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Letter to the Editor

The Ca II infrared triplet as indicator of anomalous Ca isotopic mixture in HgMn stars*

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Abstract. For the first time we present observational evidence for an anomalous isotopic structure of Ca II in mercury–manganese (HgMn) stars. The centroid wavelengths of Ca II infrared triplet lines in a number of stars have been found redshifted with respect to the centroids of the terrestrial Ca II lines. The record holder is the star HD 175640 for which the measured wavelength is consistent with Ca II being present in the atmosphere entirely in form of the heaviest stable isotope ^{48}Ca. This is a very striking result as ^{48}Ca makes up only 0.187% of the terrestrial Ca mixture.

Key words. stars: abundances – stars: atmospheres – stars: chemically peculiar – stars: atomic data – stars

1. Introduction

The HgMn stars constitute a well-defined sub-group of peculiar late B-type stars. The heavy elements Ga, Sr, Y, Zr, Xe, Pt, Au, Hg and Bi are generally overabundant as compared with normal population I main-sequence stars. The relative abundances of iron-peak elements vary from star to star, but Mn is generally overabundant up to 3 dex. Abnormal variations in the relative isotopic abundances of Hg and Pt from star to star have been detected a few decades ago (e.g., White et al. 1976; Dworetsky & Vaughan 1973). Hg and Pt lines in many HgMn stars are shifted with respect to the centroids of the terrestrial Hg and Pt lines. The anomalies are analogous for both elements, with heavier isotopes predominant in cooler HgMn stars (e.g., Hubrig et al. 1999; Dolk et al. 2003). To explain the abundance and isotopic anomalies in the outer layers of HgMn stars, radiatively driven selective diffusion is most often invoked. However, neither it nor any other theory until now can account satisfactorily for the observed abundance pattern and for the variations of the isotope mix of the heavy elements among the HgMn stars (e.g., Proffitt et al. 1999).

Recently, we have undertaken an extensive abundance study of the sharp-lined HgMn star HD 175640 (Castelli & Hubrig 2004) using high-resolution UVES spectra in the wavelength range from 3040 to 10 000 Å. The low $v \sin i$ = 2.5 km s^{-1} enabled us to perform an accurate line identification and line profile studies taking into account hyperfine and isotopic structures of some ions like Mn II, Ga II, Ba II, Hg I and Hg II. To our surprise, the two lines of the Ca II infrared triplet at 8498.02 Å and 8662.14 Å (the line Ca II λ 8542 is lost in the gap between the UVES echelle orders) have been found redshifted by 0.2 Å relative to all other observed spectral lines. The inspection of a FEROS spectrum of HD 175640 has confirmed the shifts, removing the suspicion of an instrumental or incorrect data reduction origin. We also searched for similar shifts in nine other HgMn stars and two normal late B and A stars with available high-resolution spectra. We found that in addition to HD 175640 there are also three other HgMn stars, HD 158704, HD 178065 and HD 1909 showing redshifted Ca II infrared profiles. In this paper we suggest that the observed shifts are due to an anomalous isotopic composition of calcium in the atmosphere of the stars.

2. Observations

The basic data of our sample, which includes ten HgMn stars and two normal stars of spectral type late B and A0, are presented in Table 1. The first five columns indicate, in order, the HD number of the star, another identifier, the spectral type, the instrument used to obtain the spectrum, and the resolving power $R = \lambda/\Delta\lambda$. The other columns list the stellar parameters, their source, and the average wavelength shift $\Delta\lambda$

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* Based on observations obtained at the European Southern Observator, La Silla and Paranal, Chile (ESO programme Nos. 65.L-0316 and 67.D-0579).

Table 1. Basic data of studied HgMn and normal stars.

HD	Other	Sp. type	Instr.	R	$T_{\rm eff}$	log g	v sin i	Ref.	$\Delta\lambda$ (Å)
1909	HR 89	HgMn,SB2	UVES	115 000	12 400	4.00	12.0	(1)	0.13 ± 0.02
84461	HR 3875	A0 IV	UVES	80 000	10 350	4.00	35.0	(2)	0.00 ± 0.02
101189	HR 4487	HgMn	FEROS	48 000	11 020	3.92	18.0	(1)	0.07 ± 0.05
124740	CD -40°8541	HgMn,SB2	FEROS	48 000	10 350	4.00	2.0	(1)	0.05 ± 0.05
149121	28 Her	HgMn	FEROS	48 000	10 908	3.83	9.0	(1)	0.07 ± 0.05
158704	HR 6520	HgMn,SB2	FEROS	48 000	13 163	4.22	2.8	(3)	0.15 ± 0.05
165493	HR 6759	HgMn	FEROS	48 000	13 890	3.90	2.5	(1)	0.12 ± 0.05
175640	HR 7143	HgMn	UVES	115 000	12 000	3.95	2.5	(3)	0.20 ± 0.01
175640	HR 7143	HgMn	FEROS	48 000	12 000	3.95	2.5	(3)	0.20 ± 0.05
178065	HR 7245	HgMn,SB1	UVES	115 000	12 250	3.60	1.7	(4)	0.14 ± 0.02
178065	HR 7245	HgMn,SB1	FEROS	48 000	12 259	3.60	1.7	(4)	0.14 ± 0.05
186122	HR 7493	HgMn	FEROS	48 000	12 750	3.80	0.0	(4)	0.11 ± 0.05
196426	HR 7878	B8 III	FEROS	48 000	12 815	3.89	3.0	(3)	0.04 ± 0.05
221507	HR 8937	HgMn	UVES	80 000	12 476	4.13	25.0	(1)	–

(1) Dolk et al. (2003); (2) this paper; (3) Hubrig et al. (1999); (4) Hubrig & Castelli (2001).

of the Ca II infrared triplet lines. Last column is explained in Sect. 4. Spectra of the HgMn stars HD 1909, HD 175640 and HD 178065, have been recorded in June 2001 with the VLT UV-Visual Echelle Spectrograph UVES at UT2. We used the UVES Dichroic standard settings covering the spectral range from 3030 to 10 000 Å. The slit width for the observations with the red arm was set to 0.″3, corresponding to a resolving power of $\lambda/\Delta\lambda \approx 1.15 \times 10^5$. The signal-to-noise ratios of the resulting UVES spectra range from 200 to 500 per pixel in the one-dimensional spectrum. Other spectra used in this study have been obtained in May 2000 using the echelle spectrograph FEROS on the 1.52 m telescope at La Silla. These spectra cover the wavelength region between 3530 and 9220 Å, and have a nominal resolving power of 48 000. The FEROS spectra of HD 175640, HD 178065 have been used to confirm the shifts of the infrared Ca II triplet lines observed in the UVES spectra. The spectra of HD 221507 and of HD 84461 have been retrieved from the ESO archive.

3. Isotopic structure and atomic data for the Ca II infrared triplet

Calcium has six stable isotopes with mass numbers 40, 42, 43, 44, 46 and 48. The terrestrial isotopic mixture (in percent) is 96.941, 0.647, 0.135, 2.086, 0.004 and 0.187, respectively (Anders & Grevesse 1989). The maximum isotopic shifts between the isotopes ^{40}Ca and ^{48}Ca for the Ca II lines at 3968.47 Å (H-line) and at 3933.64 Å (K-line) is of the order of only ≈9 mÅ (Martensson-Pendrill et al. 1992), so that these lines are pratically unaffected by possible calcium isotopic composition anomalies. On the other hand, the largest isotopic shift in the Ca II infrared triplet at 8498.023 Å, 8542.091 Å and 8662.141 Å, due to $3d^2D_j \rightarrow 4p^2P_j$ transitions, is about 0.2 Å, according to Nörtershäuser et al. (1998) (Table 2). Therefore, the measurement of the exact wavelengths of the Ca II infrared lines may give information on the isotopic composition of slowly rotating stars observed at high-resolution and high S/N ratio. Nörtershäuser et al. (1998) measured the isotope shifts of all stable isotopes with respect to the most abundant isotope ^{40}Ca by means of fast ion beam collinear laser spectroscopy. They also measured the hyperfine structure of ^{43}Ca (which is not fully resolved in all cases). Within the accuracy of the measurements the three transitions exhibit identical isotopic shifts. Isotopic shifts are not available for the isotope ^{46}Ca in the transitions $^2D_{\frac{3}{2}} \rightarrow {}^2P_{\frac{1}{2}}$ and $^2D_{\frac{3}{2}} \rightarrow {}^2P_{\frac{3}{2}}$. Table 3 lists the atomic data that we adopted for computing the Ca II infrared profiles. They were taken from Chmielewski (2000), except for the Stark broadening constant, which was taken from Griem (1974). In particular, log gfs are from Gallager (1967) and the radiative and Van der Waals broadening constants are from Smith & Drake (1988).

Table 2. Isotopic shifts $\Delta\lambda$ in the 3d ^2D_j–4p ^2P_j transitions of Ca II (Nörtershäuser et al. 1998).

A	Atom percent	8498.023 3/2→3/2	8542.091 5/2→3/2	8662.14 3/2→1/2
		$\Delta\lambda$ (Å)		
40	96.941	–	–	–
42	0.647	0.057	0.057	0.059
43	0.135	0.083	0.084	0.087
44	2.086	0.108	0.109	0.113
46	0.004	–	0.158	–
48	0.187	0.200	0.202	0.207

Table 3. The atomic constants for the Ca II infrared triplet.

λ	log gf	$\gamma_{\rm rad}$	(γ_e/N_e) T = 20 000	(γ_H/N_H) T = 5000
8498.023	−1.45	1.5×10^8	2.82×10^{-6}	2.14×10^{-8}
8542.091	−0.50	1.5×10^8	2.82×10^{-6}	2.06×10^{-8}
8662.140	−0.76	1.5×10^8	2.82×10^{-6}	2.00×10^{-8}

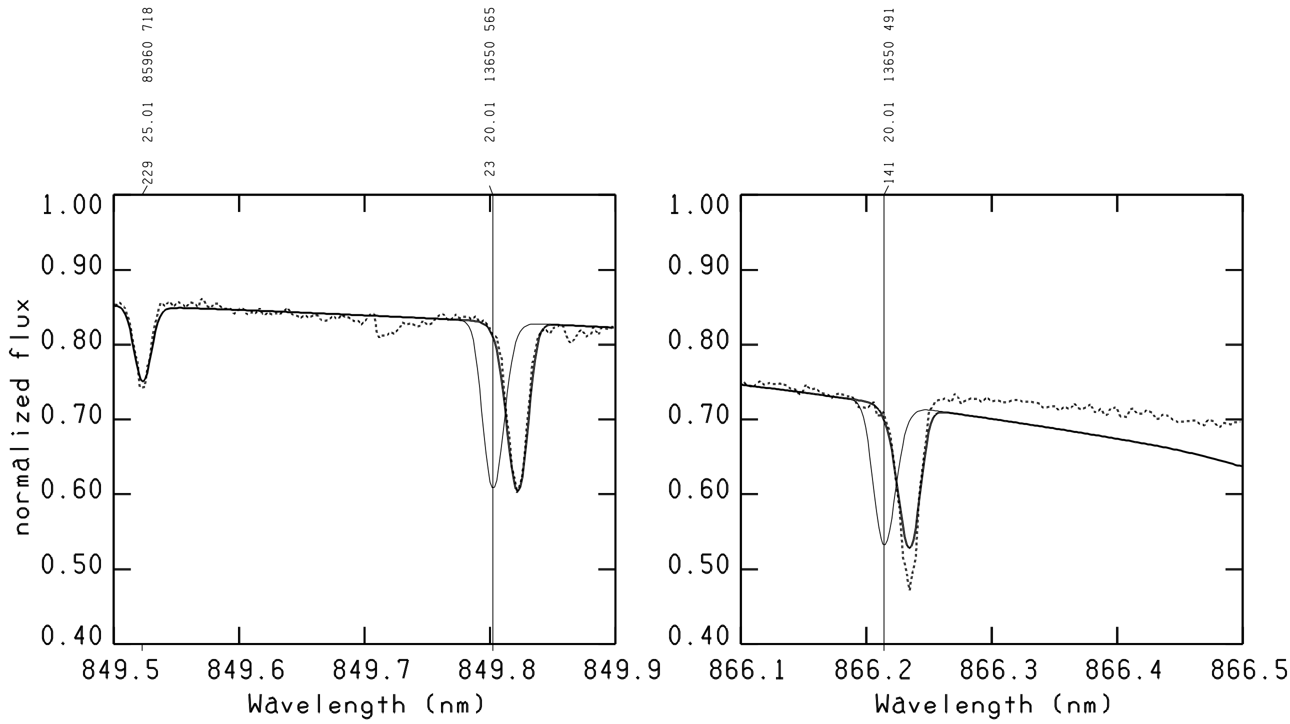

Fig. 1. Comparison of Ca II infrared lines in HD 175640 observed with UVES (dotted lines) with lines computed with two different calcium isotopic mixtures: **a)** the terrestrial isotopic mixture given in Table 2 (thin lines), **b)** by assuming 0.187% abundance for isotope 40 and 96.941% abundance for isotope 48 (thick lines). The meaning of the line identification labels like 229 25.01 85960 718 is: 229, last 3 digits of wavelength in nm (849.5229); 25.01, element (25) and charge (01), i.e. Mn II; 716, per mil residual flux of isolated line before rotational and instrumental broadening.

4. Observed and computed Ca II infrared triplet profiles

All model atmospheres were computed with the ATLAS9 code (Kurucz 1993a), except that for HD 175640, which is an ATLAS12 model (Kurucz 1997) computed for the individual stellar abundances. All the synthetic profiles were computed with the SYNTHE code (Kurucz 1993b).

In the course of our accurate spectroscopic study of the HgMn star HD 175640 (Castelli & Hubrig 2004), performed on UVES spectra, we have analyzed a large number of profiles in the whole wavelength range λ 3040–10 000 Å. The atlas of the observed and computed profiles is available at `http://wwwuser.oat.ts.astro.it/castelli/stars.html`. This study enabled us to fix the wavelength shift needed to overimpose the observed spectrum to the computed spectrum within an uncertainty of the order of 0.5 km s^{-1} for each line examined. The detected 0.2 Å redshift of two Ca II lines at 8498 Å and 8662 Å is therefore larger than any observed or laboratory wavelength uncertainty. The inspection of an available FEROS spectrum of HD 175640 has confirmed the shifts, eliminating any suspicion of improper reduction procedures for the UVES spectra. By exchanging their respective solar abundances, we found that an anomalous isotopic mixture of calcium with 96.941% of isotope 48 and 0.187% of isotope 40 can explain the observed redshifts. Figure 1 compares Ca II lines at $\lambda\lambda$ 8498 Å and 8662 Å observed in UVES spectra (dotted lines) with the synthetic spectra computed both with the terrestrial Ca isotopic composition given in Table 2 (thin lines) and with the anomalous Ca isotopic composition obtained by exchanging the abundances of the isotopes 40 and 48 (thick lines). The calcium abundance is $\log(N(\mathrm{Ca})/N_{\mathrm{tot}}) = -5.54$ from Castelli & Hubrig (2004). We note that the agreement in the positions of the observed and computed line Mn II at 8495.229 Å supports the reliability of the wavelength scale. It is obvious that the heaviest stable isotope is the predominant one. The vertical lines in Fig. 1 indicate the position of the ^{40}Ca isotopic component. Identification labels, whose meaning is explained in the figure caption, are plotted for the Ca terrestrial isotopic composition and only for lines with residual flux lower than 0.740.

We searched in other stars (Table 1, Col. 10) for shifts similar to those observed in HD 175640. The wavelength shifts have been determined by using lines lying as close as possible to the Ca II infrared profiles. If appropriate, the lines Mn II8448.449, Mn II8495.229, Fe II8499.606, Mn II8695.2, Mn II8683.690, Mn II8565.89, N I8680.282 and O I triplet at λ 8446 Å have been used as reference lines.

In addition to HD 175640, the only star with both UVES and FEROS spectra available is HD 178065. The comparison of the two spectra of HD 178065 is very similar to that we obtained for HD 175640, but the redshift is lower than that shown in Fig. 1 and it amounts to 0.14 ± 0.02 Å in the UVES spectrum. For both stars the Ca II profile at λ 8542.091 Å can be observed only in the FEROS spectra. Because this line lies just at the beginning of the echelle order we have given lower weight to it. Anyway, it is redshifted in the observed spectra like the other two lines of the Ca II triplet. Among the stars of Table 1 also HD 1909 and HD 158704 show Ca II profiles which are redshifted by 0.13 ± 0.02 Å and 0.15 ± 0.05 Å, respectively. As a consequence, Ca II could be concentrated in HD 1909, HD 158704, and HD 178605 in the isotopes ^{44}Ca, ^{46}Ca and ^{48}Ca. The deviation from the terrestrial composition for the remaining HgMn stars with smaller wavelength shifts is more difficult to assess because of the lower quality of the FEROS red spectra in comparison to UVES spectra. No conclusion could be drawn about the Ca isotopic structure in the HgMn star HD 221507 which has the rotational velocity $v \sin i$ too large (25 km s^{-1}) to allow the detection of shifts smaller than 0.2 Å. The two normal stars in our sample, HD 84461 and HD 196426, show terrestrial Ca isotopic proportions as no wavelength shifts have been found for them.

We also compared the observed solar Ca II profiles with profiles computed both with the isotopic components and without them. The observed spectrum was the Solar Flux Atlas from Kurucz et al. (1984), while the synthetic spectrum was computed for an ATLAS9 model with parameters $T_{\rm eff} = 5777$ Å, $\log g = 4.4377$ and microturbulent velocity $\xi = 1.0$ km s^{-1}. Synthetic profiles were broadened for a rotational velocity $v \sin i = 2$ km s^{-1}, a Gaussian instrumental profile corresponding to a resolving power $R = 523\,000$, and a Gaussian macroturbulent velocity $\xi_{\rm M} = 3.25$ km s^{-1}. As a result of our synthesis, the computed cores appeared much narrower than the observed ones when the isotopic components were neglected, and became broader when the isotopic components have been considered, giving a much better agreement with the observations (Hubrig & Castelli, in preparation). The solar case points out the no-negligible effects of the isotopic components on the cores of the Ca II infrared profiles in cool stars.

5. Discussion

For the first time we present here observational evidence for an anomalous isotopic structure of Ca II in a small number of HgMn stars where the centroid wavelengths of Ca II infrared triplet lines have been found redshifted with respect to those of the terrestrial Ca II lines, indicating that Ca II is concentrated in the heaviest stable isotopes. For one star, HD 175640, the measured wavelength is consistent with Ca II being present in the atmosphere entirely in form of the heaviest stable isotope ^{48}Ca. This is a very striking result as ^{48}Ca makes up only 0.187% of the terrestrial Ca mixture (Table 2). We found that in the Sun the Ca stable isotopes significantly affect the cores of Ca II infrared profiles and cannot be ignored in the calculations aimed to reproduce the observed lines. More studies of variations in isotopic composition from star to star are needed to provide clues as to the types of physical processes occurring in the atmospheres of HgMn stars. Further insights into the nature of the HgMn stars would benefit from the study of other Ca lines, provided that $\log gf$s and isotopic and hyperfine structures are known from the laboratory and atomic physics studies. However, the isotopic separations for Ca II H and K lines are too small to allow unambiguous isotopic abundances to be found. Also our analysis of other Ca lines in the spectrum of HD 175640 has shown that many Ca lines are weak or blended with other lines. As pointed out by U. Munari (2004, private communication), we would like to note that a study of variations in isotopic composition in different stars is of great relevance to ESA's coming GAIA mission, which will record stellar spectra over the whole sky in a spectral interval centered on the Ca II infrared triplet. The expected accuracy of GAIA radial velocities will be of the order of 1 km s^{-1}. However, the 0.2 Å shift caused by the isotopic anomaly translates into a 7 km s^{-1} uncertainty in GAIA radial velocities.

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