Evolutionary separation of mercury isotopes in atmospheres of chemically peculiar stars

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PhD Thesis Defence

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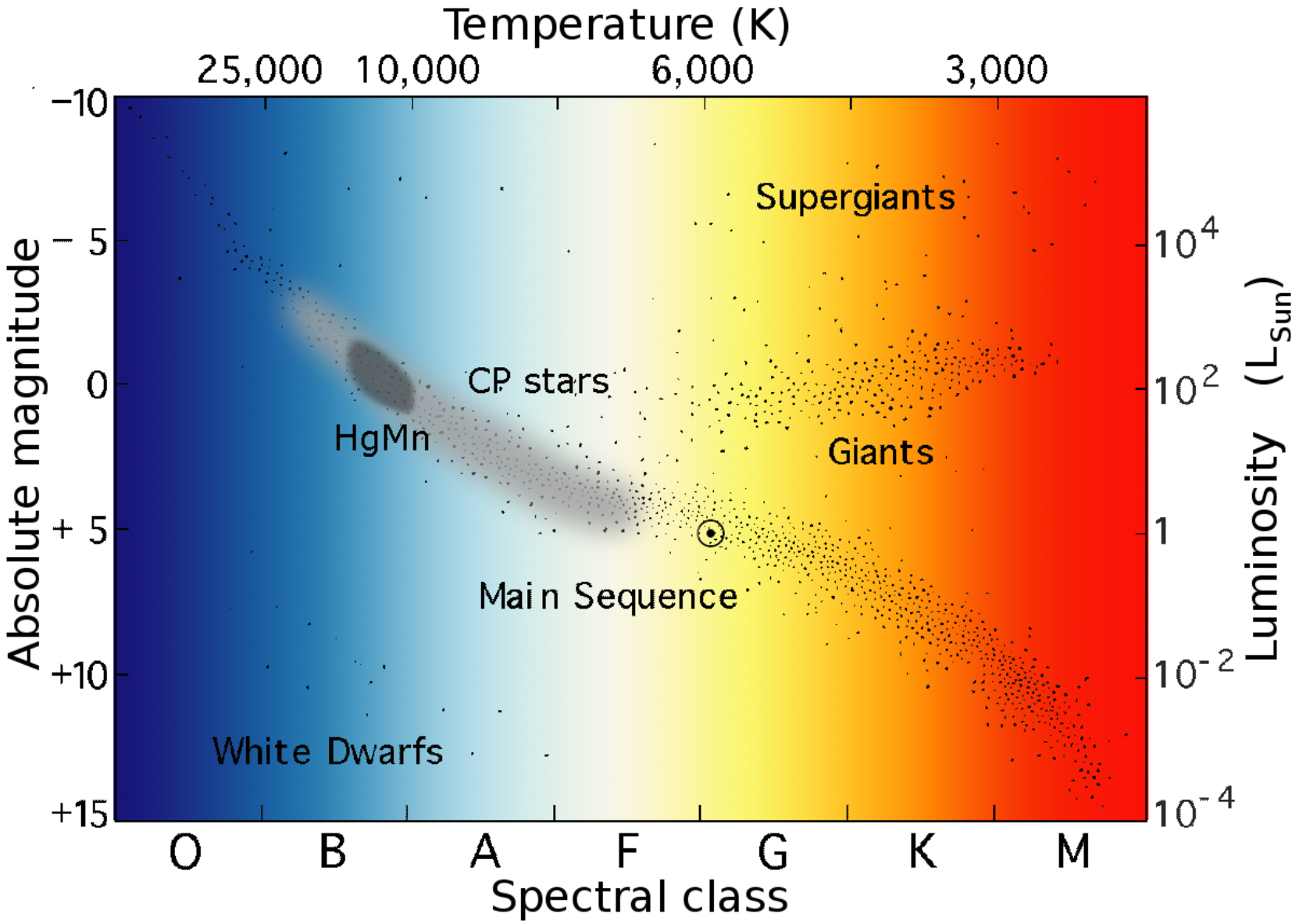
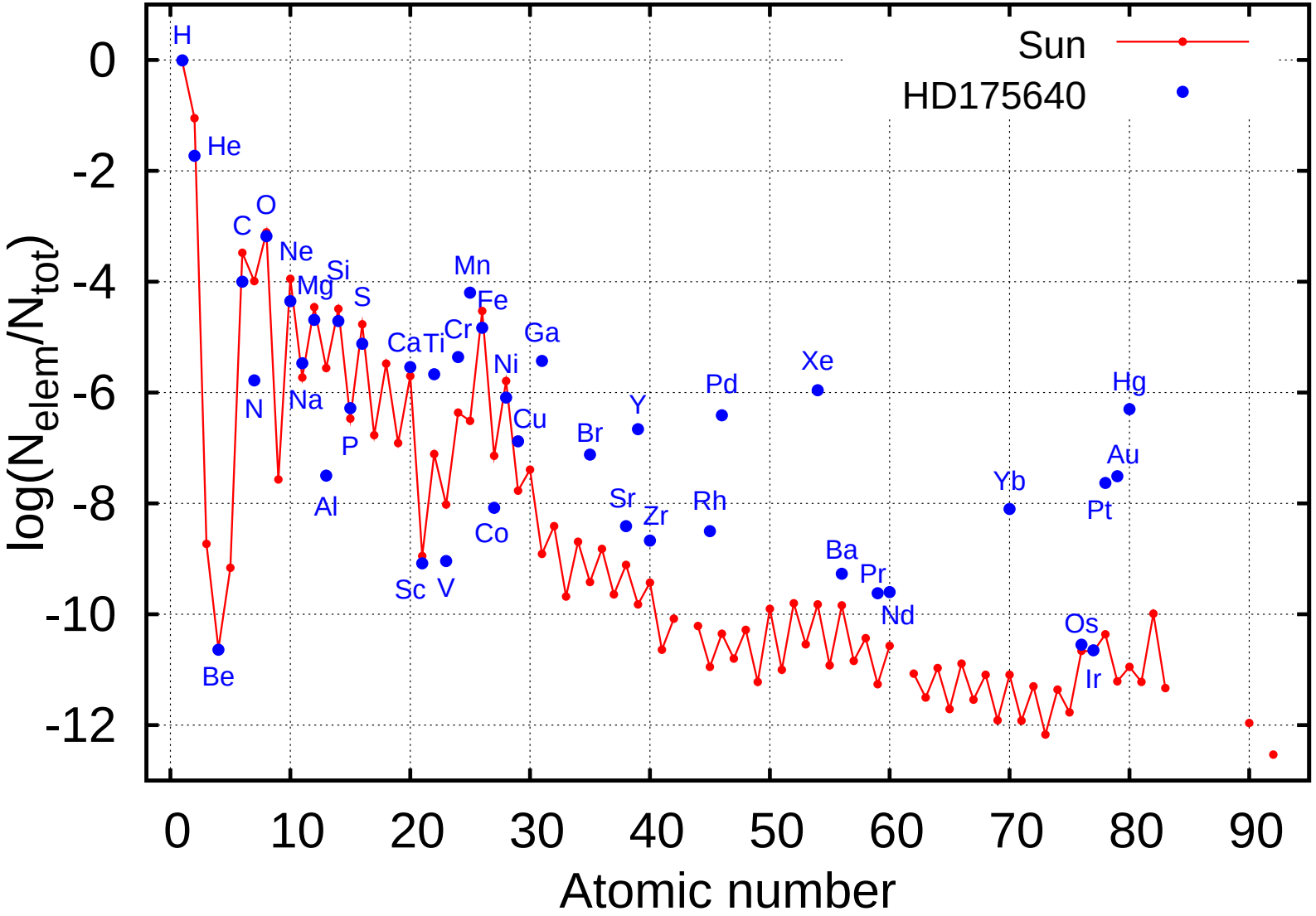
June 5, 2009

Chemically peculiar (CP) stars are hot main-sequence stars with distinctly unusual abundances of certain elements



Example of abundance pattern

HgMn star HD 175640 (B9 V spectral type): $T_{\rm eff}$=12 000 K, $\log g$=3.95



Castelli & Hubrig 2004, A&A 425, 263

Classification of CP stars (Preston 1974)

- **CP1**: Am stars ($T_{\rm eff}$ = 7 000 – 10 000 K, F5 – A4)
- **CP2**: Ap stars ($T_{\rm eff}$ = 8 000 – 15 000 K, F0 – B5) – magnetic
- **CP3**: HgMn stars ($T_{\rm eff}$ = 10 000 – 15 000 K, A2 – B8) non-variable non-magnetic stars with large overabundance of Hg (up to 6 dex) and Mn (up to 3 dex). Enhancement of heavy metals and deficiency of He, Al, Zn, Ni, Co. Isotopic anomalies.
- **CP4**: He stars
  - He-weak stars ($T_{\rm eff}$ = 14 000 – 21 000 K), He isotopic anomalies
  - He-rich stars ($T_{\rm eff}$ = 21 000 – 30 000 K)

Isotopic anomalies in CP stars

High quality observational spectra are necessary to derive isotope ratios $\Rightarrow$ most data are obtained during last decade

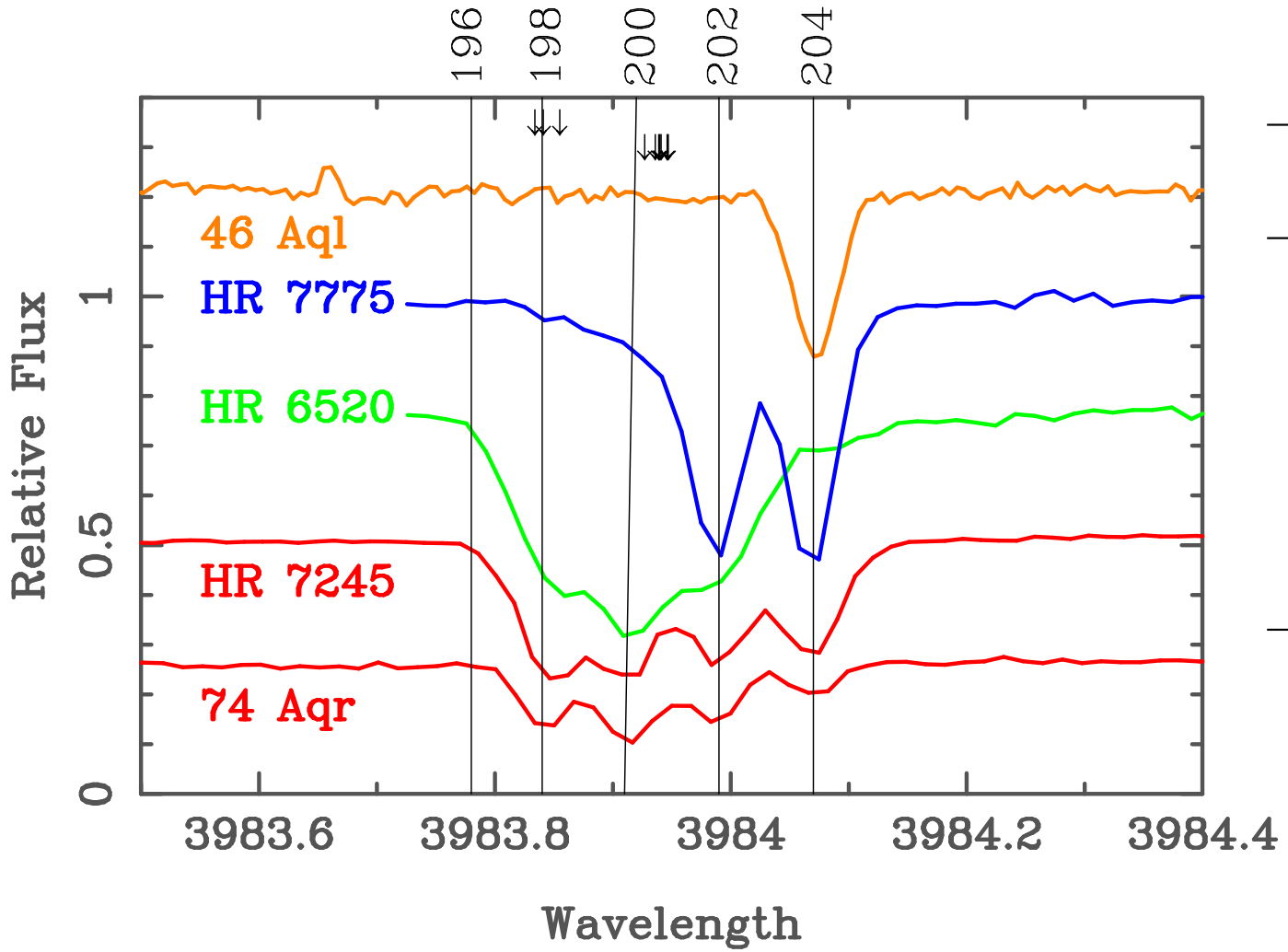
Anomalous isotope ratios have been observed for:

- heavy elements **Hg, Pt, Tl, Os, Ca**
- light elements **He, Li**

General trend

- Heavy elements: heavier isotopes are overabundant
- Light elements: lighter isotopes are overabundant

Isotopic anomaly of mercury in CP stars



Hg	Terr. %	46 Aql %
196	0.15	0.0
198	9.97	0.0
199	16.87	0.0
200	23.10	0.0
201	13.18	1.5
202	29.86	2.5
204	6.87	97.0

Spectra of the λ3984 Å region in 5 HgMn stars (ESO VLT). Vertical lines indicate the wavelengths of the stable, even-A isotopes, indicated above the plot. Short arrows indicate the hyperfine components of ^{199}Hg and ^{201}Hg, the stable, odd-A isotopes.

Formation of peculiarities – diffusion theory

Diffusion theory proposed by G. Michaud almost 40 years ago is widely accepted nowadays as the only viable scenario for the buildup of abundance peculiarities in CP stars.

Main statements of diffusion theory:

- anomalous abundances form in atmosphere of a star, the bulk composition of the entire star is normal;
- abundance anomalies in CP stars are generated by atomic diffusion;
- stratification of elements is mainly determined by competition between gravitational and radiative forces;
- particle diffusion only works in quiet atmospheres (i.e. convection and turbulence, mass loss and meridional flows are weak);

Diffusion in plane-parallel model atmosphere

Time-dependent stratification process in stellar atmospheres is described by two main equations:

Continuity equation for element i

$$\frac{\partial \rho_i}{\partial t} + \frac{\partial(\rho_i v_i)}{\partial r} = 0$$

Equation of diffusion velocity

$$v_i = D_i \left(\frac{m_i}{kT}(a_i^{\text{radiative}} - g) - \frac{d \ln N_i}{dr} \right)$$

ρ_i – density of element i
m_i – mass of element i
N_i – number density
v_i – diffusion velocity
D_i – diffusion coefficient
g – gravity
t – time
r – radial coordinate
T – temperature
k – Boltzmann constant

Diffusion in non-magnetic stellar atmosphere is mainly determined by competing gravitation and radiative fields.

In main sequence stars $a_i^{\text{rad}} \sim 10 - 10^7$, while $g \sim 10^4$ cm/s^2!

Research objective

The diffusion theory has been successful in explaining observed abundance anomalies in CP stars

HOWEVER

Isotopic anomalies cannot be explained by radiative-driven diffusion alone

Atutov & Shalagin (1988):
Effect of **light-induced drift** may play essential role.

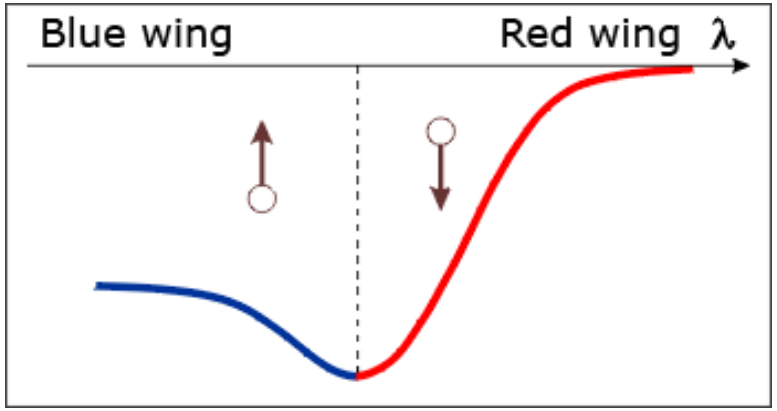
$$\Downarrow$$

Main objective

Evaluate the phenomenon of light-induced drift as possible mechanism of isotope separation in atmospheres of CP stars.

Light-induced drift (LID)

Light-induced drift appears when radiation flux absorbed by colliding plasma particles is anisotropic within the spectral line width of an ion



⇑ Upward flow of particles

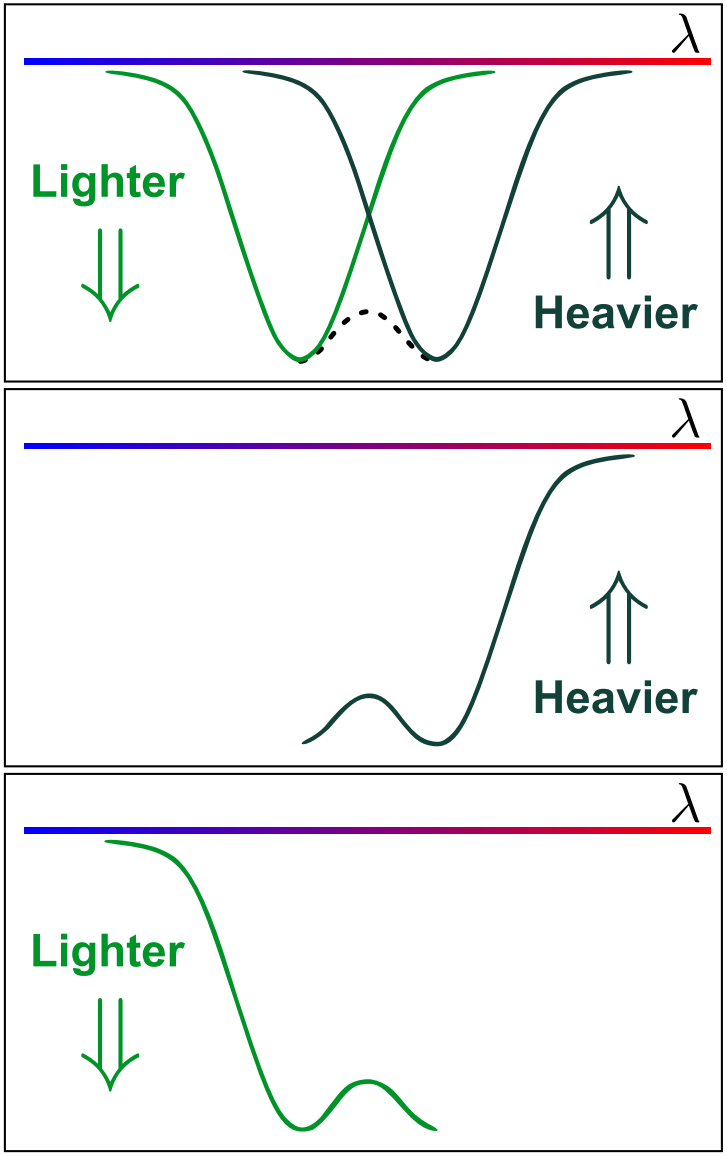
Radiative flux < Radiative flux
Number of excited particles < Number of excited particles
Mobility > Mobility (due to $\sigma^*_{\mathrm{coll}} > \sigma_{\mathrm{coll}}$)

- Larger flux in the red wing ⇒ upward flow of particles
- Larger flux in the blue wing ⇒ downward flow of particles

Resulting LID (sum over all lines) is essential only if there is a systematic asymmetry in spectral lines

Light-induced drift of isotopes

Spectral lines of isotopes of a heavy element



Isotopes with slightly shifted energy levels have overlapping spectral lines, giving systematically similar asymmetry in line profiles. For heavy elements spectral lines of heavier isotopes are shifted to longer wavelengths.

Heavier isotope has larger flux in the red wing

Heavier isotope rises

Lighter isotope has larger flux in the blue wing

Lighter isotope sinks

Main formulae for light-induced drift

Acceleration due to bound-bound transitions including LID effect

$$a_j^{\mathrm{rad}} \quad \Longrightarrow \quad a_j^{\mathrm{total}} = a_j^{\mathrm{rad}} + a_j^{\mathrm{LID}}$$

$$V(u_\nu, a) \quad \Longrightarrow \quad V(u_\nu, a) + \varepsilon q \frac{\partial V(u_\nu, a)}{\partial u_\nu}$$

LID efficiency: $\varepsilon = \dfrac{C_u - C_l}{C_u} \cdot \dfrac{C_u}{A_u + C_u} = \dfrac{C_u - C_l}{A_u + C_u}$

Ratio of ion and photon momenta: $q = \dfrac{m_j v_T c}{2h\nu} = \dfrac{m_j v_T}{2} : \dfrac{h\nu}{c}$

$V(u_\nu, a)$ – Voigt spectral line profile function
C_u and C_l – collision frequencies of ion j in upper and lower state
A_u – frequency of spontaneous transitions from the upper state
m_j – mass of ion j
v_T – thermal velocity.

Computation of LID

- Spectral line data including isotopic and hyperfine splitting of lines are necessary for the studied element.
- Effective acceleration is found summing over all lines of the element.
- Computation of LID demands high-resolution ($\Delta\lambda/\lambda = 5\ 000\ 000$) synthetic spectra at all depths of model stellar atmosphere.
- Radiative flux has to be found through the detailed resolution of the radiative transfer equation.

Program SMART

Spectra and Model Atmospheres by Radiative Transfer

Authors: Arved Sapar, Raivo Poolamäe and Anna Aret

Model stellar atmospheres of O, B and A spectral classes (9 000 – 40 000 K)

Fortran 90, Windows and Linux

Minimum system requirements:
2 GB of system memory and 2 GHz processor

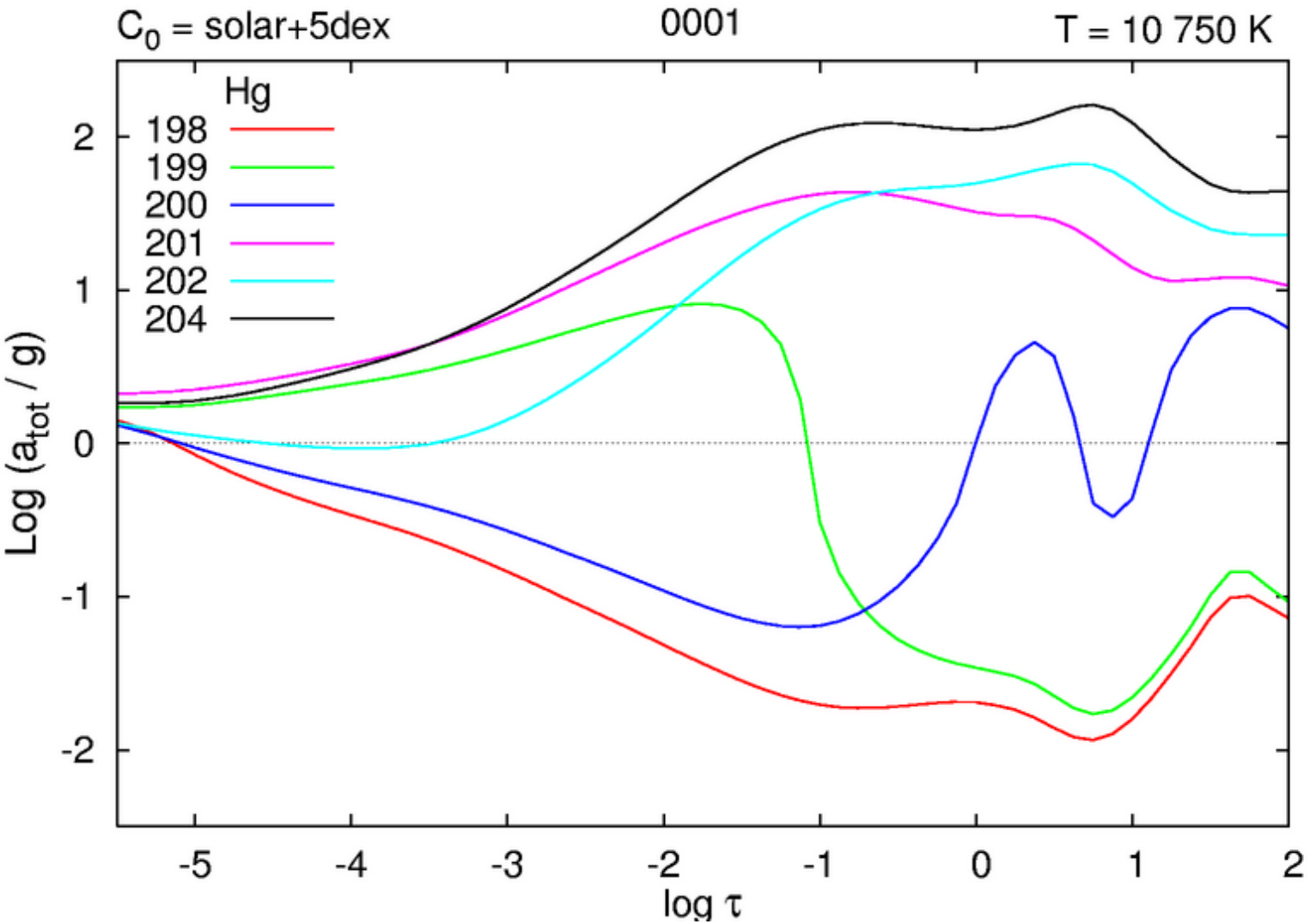
Computed evolutionary scenarios of Hg isotope separation

Model atmospheres: $\log g = 4$, $T_{\rm eff} = 9\,500$, $10\,750$ ja $12\,000$ K
Initial Hg abundance: $C^0_{\rm Hg} =$ solar, solar+3 dex ja solar+5 dex

Initial state for all scenarios:

- Homogeneous abundance of Hg throughout the atmosphere;
- Solar system (terrestrial) ratios of isotope abundances.

Acceleration $a^{\mathrm{rad}} + a^{\mathrm{LID}}$ of mercury isotopes



$\Delta t = 1$ yr

Modified logarithmic scale $\mathrm{sign}(a)\log\left(\left|\frac{a}{g}\right| + 1\right)$ Click on figure to play movie.

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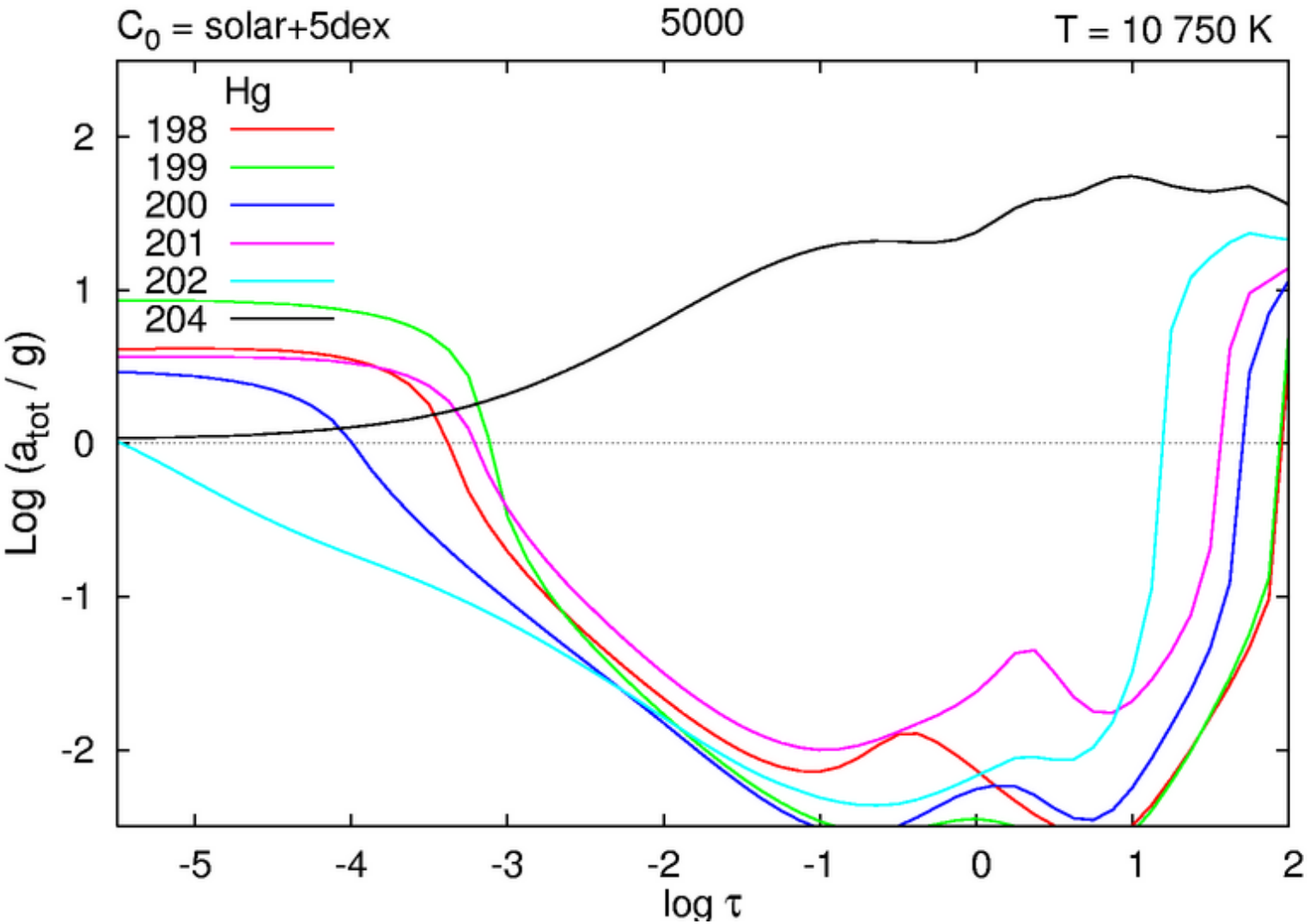

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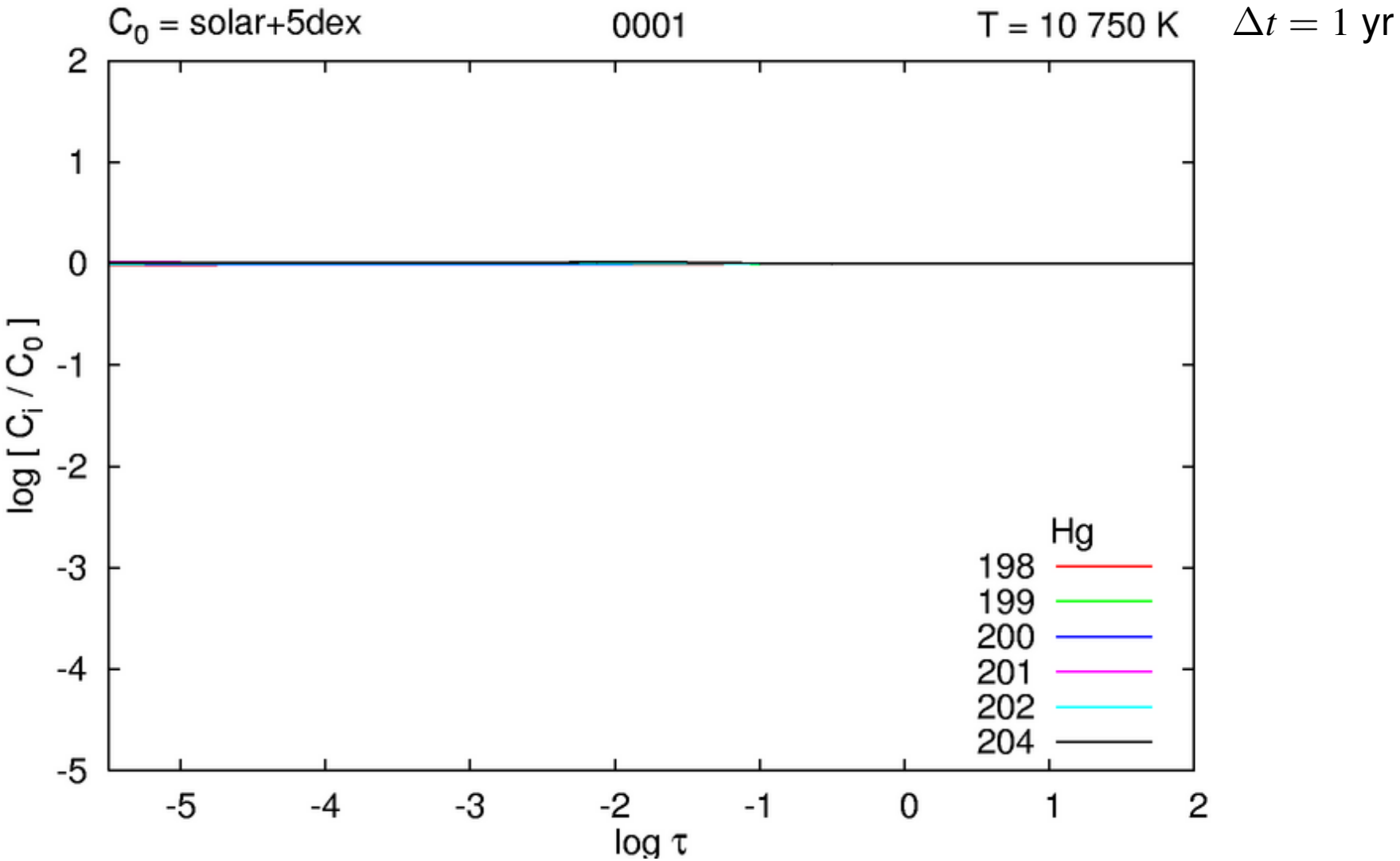
Evolution of concentrations $\log(C_i/C_0)$



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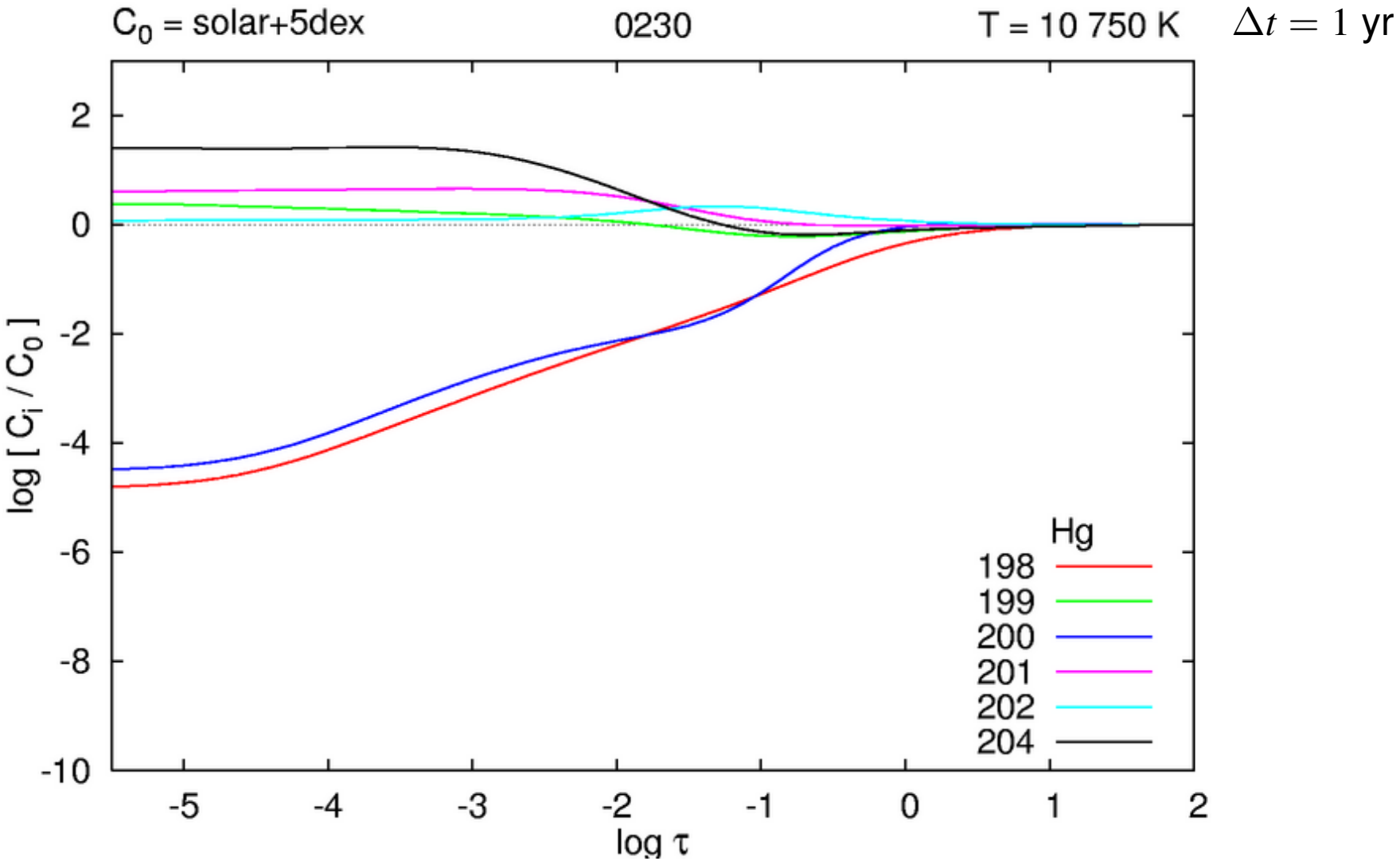

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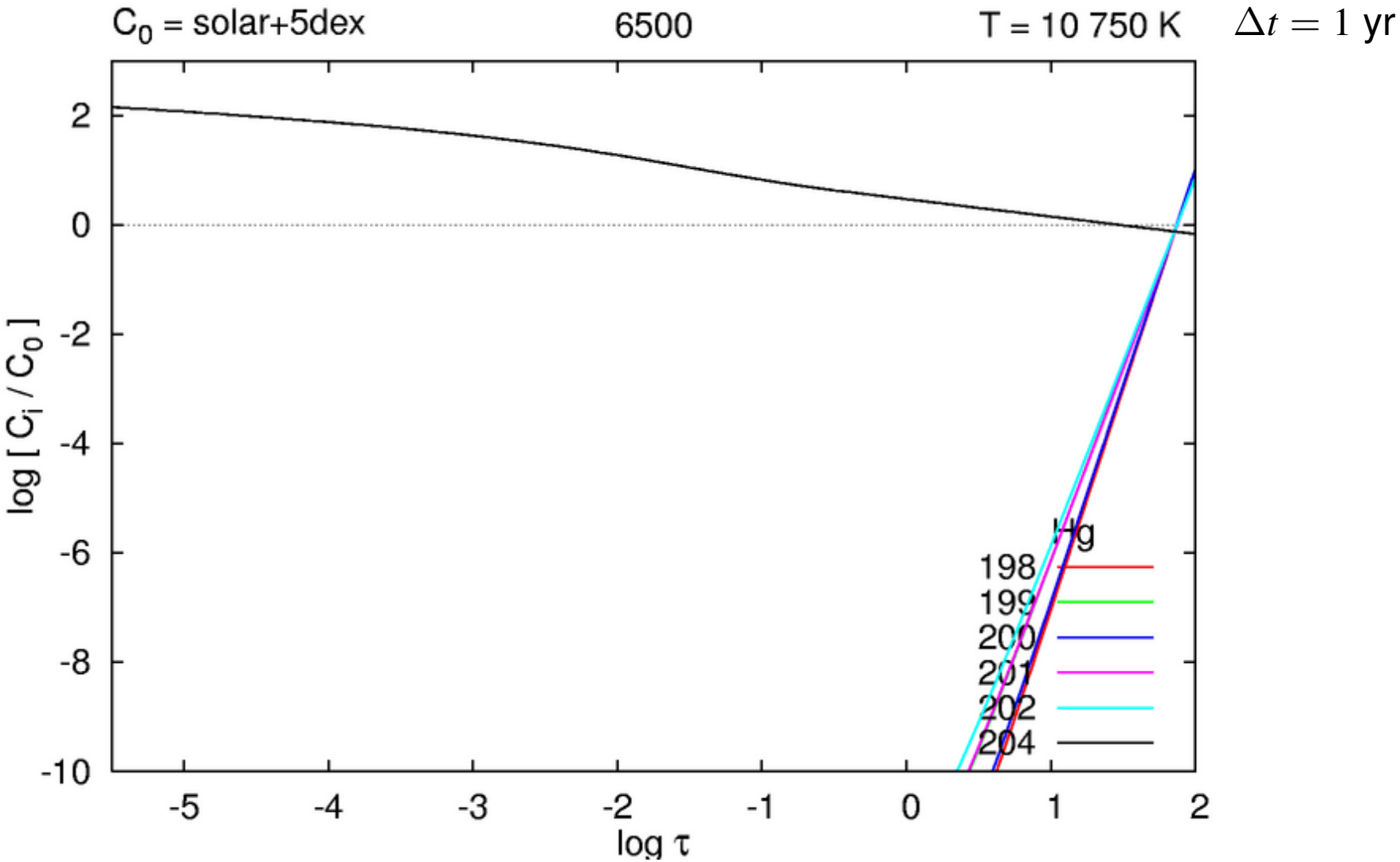

Only the heaviest isotope is left in the atmosphere.

Main results of the thesis

1. Formulae for LID in stellar atmospheres have been derived.
2. Model atmosphere code SMART has been supplemented with additional software blocks for computation of diffusional separation of isotopes of chemical elements.
3. The data bank of splitted spectral lines of mercury has been composed.
4. Evolutionary scenarios of mercury isotope separation have been computed for set of model atmospheres corresponding to HgMn stars. Main features of the separation have been elucidated.

Main conclusion

Current study confirms that effect of light-induced drift plays important role in separation of mercury isotopes in the quiescent atmospheres of chemically peculiar HgMn stars and may explain observed anomalous isotope ratios.