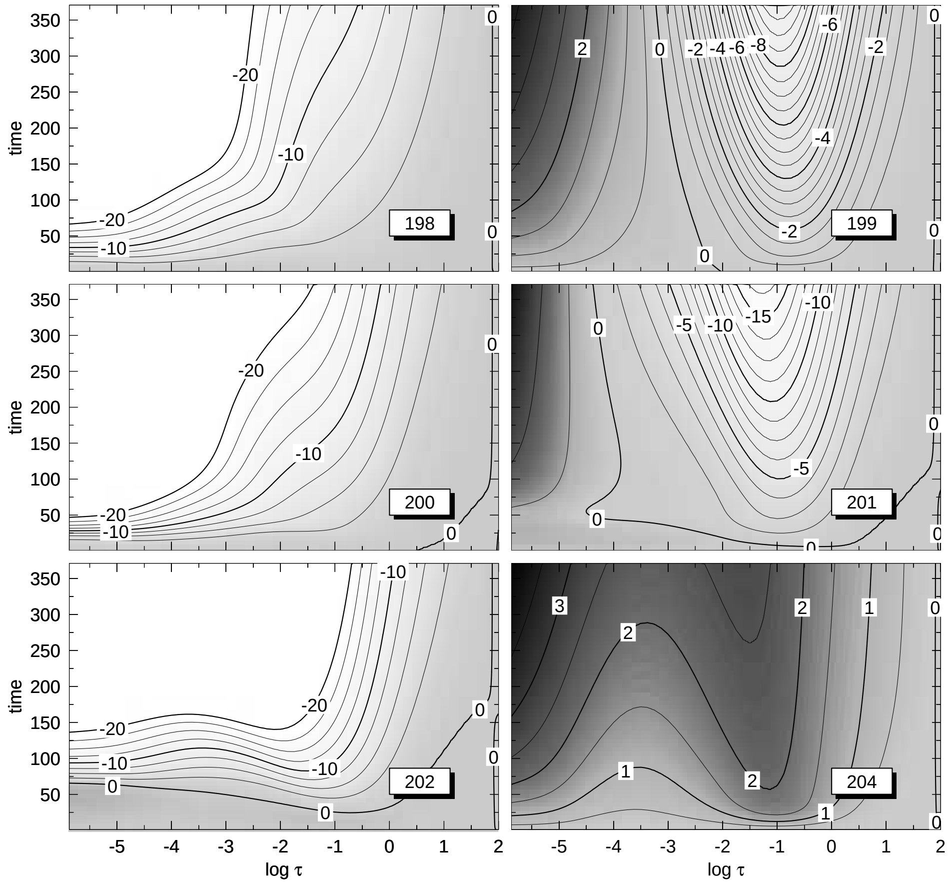

Fig. 1. Evolutionary changes of the ratio C_i of Hg isotope abundances to their initial values in the logarithmic scale, i.e. $\log C_i$ for the initial $\log N_{\rm Hg}$ = solar + 6 dex. Atomic weights of Hg isotopes are shown in panels. Time scale (yrs) is tentative, illustrating trends of evolutionary changes since microturbulence has been ignored. According to our estimates the turbulent mixing should decelerate the diffusion processes from about 1000 times in the outer layers to millions times in the deepest layer.

hyperfine splitting of spectral lines are necessary. Spectral line data were mostly taken from the lists by Kurucz (CD18) and Vienna database VALD. Isotopic splitting for most of Hg lines was calculated using relative shifts (Striganov & Dontsov 1955). Hyperfine and isotopic structure and oscillator strengths of Hg lines, available in papers by Proffitt *et al.* (1999) and Smith (1997) were used to improve our line list. Calculations were carried out for the model atmosphere corresponding to the star HR7775 ($T_{eff} = 10750, \log g = 4, V \sin i = 0, V_{turb} = 0$) with different initial mercury abundances: solar abundance $\log N_{\rm Hg}$= -10.9 (Anders & Grevesse

1989), solar + 6 dex and isotopic mixture of HR7775 (Dolk *et al.* 2003).

The boundary values of velocities at the outermost layer were assumed to be zero and at the bottom the isotope flows were linearly extrapolated. Evolutionary changes in the quiescent stellar atmospheres are proceeding very rapidly, especially in outer layers. In the beginning of the evolution process in the star with solar abundances of Hg isotopes the radiative drive is dominant, causing rise of abundance of all Hg isotopes. In outer layers this process is much faster than in deeper layers of atmosphere. The radiative acceleration is dominant at low Hg abundances because then the weak mutual influence of Hg lines cannot produce any essential asymmetry of spectral line profiles. The same holds for outer layers where the electrons of excited states return to lower states before they collide. With increasing of the Hg abundance the role of LID also increases causing levitation of heavier and sedimentation of lighter isotopes (Fig. 1). In the case of HR7775 where only two heaviest isotopes are present the LID causes sedimentation of ^{202}Hg and levitation of ^{204}Hg. Hyperfine splitting evokes somewhat more complicated picture of evolutionary changes of isotope abundances. Diffusion processes in the case of initial solar abundances turned out to be more than 100 times slower than in atmosphere with initial $\log N_{\mathrm{Hg}} = \mathrm{solar} + 6\mathrm{dex}$.

4 Main conclusions

We conclude that LID is important for diffusional segregation of isotopes of heavy elements. The concept of quiescent atmospheres can explain generally the LID phenomenon in CP stars. To describe it in more detail, the microturbulence must be taken into account and the computations of stellar atmospheres must be extended for stellar envelopes. For heavy chemical elements LID causes the levitation of the heaviest isotope and generally sedimentation of the lighter ones. Our calculations show that abundances of mercury isotopes vary throughout the CP star atmosphere, what is supported also by observations.

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