Modelling of Stellar Atmospheres
IAU Symposium, Vol. 210, 2003
N. E. Piskunov, W. W. Weiss, D. F. Gray, eds.

Light–Induced Drift in Atmospheres of CP Stars

A. Aret and A. Sapar

Tartu Observatory, Tõravere 61602, Estonia

Abstract. The efficiency of the light–induced drift (LID) for formation of anomalous abundance of mercury and its isotopes in the atmospheres of HgMn stars has been studied. Generation of elemental abundance anomalies in quiescent atmospheres of chemically peculiar (CP) stars can generally be explained by the mechanism of diffusive segregation of chemical elements due to oppositely directed gravitational and radiative forces. It has been shown that formation of the observed isotopic anomalies of Hg, and eventually also of other heavy elements, can be successfully explained by a diffusion due to LID. The observed ratios of isotopes can be used to estimate the evolutionary stages of CP stars.

1. Introduction

It is established that anomalous elemental abundances of CP stars are the result of radiative driven diffusion in stellar atmosphere (Michaud 1970, Michaud et al. 1983). Atutov and Shalagin (1988) have suggested that light–induced drift (LID) can be in many cases more efficient for generating abundance anomalies than the usual radiative acceleration. We have improved the theory of LID for stellar atmospheres showing that it can be duly taken into account by an additive acceleration term (Sapar & Aret 1995, Aret & Sapar 1998, 2002). LID gives essential contribution for segregation of heavy elements and it is the dominant mechanism for isotope segregation, causing for heavy elements generally sequential sedimentation of lighter and levitation of heavier isotopes. The effect is essential if there is partial overlap of isotope spectral lines, generating thus asymmetrical spectral line profiles which trigger corresponding LID.

We and R. Poolamäe have composed a code SMART for computing radiative transfer and spectra in model stellar atmospheres of O – A stars. This code also enables to compute the radiative accelerations including the LID term and corresponding diffusion velocities of chemical elements and their isotopes. Calculations made for Hg isotopes in some model atmospheres have confirmed important role of LID in diffusion processes. Acceleration due to LID can exceed the usual one by a factor of several dex. For exact computations both isotopic and superfine spectral line splitting should be taken into account.

2. Radiative and LID Acceleration in CP Star Atmospheres

Light–induced drift appears when atomic particles absorb radiation in spectral line with asymmetric profile. Assume that the flux in the red wing of spectral line is larger than the flux in the blue wing. Since the radiation in the red wing is absorbed by the downwards moving particles and in the blue wing vice versa, then there will be more excited downward–moving ions in the atmosphere. The collision cross–sections are larger for atomic particles in the excited (upper) states than in the ground (lower) state. As a result, the free paths for particles moving downwards are shorter and thus upwards directed drift appears.

We have shown (Aret & Sapar 2002), that force density expression including LID can be written in the form

$$f^r_{ul} = \frac{\pi}{c} \int\limits_{-\infty}^{+\infty} n_l \, \sigma^0_{ul} w(u_\nu, a) \, F_\nu \, d\nu \ , \qquad (1)$$

where the Voigt function $W(u_\nu, a)$ in the usual radiative acceleration expression is replaced by

$$w(u_\nu, a) = W(u_\nu, a) + qD \frac{\partial W(u_\nu, a)}{\partial u_\nu} \ . \qquad (2)$$

Dimensionless argument of the Voigt function is $u_\nu = (\nu - \nu_0)/\Delta\nu_T$, its parameter a is the ratio of characteristic widths of Lorentz and Doppler profiles, $a = \Gamma_{ul}/(4\pi\Delta\nu_T)$, where $\Delta\nu_T$ is the thermal Doppler width of spectral line. Value q is determined by the ratio of particle and photon momenta, namely

$$q = \frac{M v_T}{2} \frac{c}{h\nu},$$

where M is mass and v_T is the mean thermal velocity of given atomic particle species. The efficiency of LID in Eq. (2) is given by

$$D = \frac{C_u - C_l}{A_u + C_u} \ ,$$

where C_u, C_l are collision frequencies for the upper and lower state and A_u is the Einstein spontaneous radiation coefficient for the upper state. These formulae are starting point for computations. The rate q is a large number of the order 10 000, amplifying the momentum input into the LID. The LID efficiency D decreases from value about 0.25 in the deep atmospheric layers to 0.001 or less in the outermost layers, thus decreasing essentially the LID phenomenon in the outer layers of atmospheres.

3. Computations

Our code SMART for computation of synthetic stellar spectra is handy, short and compact. The radiative transfer has been computed integrating over layers of atmospheres with source function approximated in each of them to quadratic polynomial. We use a sampling method with constant step $\Delta\nu/\nu = 1/R$. Integration over wide spectral interval is carried out piecewise. The code is described in the A. Sapar and R. Poolamäe paper in ASP Conference Series issue of the Workshop on Stellar Atmosphere Modelling (April 8 - 12, 2002, Tübingen). Using SMART we computed the accelerations due to usual radiative force and due to LID for some chemical elements and their isotopes in the CP star atmospheres taking for the resolution the value $R = 5 \cdot 10^6$. Such a high value is needed because spectral lines of heavy elements are very narrow and their isotopic shifts are small. We emphasize that for isotope segregation very exact data both for isotope splitting of spectral lines and for their mutual overlap are needed.

Accelerations for mercury isotopes (Hg 198, 199, 200, 201, 202, 204) and for manganese have been calculated using the Kurucz (1993) model stellar atmosphere with $T_{eff} = 10750$ K, $\log g = 4$ and $v \sin i = 0$, corresponding to parameters of HgMn star HR7775. Computations were made for the mercury abundances from its solar value to the solar abundance + 5 dex by 1 dex step with solar mixture of isotopes. We used for mercury the solar abundance and the solar isotope ratios (Table 1) by Anders & Grevesse (1989). Calculations for HR7775 atmosphere with vast overabundance of mercury (+ 5.2 dex) and peculiar isotope mixture given in Table 1 (Jomaron et al. 1998) also have been carried out. The Kurucz line list gfhyperall.dat (2001), which incorporates about 500 000 atomic lines, has been used. It included 2 resonance lines and 25 subordinate lines for HgI and 5 resonance lines and 26 subordinate lines for HgII. This line list includes essentially more atomic lines of different species than the list used in our previous paper (Aret & Sapar 2002). As a result, the acceleration due to LID differs quantitatively from previous results since LID is very sensitive to overlaps of spectral lines. We found isotope shifts of Hg lines adopting the relative isotope shifts as the mean values found by Striganov & Dontsov (1955), scaled relative to shift $[202-200] = 1$. In these units $[198-200] = -0.94$, $[199-200] = -0.80$, $[201-200] = 0.30$, $[204-200] = 1.98$. For scaling these relative shifts to wavenumbers, we have taken into account that $[202-200] = 0.179$ cm^{-1} for HgI and $[202-200] = 0.508$ cm^{-1} for HgII. The Hg lines used are located in the spectral interval from 800 to 12 000 Å. Our computations show that the dominant contribution in the LID is given by resonance lines.

Table 1. Adopted isotopic composition (%).

	Solar[a]	HR7775[b]	χ Lup A[c]
Hg204	6.87	61.7	98.8
Hg202	29.89	37.2	1.1
Hg201	13.18	0.4	0.1
Hg200	23.10	0.3	–
Hg199	16.87	0.2	–
Hg198	9.97	0.2	–

[a] Solar mercury abundance $\log N(\mathrm{Hg}) = -10.91$ (in scale $\log N_{total} = 0$)
[b] HR7775 mercury abundance: solar + 5.2 dex
[c] χ Lup A mercury abundance: solar + 5 dex

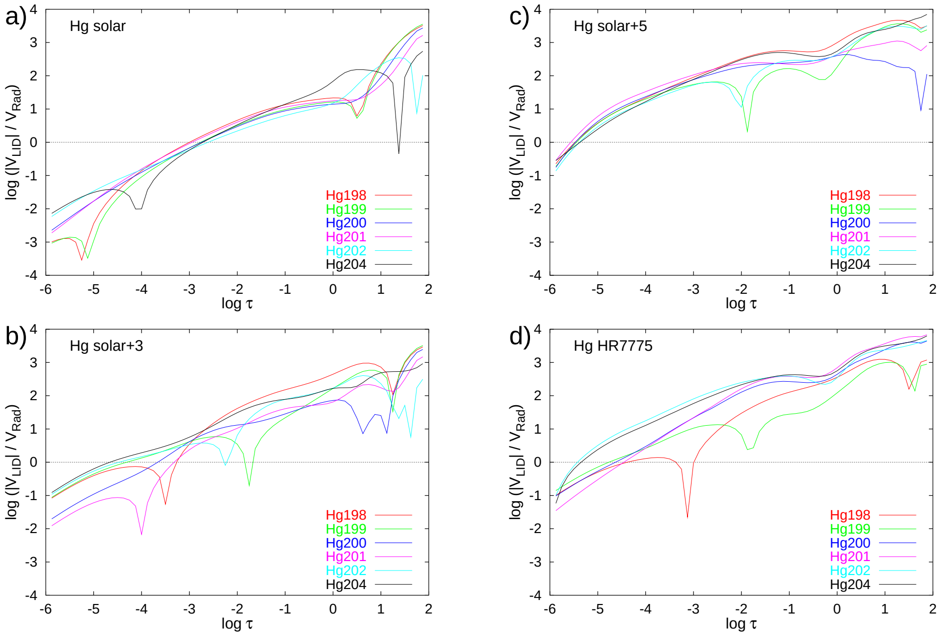

Figure 1. The run of ratio of absolute values of LID velocity V_{LID} and of usual radiative velocity in spectral lines V_{Rad} in logarithmic scale at four Hg abundances: a) solar, b) solar + 3 dex, c) solar + 5 dex and d) abundances of CP star HR7775. Model atmosphere: T_{eff}=10750 K, $\log g$=4.0, $v \sin i$=0.

4. Results and discussion

We represent in the logarithmic scale the ratios v_{LID}/v_{Rad} (Fig. 1), the total values of the accelerations a_{tot} for Hg isotopes (Fig. 2) and the radiative and LID contributions to the total acceleration on Hg isotopes (Fig. 3) for atmospheres with different mercury abundance and isotopic structure. The quantities describing LID are the sign–changing and they vary in large range. For such quantities y an adequate visualization is obtained using the expression $\mathrm{sign}(y)(\log(|y|+1)$ as the ordinate.

Ratio of absolute values of LID velocity V_{LID} and of the usual radiative velocity in spectral lines V_{Rad} (Fig. 1) shows the important role of LID. For all Hg isotopes LID is dominant in deep layers of atmosphere, in outer layers the LID diminishes primarily due to decrease of the LID efficiency D. In atmospheres with strong overabundance of Hg the LID dominates almost throughout the atmosphere.

All isotopes of Hg have largest absolute values of a_{total} in the layers where τ is between 1 and 10 (Fig. 2). Curves in modified logarithmic scale reveal presence of regions of abrupt change of total acceleration in the CP star atmospheres. These steep slopes are due to LID. The zone of rarefication of the isotope is forming on the outer (left) slope of these curves and on the inner

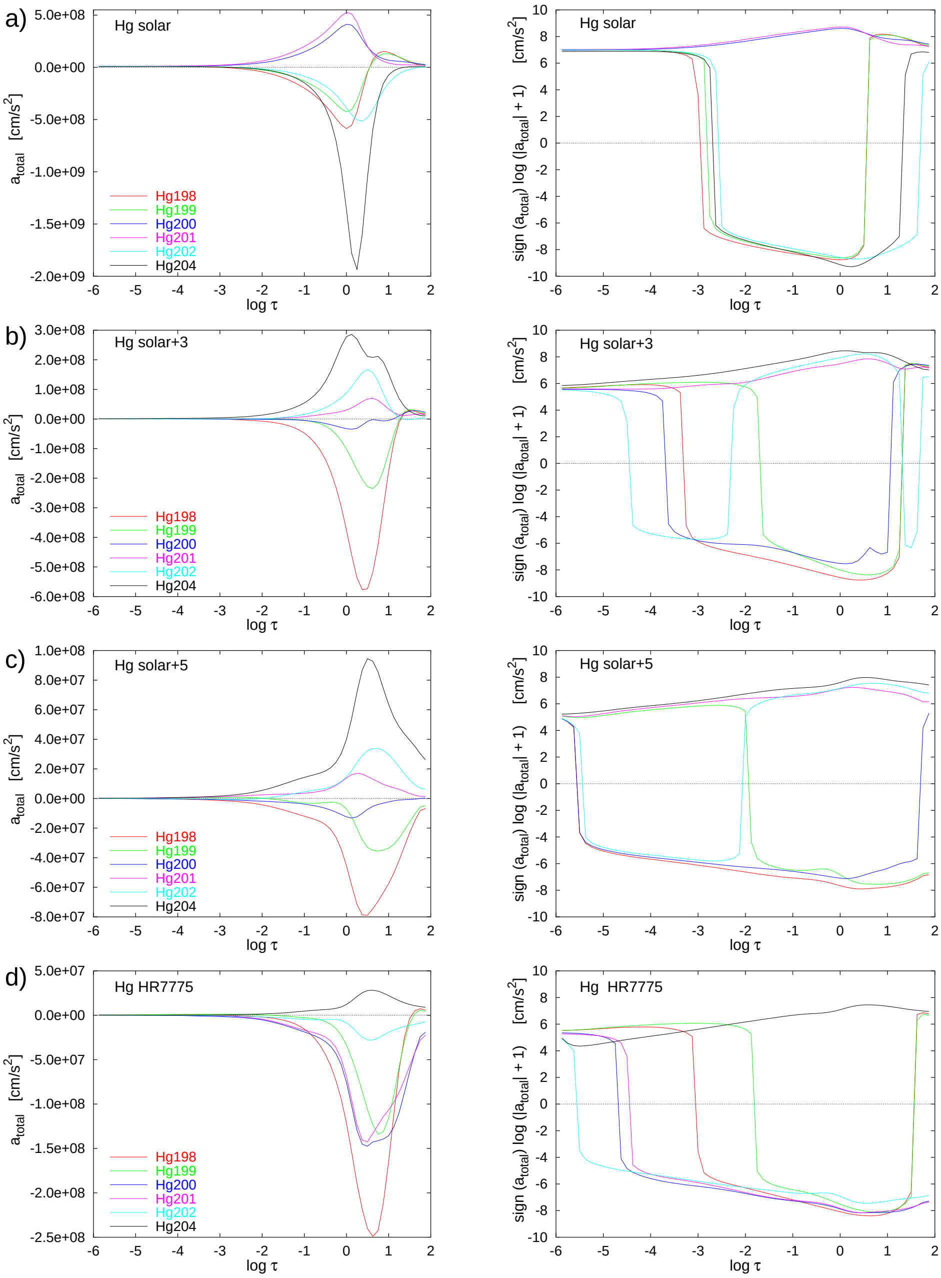

Figure 2. Total acceleration ($a_{total} = a_{Rad} + a_{LID} - gravity$) on Hg isotopes at four Hg abundances: a) solar, b) solar + 3 dex, c) solar + 5 dex with solar isotopic ratio and d) abundances of CP star HR7775. Model atmosphere: T_{eff}=10750 K, $\log g$=4.0, $v \sin i$=0. Left panels – linear scale, right panels – modified logarithmic scale suitable for sign-changing quantities having large range changes.

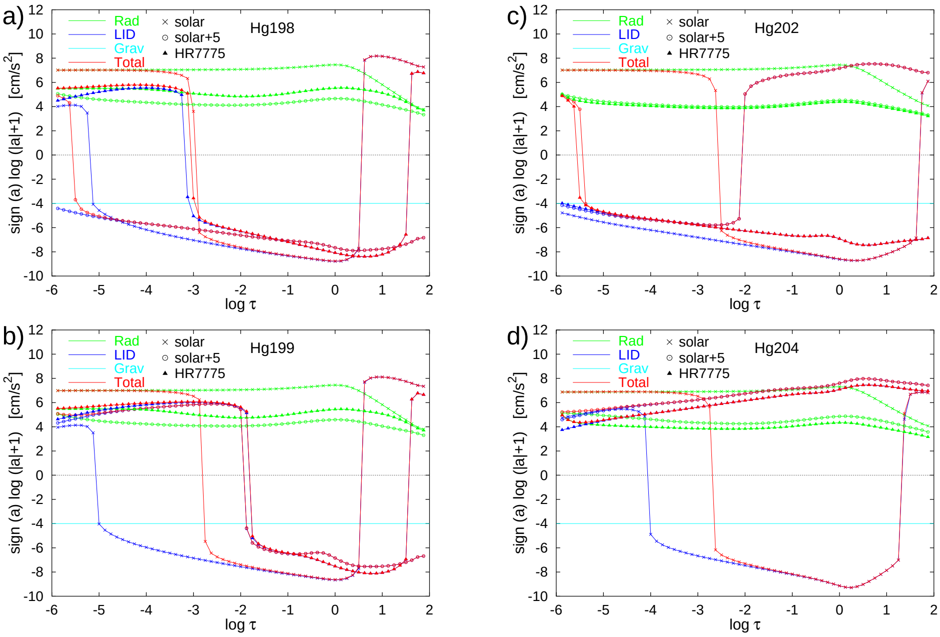

Figure 3. Accelerations on mercury isotopes ^{198}Hg (a), ^{199}Hg (b), ^{202}Hg (c) and ^{204}Hg (d) due to usual radiative acceleration a_{rad}, light–induced drift a_{LID} and gravity at three Hg abundances: solar (crosses) and solar + 5 dex (circles) with solar isotopic ratio, and for abundances of CP star HR7775 (triangles). Model atmosphere: T_{eff}=10750 K, $\log g$=4.0, $v \sin i$=0.

(right) slope — the zone of accumulation. Therefore the real isotope abundance in CP star atmospheres must be highly dependent on the optical depth.

Diffusion of Hg isotopes at low abundances is determined by blending with lines of other elements rather than mutual overlap. Therefore it has features unpredictable without detailed computations. At higher abundances the mutual overlap of spectral lines of different Hg isotopes is dominant for the LID generation. This causes sequential sedimentation of lighter isotopes and levitation of heavier isotopes. In the atmosphere of HR7775 where mostly two heaviest Hg isotopes (^{202}Hg and ^{204}Hg) have been observed, the levitation of lighter of them (^{202}Hg) has changed to sedimentation. The abrupt decrease of a_{Rad} and a_{LID} in deep layers (Figs. 2 and 3) is an artifact due to lack of spectral line data for HgIII prevailing in the region.

Total acceleration is mostly determined by LID, except only the outermost layers of atmosphere (Fig. 3). In atmospheres with high abundance of Hg the radiative acceleration is almost in equilibrium with gravitation, thus segregation of isotopes is due to the LID. Radiative acceleration exceeds gravity for solar and solar + 3 dex abundances and is of the same order for solar + 5 dex and HR7775 models.

As mentioned above, the light–induced drift generated by the overlap of splitted spectral lines of Hg isotopes causes consequent sedimentation of lighter isotopes and thus in the late evolutionary stages only the heaviest isotope ^{204}Hg survives in CP star atmospheres. While two heaviest isotopes of mercury, ^{202}Hg and ^{204}Hg, are strongly overabundant in the atmosphere of HR7775, only spectral lines of the heaviest mercury isotope ^{204}Hg have been detected in the atmosphere of χ Lupi. Thus, we may conclude that χ Lupi is evolved somewhat further than HR7775. To specify the age of these CP stars, the evolutionary run for elemental abundances is to be computed. We emphasize that CP star atmospheres have been assumed to be quiescent, i.e. presence of stellar wind, meridional circulation due to stellar rotation and turbulence have been ignored. Also magnetic field has been assumed to be lacking.

The given results of computations confirm that LID is important for diffusion of heavy elements and dominating for segregation of isotopes in atmospheres of CP stars. The results show that only the studies of evolutionary changes can yield more exact picture of changes of isotope abundances in CP star atmospheres.

Acknowledgments. We are grateful to R. Kurucz for making available his line data files and to Estonian Science Foundation for grant ESF-4701.

References

Anders, E., & Grevesse, N.: 1989, Geochim. Cosmochim. Acta, 53, 197

Aret, A., & Sapar, A.: 1998, Contr. Astron. Obser. Skalnaté Pleso, 27, 329

Aret, A., & Sapar, A.: 2002, Astron. Nachr., 323, 1, 21

Atutov, S. N., & Shalagin A. M.: 1988, Soviet Astron. Lett., 14, 285

Jomaron, C.M., Dworetsky, M.M., Bohlender, D.A.: 1998, Contr. Astron. Obser. Skalnaté Pleso, 27, 324.

Kurucz, R.: 1993, SYNTHE Spectrum Synthesis Programs and Line Data. Kurucz CD-ROM No. 18. Cambridge, Mass.: Smithsonian Astrophysical Observatory

Michaud, G.: 1970, ApJ, 160, 641

Michaud, G., Vauclair, G., Vauclair, S.: 1983, ApJ, 267, 256

Sapar, A., & Aret, A.: 1995, Astron. Astrophys. Trans., 7, 1

Sapar, A., & Poolamäe, R.: 2003, ASP Conf. Series, in press

Striganov, A.R., & Dontsov, Yu.P.: 1955, Uspekhi Fizicheskikh Nauk, 55, 315 (in Russian)