# ISOTOPIC ANOMALIES IN CP STARS

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ABSTRACT. In the present paper we analyze the anomalies in the atmospheres of HgMn stars. The abundance anomalies include both overabundances and underabundances of heavy elements. Recent observations show strongly anomalous isotopic composition of Hg, Pt, Tl and of He. Generation of abundance anomalies in quiescent atmospheres of CP stars is successfully explained by the mechanism of diffusional segregation of elements due to oppositing gravitational and radiative forces, but the formation of isotopic anomalies is not yet well explained. New diffusion mechanism called light-induced drift (LID), added to the one of radiative acceleration, successfully explains the observed isotopic anomalies. We have refined the theory of LID and applied it to CP star atmospheres. The results of computations confirm the important role of LID for diffusive segregation of isotopes.

**Key words**: diffusion; stars: abundances; stars: chemically peculiar

## 1. Introduction

Elemental abundances of about 15 % of atmospheres of main sequence stars of spectral classes B5–F5 are anomalous. Generation of these anomalies in quiescent atmospheres of CP (chemically peculiar) stars are ascribed to elemental diffusion due to radiative acceleration (Michaud 1970). In the present paper we analyze the anomalies in the atmospheres of mercury–manganese (HgMn) stars. The HgMn stars have $T_{eff}$ between 10 000 and 16 000 K. Their abundance anomalies include both overabundances (Mn, Sr, Pt, Hg, Ga et al.) and underabundances (Al, Ni, Co et al.). Recent observations show strongly anomalous isotopic composition for Hg, Pt, Tl (overabundancy of heavier isotopes) and He (overabundancy of $^3$He). The HgMn stars have low rotational velocities ($v\sin i = 1 - 20$ km s$^{-1}$) and no detected magnetic fields. The adopted values of parameters of MnHg stars $\chi$ Lup and HR7775 are given in Table 1 as an example (Adelman 1994, Jomaron et al. 1998, Kalus et al. 1998, Smith & Dworetsky 1993, Wahlgren et al. 1994, 1995). The element abundances are given relative to the solar system values by Anders & Grevesse (1989).

Table 1: The adopted parameters of HgMn stars

| | $\chi$ Lup A | HR7775 | |
|---|---|---|---|
| $T_{EFF}$ | 10 650 | 10 800 | |
| log g | 3.9 | 3.95 | |
| Vsin i (km/s) | 0 | 1 | |
| [Hg/H] | +5.0 | +5.2 | |
| [Mn/H] | +0.3 | +0.8 | |
| [Pt/H] | +4.2 | +4.7 | |
| [Au/H] | +4.6 | +3.8 | |
| Isotopic composition, % | | | Terrestrial |
| Hg204 | 98.8 | 61.7 | 6.87 |
| Hg202 | 1.1 | 37.2 | 29.86 |
| Hg201 | 0.1 | 0.4 | 13.18 |
| Hg200 | – | 0.3 | 23.10 |
| Hg199 | – | 0.2 | 16.87 |
| Hg198 | – | 0.2 | 9.97 |

In general the theory of radiatively driven diffusion describes adequately the observed abundances of elements. It resulted that for line–rich metals the expelling radiative force highly exceeds the gravity, being thus the dominant factor for formation of observed metal overabundances in the CP stellar atmospheres. However, essential discrepancies between observed isotopic anomalies and predictions of the theory still remain. The situation can be changed by taking into account additional diffusion mechanism called light–induced drift.

## 2. Light-induced drift (LID)

The important role of LID in segregation of elements in CP stellar atmospheres was proposed about a decade ago by Atutov and Shalagin (1988). LID can be considered as an additional effect to radiative acceleration due to selective transfer of photon momentum to an atomic particle in the line absorption process. Let us consider absorption in a spectral line with asymmetrical wings (due to overlapping with a line of some other element or due to local slope of continuum). As a result of this asymmetry there appears also an asymmetry in the excitation rates of atoms and ions with different Doppler shifts of thermal velocities. If the flux in the

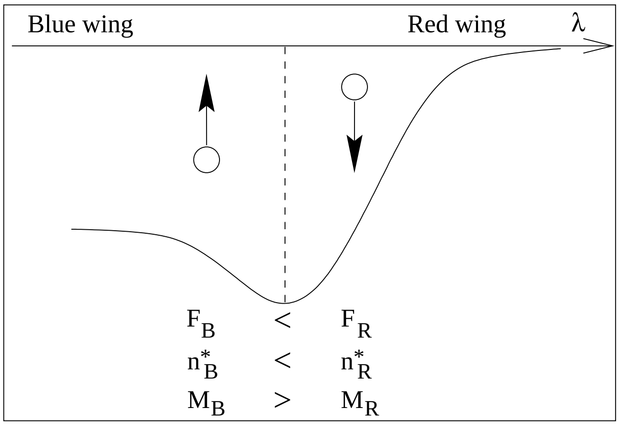


Figure 1: Scheme of the LID generation

red wing $F_R$ is larger than the flux in the blue wing $F_R$ (Fig. 1), there will be more excited ions moving downwards in atmosphere than moving upwards. The collisional cross–section is larger for atomic particles in the excited (upper) states than in the ground (lower) state and thus the mobility of particles in the excited states is lower than in the ground state. In Fig. 1 the mobility of particles moving downwards $M_R$ is lower than the mobility of particles moving upwards $M_B$, causing thus an effective upward flow of particles. The drift direction depends on asymmetry in spectral line: larger flux in the red wing produces upward drift, large flux in the blue wing — downward drift.

Isotopes with slightly shifted energy levels have overlapping spectral lines giving systematically similar asymmetry in line profiles. Thus, the LID is most effective for diffusive segregation of isotopes. Consider, for example, a heavy element with only two isotopes. Its lighter isotope has the blueward spectral lines and heavier isotope has the redward ones. As a result, one isotope induces a drift of another. Lighter isotope with larger flux in the blue wing drifts downwards and heavier isotope with larger flux in the red wing drifts upwards. For light elements (say, for He) the isotopic line shift and thus the LID direction are opposite. This means that the overabundance of $^3$He isotope and of the heaviest isotopes of Hg, Pt and some other heavy elements is expected.

### *2.1. Equations for LID*

Let the lower state of atomic particle be $l$ and the higher (upper) bound state $u$. In the result of photon absorption the radiation flux acts on particles in state $u$ with force density

$$\vec{f}^{\,r}_{ul} = \frac{\pi}{c} \int_{-\infty}^{+\infty} n_l\, \sigma_0 W(u_\nu, a)\, \vec{F}_\nu\, d\nu \ , \tag{1}$$

where $\pi\vec{F}_\nu$ is the total monocromatic flux, $n_l$ – the number density of particles in state $l$ and $\sigma_0$ – the cross–section of photon absorption in transition $l \to u$. The normalized frequency distribution in a spectral line or the Voigt function is the convolution of Lorentz and Doppler profiles, i.e.

$$W(u_\nu, a) = \int_{-\infty}^{\infty} W(u_\nu, a, y)dy \ , \tag{2}$$

where the integrand of the Voigt function

$$W(u_\nu, a, y) = \frac{a}{\pi^{3/2}} \frac{e^{-y^2}}{(u_\nu - y)^2 + a^2} \ . \tag{3}$$

The Voigt function parameters are $u_\nu = (\nu - \nu_0)/\Delta\nu_D$, $a = \Gamma_{ul}/(4\pi\Delta\nu_D)$ and $y = v/v_D$, where $v_D = \sqrt{2kT/M}$ and $M$ is the mass of the light–absorbing ion.

The light–induced drift starts with the process of transfer of thermal momentum from atomic particle in lower state to the particle in upper state induced by photon absorption. The momentum transferred in this way per unit volume and unit time interval $\vec{f}^{\,D}_{ul}$ is proportional to the volume density of particles $n_l$ and the photon flow $\vec{i}I_\nu/h\nu$, to the momentum of particle in the direction of photon propagation $Mv$ and to the photon absorption cross–section in line $\sigma_0 W(u_\nu, a, y)$, namely:

$$\vec{f}^{\,D}_{ul} = \int_0^{+\infty} \int_{-\infty}^{+\infty} \int_{4\pi} n_l M v \sigma_0 W(u_\nu, a, y) \vec{i} \frac{I_\nu}{h\nu} d\nu dy d\Omega \ . \tag{4}$$

Taking into account, that $v = v_D y$, $\int_{4\pi} \vec{i} I_\nu d\Omega = \pi\vec{F}_\nu$ and that from Eqs.(2) and (3) follows

$\partial W(u_\nu, a)/\partial u_\nu = -2 \int_{-\infty}^{+\infty} y W(u_\nu, a, y) dy$

we find expression for the transferred force density

$$\vec{f}^{\,D}_{ul} = -q\frac{\pi}{c} \int_0^{+\infty} n_l \sigma_0 \frac{\partial W(u_\nu, a)}{\partial u_\nu} \vec{F}_\nu d\nu \ , \tag{5}$$

where $q = \frac{M v_D}{2} \frac{c}{h\nu}$. The ratio of mean thermal momentum of atomic particle M to the momentum of absorbed photon is about $10^4$. That is why LID is important even in the case of moderate asymmetry of radiative flux in the spectral line profile.

LID appears due to difference of collision rates of ions in upper and lower states $\nu_u$ and $\nu_l$. The corresponding correction factor to $\vec{f}^{\,D}_{ul}$ is $1 - \nu_l/\nu_u$.

The LID efficiency reduces due to spontaneous radiative transitions by factor $1 - A_u/(A_u - \nu_u)$, where $A_u$ is the frequency (probability) of spontaneous transitions.

The final correction factor to $\vec{f}^{\,D}_{ul}$ is

$$D = \frac{\nu_u - \nu_l}{A_u + \nu_u} \ . \tag{6}$$

The value of $D$ can be found only with rather low exactness. For rough estimates we may take $A_u = 10^8\ s^{-1}$, for upper layers of the CP star atmospheres $\nu_u = 10^6\ s^{-1}$ and for lower layers $\nu_u = 10^8\ s^{-1}$. Additionally we assume $\nu_u/\nu_l = 2$. In this approximation the characteristic values of the correction factor $D$ are about $5 \cdot 10^{-3}$ in the upper atmospheric layers of CP stars and about 0.25 in the lower layers. Thus, the effective value of $Dq$ reduces to 50 in the upper atmospheric layers and conserves large values in the deeper layers.

The total effective force on atomic particle due to both the radiative force and LID is given by

$$\vec{f}^{t}_{ul} = \vec{f}^{r}_{ul} - D\vec{f}^{D}_{ul}\ . \tag{7}$$

Thus, the effect of light–induced drift can be included by substituting the Voigt function $W(u, a)$ in the radiative force expression Eq.(1) by

$$w(u_\nu, a) = W(u_\nu, a) + qD\frac{\partial W(u_\nu, a)}{\partial u_\nu}\ . \tag{8}$$

This means that LID can be treated as an additional specific force.

## 3. Computations

We elaborated computer codes to calculate the accelerations to chemical elements and their isotopes in stellar atmosphere, extensively modifying the codes from CD–ROM18 by R. Kurucz for model atmospheres and synthetic spectra. Both the usual radiative acceleration in spectral lines due to the transfer of photon momentum to the stellar matter and the equivalent acceleration due to the light–induced drift have been taken into account (Eq.(7)).

Accelerations for mecury isotopes (Hg 198, 199, 200, 202, 204) have been calculated in model stellar atmosphere with $T_{eff} = 10750$ K, $\log g = 4$, $v \sin i = 0$. Three different abundances of mercury were used: solar abundance ($log\frac{N_{Hg}}{N_H} = -10.95$), solar abundance + 5 dex (both with terrestrial mixture of isotopes) and the HR7775 isotope mixture given in Table 1.

The Kurucz CD–ROM18 line lists have been used. The number of used HgI spectral lines was 27 including 2 resonance lines and the number of HgII spectral lines was 31 including 5 resonance lines. Our computations showed that the dominant contribution in LID is given by resonance lines.

We adopted the relative isotope shifts as the mean values found by Striganov & Dontsov (1955): we have taken $[198-200] = -0.94$, $[199-200] = -0.80$, $[201-200] = 0.30$, $[202-200] = 1$, $[204-200] = 1.98$. In wavenumbers $[202-200] = 0.179$ cm$^{-1}$ for HgI and $[202-200] = 0.508$ cm$^{-1}$ for HgII.

The computations were carried out for the spectral interval from 800 to 12 000 Å with resolution $R = 5 \cdot 10^6$. Such a high resolution is needed because spectral lines of mercury are narrow and their isotopic shifts are small.

## 4. Results

The effective acceleration on mercury isotopes due to LID cannot be expected to be large in the case of solar abundances of isotopes because the blending with strong neighbouring lines is more important than the mutual influence of very weak lines of mercury isotopes. Nevertheless it turned out, that although the usual radiative acceleration plays the dominant role in this case, the value of LID is of the same order of magnitude reducing upwards directed total acceleration for $^{198}$Hg and increasing it for $^{204}$Hg.

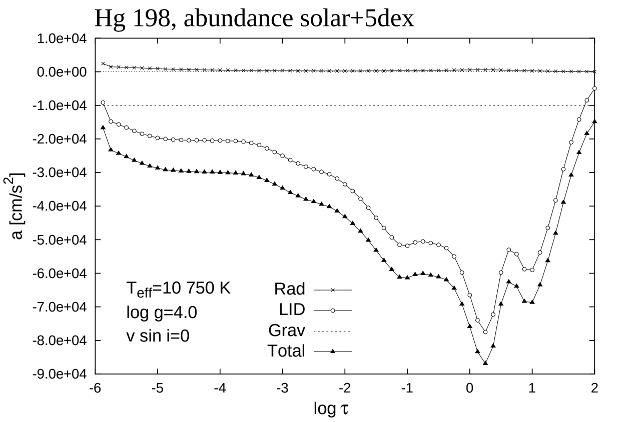


Figure 2: Accelerations on $^{198}$Hg ions due to radiative force, LID, gravity and the total acceleration

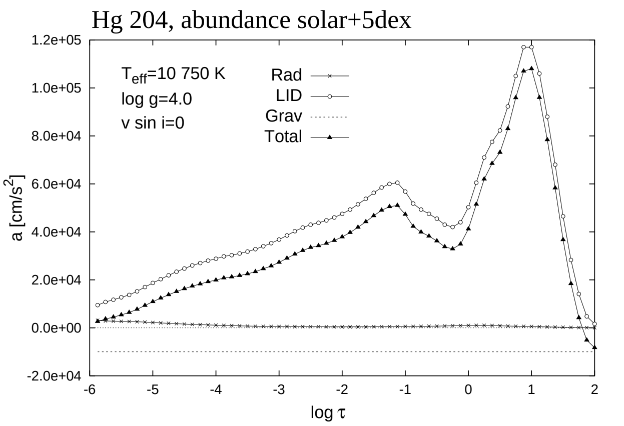


Figure 3: Accelerations on $^{204}$Hg ions due to radiative force, LID, gravity and the total acceleration

The situation is drastically different in the atmosphere with high mercury abundance (solar + 5 dex). The mercury lines in such an atmosphere are strong and the mutual influence of overlapping isotope lines is dominant generating large drift. Effective acceleration due to LID exceeds radiative accelaration up to two orders of magnitude, determining the total acceleration on mercury isotopes due to radiative force, LID and gravity. As expected, the acceleration on lightest isotope $^{198}$Hg is directed downwards (Fig.2) and the acceleration on heaviest isotope $^{204}$Hg is directed upwards (Fig.3). Total acceleration on the second heavy isotope $^{202}$Hg is also directed upwards, being smaller than $^{204}$Hg acceleration. Thus, LID causes sinking of lighter isotopes and rising of heavier ones leading to the segregation of isotopes.

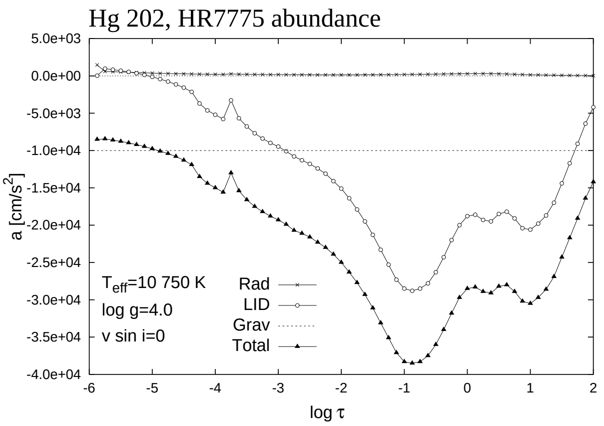


Figure 4: Accelerations on $^{202}$Hg ions due to radiative force, LID, gravity and the total acceleration

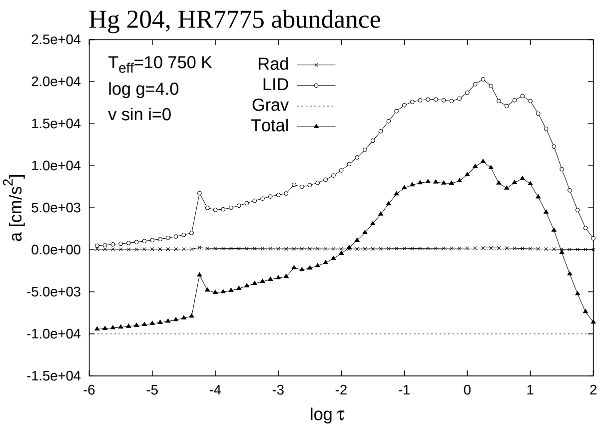


Figure 5: Accelerations on $^{204}$Hg ions due to radiative force, LID, gravity and the total acceleration

In the atmosphere of HR7775 the abundance of mercury exceeds solar abundance by 5 dex, at the same time the isotopic structure differs drastically from terrestrial (Table 1). As a result of segregation of isotopes only two heaviest isotopes remained and the segregation due to LID continues. Lighter of remained isotopes $^{202}$Hg which rised in atmosphere with solar mixture of isotopes now sinks (Fig.4). Accumulation of $^{204}$Hg continues (Fig.5).

Basing on our results we may conclude that isotopic composition in mercury–manganese stars evolves from solar mixture to mixture in HR7775 and further to extreme isotopic structure of $\chi$ Lup.

## 5. Concluding remarks

Light–induced drift turned out to be of the same order of magnitude as the usual radiative acceleration in atmospheres of the main–sequence A–stars for line–rich elements (such as iron and manganese). This means that the LID cannot be neglected in the evolutionary calculations of element abundances in atmospheres of CP–stars (Sapar & Aret 1995, Aret & Sapar 1998).

Computations of the isotope segregation need the extremely high spectral resolution, exact and complete line databases, where also the isotopic and hyperfine structure splitting are taken into account.

The LID is much smaller for ionized than for neutral elements since the dominating component of the collision cross–section for ionized particle is Coulomb cross–section which is almost the same in the excited and in the ground state. The effective cross–section of two colliding charged particles is about 2 dex larger than of two colliding neutral particles or a neutral particle and an ion. This circumstance reduces efficiency of LID for ions almost proportsionally to the mean degree of ionization.

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