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Letter to the Editor

The calcium isotopic anomaly in magnetic CP stars⋆

C. R. Cowley[1] and S. Hubrig[2]

[1] Department of Astronomy, University of Michigan, Ann Arbor, MI 48109-1090, USA
e-mail: cowley@umich.edu
[2] European Southern Observatory, Casilla 19001, Santiago 19, Chile
e-mail: shubrig@eso.org

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Abstract. Chemically peculiar stars in the magnetic sequence can show the same isotopic anomaly in calcium previously discovered for mercury-manganese stars in the non-magnetic sequence. In extreme cases, the dominant isotope is the exotic ^{48}Ca. Measurements of Ca II lines arising from 3d−4p transitions reveal the anomaly by showing shifts up to 0.2 Å for the extreme cases – too large to be measurement errors. We report measurements of miscellaneous objects, including two metal-poor stars, two apparently normal F-stars, an Am-star, and the N-star U Ant. Demonstrable anomalies are apparent only for the Ap stars. The largest shifts are found in rapidly oscillating Ap stars and in one weakly magnetic Ap star, HD 133792. We note the possible relevance of these shifts for the GAIA mission.

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

1. Introduction

Isotopic anomalies among the mercury-manganese (HgMn) chemically peculiar (CP) stars have been known since the early 1960's. Bohlender et al. (2003), and Proffitt et al. (1999) give recent summaries and references.

Castelli & Hubrig (2004) described a new isotopic anomaly in HgMn stars that is revealed by wavelength shifts in the infrared triplet of Ca II. They discovered in the course of their abundance work on HR 7143 (HD 175640) that the two available Ca II lines of the triplet were displaced 0.2 Å to the red of their expected positions. The magnitude of the displacements for $\lambda\lambda$8498 and 8662 are just those expected if the calcium in the star were nearly pure ^{48}Ca. The strongest line of the triplet, λ8542, was unavailable to Castelli & Hubrig because of a gap in the coverage of their UVES spectra. This line was (mostly) unavailable in the present work for the same reason.

Castelli & Hubrig noted the relevance of a large isotopic shift in the Ca II infrared triplet for the Gaia mission (cf. Katz et al. 2004). While large shifts may be confined to a few exotic objects, workers should be aware that they can occur.

The relevant laboratory measurements were described by Nörtershäuser et al. (1998). The relatively large wavelength displacements are caused by mass-dependent, collective motions of the electrons and the atomic nucleus. These interactions cause the *specific mass shifts* (SMS). The SMS are well known to be difficult to calculate accurately (Cowan 1981).

Other lines of Ca II do not show these large shifts, which are due to the singular behavior of the 3d orbitals. In Ca II the 3d−4p transitions make up the lines of Multiplet 2, $\lambda\lambda$8498, 8542, and 8662. No transitions, other than those of the infrared triplet, involving 3d orbitals are available. Transitions from 3d to 5p levels fall near 2130 Å. Fortunately, the measured shifts are quite large (from 0.200 Å for λ8498 to 0.207 Å for λ8662) between ^{48}Ca II and ^{40}Ca II.

2. Stellar sample

The studied sample includes 19 magnetic chemically peculiar stars (Ap), two metal-poor halo stars, one Am star, the N-star U Ant, and Arcturus. Among Ap stars six are rapidly oscillating Ap (roAp) stars which pulsate in high-overtone, low-degree, nonradial *p*-modes, with periods in the range 6–15 min (Kurtz 1990). The atmospheres of roAp stars are definitely abnormal showing remarkable ionization disequilibria of rare earths elements (e.g. Ryabchikova et al. 2004). The basic data of our sample are presented in Table 1. The columns indicate, in order, the HD number of the star, another identifier, and the spectral type, as it appears in the catalogue of Renson et al. (1991). The last two columns list the measured longitudinal field or, if available, the surface magnetic field (in kG) and their source.

All but one of the spectra have been obtained with the VLT UV-Visual Echelle Spectrograph UVES at UT2. Most of the spectra of magnetic stars have been retrieved from the ESO UVES archive (ESO programme No. 68.D-0254). Spectra of one roAp star, HD 24712, one Am star, HD 27411, one N-star, HD 91793, and two metal-poor stars, HD 140283 and

⋆ Based on observations obtained at the European Southern Observatory, La Silla and Paranal, Chile (ESO programme Nos. 65.L-0316, 68.D-0254 and 266.D-5655).

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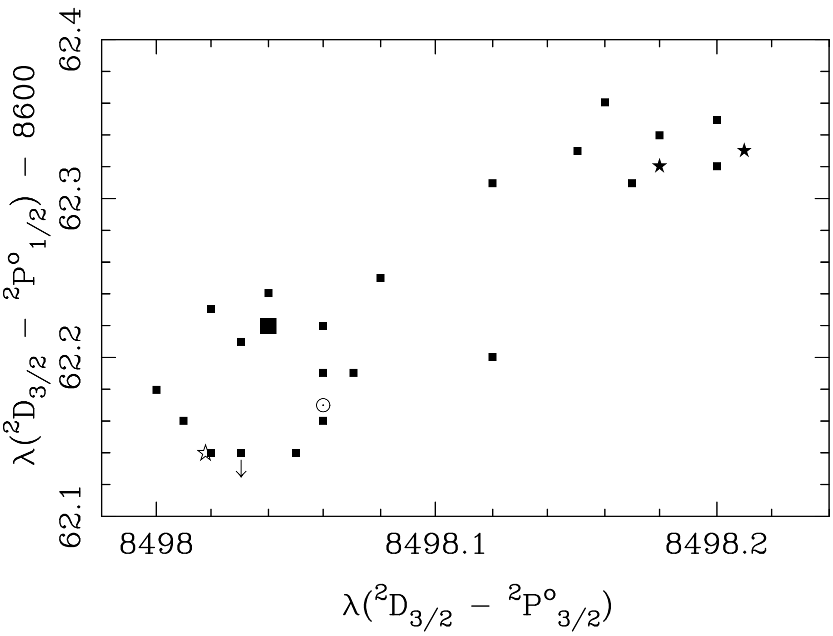

Fig. 1. Wavelengths for the Ca II λ8662-line vs. those of the λ8498-line. The open star is the laboratory position (NIST). The sun symbol marks the photospheric wavelengths. Stars showing the ^{48}Ca anomaly are in the upper-right portion of the diagram. There are two points (filled stars) for HD 101065. The large square is for HD 27411 and HD 187474 whose points overlap. The two halo stars, HD 140283 and HD 122563 are not plotted because the λ8662 line was not available. The sunspot was also not plotted because of the complexity of the λ8662 profile.

HD 122563 were downloaded from the UVESPOP web site (Bagnulo et al. 2004). All spectra were observed with Dichroic standard settings covering the spectral range from 3030 to 10 000 Å at the resolving power of $\lambda/\Delta\lambda \approx 0.8 \times 10^5$. They were reduced by the UVES pipeline Data Reduction Software (version 1.4.0), which is an evolved version of the ECHELLE context of MIDAS. One additional spectrum of HD 101065 used in this study was obtained with the echelle spectrograph FEROS (Fiber Range Optical Spectrograph) on the 1.52 m telescope at La Silla. It covers the wavelength region between 3530 and 9220 Å, and has a nominal resolving power of 48 000. To reduce the spectrum we used the standard MIDAS pipeline for FEROS. The FEROS spectum of HD 101065 was used to confirm the shifts of the infrared Ca II triplet lines observed in the UVES spectrum of this star.

3. Wavelength determination and accuracy

ASCII files of the ESO spectra were interpolated to give a point every 0.02 Å, and mildly filtered using a standard Brault-White (1971) algorithm. Several methods were used to establish the zero point of the stellar atomic lines. Most commonly, a radial velocity scan was performed, using wavelength coincidence statistics (Cowley & Hensberge 1981) for the atomic species expected to be strongly present. The radial velocity of the star was taken to be that which gave the most highly significant results. The method works very well. Uncertainties under a km s^{-1}, and typically half a km s^{-1}, result.

For the magnetic Ap stars, it can be difficult to obtain a good radial velocity from the regions of the spectra that contained the two infrared Ca II lines. There are relatively few easily identifiable strong lines in this region, and the Zeeman splitting increases quadratically with wavelength. The magnetic null lines Fe II λ7224 and Fe I λ7389 were useful as a check in such instances, and in a few cases, the O I triplet $\lambda\lambda$7772, 7774, and 7775 could be used. In some cases we used a nearby region (e.g. $\lambda\lambda$5817–6834) acquired on the same night and at nearly the same time.

Both Ca II lines are found near gaps in echelle orders. The problem is particularly severe for the λ8668 line, but may also be significant for λ8498. We give two arguments that the coherence of the wavelength scale is sufficient to provide wavelengths that are accurate for the present purpose. First, we obtain reasonable wavelengths for normal stars. Second, in the instances where we claim the stars show evidence of ^{48}Ca, both Ca II lines are shifted by appropriate amounts (see Fig. 1 described below). We claim an overall wavelength accuracy in the range 0.03 to 0.04 Å; one or two measurements could be in error by as much as 0.05 Å.

Solar wavelengths were simply taken from the Rowland Tables (Moore et al. 1966). For Arcturus, we adopted the wavelength calibration of Hinkle et al. (1995). The sunspot spectrum is from Wallace et al. (1998).

4. Results

Table 2 gives the wavelength measurements for our sample (including the sun, Arcturus, and a sunspot). We also give the wavelength from the NIST site (Sansonetti & Martin 2003).

The data of Table 2 are plotted in Fig. 1. The stars generally fall into two groups. One group has points typically within a 0.04 Å radius including the sun's position. The scatter may be reasonably attributed to various calibration and measurement uncertainties, blending, and macroturbulence.

Table 1. Basic data of studied stars.

HD	Other	Sp. Type	$\langle \mathcal{B}_z \rangle / \langle \mathcal{B}_s \rangle$	Ref.
739	θ Scl	F4V	–	–
965	BD -00°21	A8 Sr	–/4.4	1
24712	HR 1217	A9 SrEuCr roAp	1.2/–	2
27411	HR 1353	A3m	–	–
47103	BD -20°1508	A SrEu	–/17.5	1
50169	BD-01°1414	A3 SrCrEu	–/4.7	1
60435	CD-57°1762	A3 SrEu roAp	–0.4/–	5
75445	CD-38°4907	A3 SrEu	–/3.0	1
91793	HR 4153	N-star	–	–
93507	CD-67°955	A0 SiCr	–/7.2	1
101065	CD-46°7232	F3 roAp	–1.0/–	3
116114	BD-17°3829	F0 SrCrEu	–/6.0	1
122970	BD+06° 2827	F0 roAp	0.2/–	4
122563	HR 5270	F8 IV halo star	–	–
124897	HR 5340	K1.5 III Arcturus	–	–
133792	HR 5623	A0p SrCr	–/1.1	5
134214	BD-13°4081	F2 SrEuCr roAp	–/3.1	1
137909	β CrB	A9 SrEuCr	–/5.5	1
137949	33 Lib	F0 SrEuCr roAp	–/4.7	1
140283	BD-10°4149	sdF3 halo star	–	–
146836	HR 6077	F6 III	–	
176232	10 Aql	A6 Sr roAp	–/1.4	6
187474	HR 7552	A0 EuCrSi	–/5.0	1
188041	HR 7575	A6 SrCrEu	–/3.7	1
216018	BD-12°6357	A7 SrCrEu	–/5.6	1
217522	CD-45°14901	A5 SrEuCr roAp	–0.7/–	3

(1) Mathys et al. (1997); (2) Leone & Catanzaro (2004); (3) Hubrig et al. (2004a); (4) Hubrig et al. (2004b); (5) Mathys & Hubrig, in preparation; (6) Leone et al. (2003).

Table 2. Observed positions of Ca II lines.

8498	8662	Star
8498.018	8662.140	NIST
8498.06	8662.17	sun
8498.09	8662.22:	sun sunspot
8498.02	8662.14	HD 124897, Arcturus
8498.07	8662.19	HD 739, θ Scl, HR 35, F4 V
8498.06	8662.19	HD 146836, HR 6077, F6 III
8498.04	8662.22	HD 27411, HR 1353, Am
8498.05	8662.14	HD 91793, U Ant, HR 4153, N-star
8498.04	8542.11	HD 140283, halo dwarf
8498.05	—[1]	HD 122563, halo giant
		Ap stars
8498.04	8662.24	HD 965
8498.00	8662.18	HD 47103
8498.03	8662.21	HD 50169
8498.08	8662.25	HD 60435
8498.12	8663.31	HD 75445
8498.03	≤8662.14	HD 93507
8498.06	8662.16	HD 116114
8498.20	8662.32	HD 133792, HR 5623
8498.12	8662.20	HD 137909, β CrB
8498.02	8662.23	HD 137949, 33 Lib
8498.06	8662.22	HD 188041, HR 7575
8498.04	8662.22	HD 187474, HR 7552
8498.01	8662.16	HD 216018
		roAp stars
8498.17	8662.31	HD 24712, HR 1217
8498.21	8662.33	HD 101065 UVES
8498.18	8662.32	HD 101065 FEROS
8498.15	8662.33	HD 122970
8498.20	8662.34	HD 134214
8498.16	8662.36	HD 176232, 10 Aql
8498.20	8662.35	HD 217522

[1]NIST position is 8542.09; λ8662 region not observed.

There is a net positive displacement of the cluster in the lower left from the laboratory position, marked by an open star. Both wavelengths are affected in the same sense. The solar wavelength of the third member of the Ca II triplet, λ8542 is also slightly displaced, positively, from the laboratory position. The possibility that this is due to an isotopic variation of solar and terrestrial material is intriguing. It is, of course, not the first such example. In any event, the stellar positions in the lower left grouping of points in Fig. 1 show the same trend.

A second group consists of seven stars; measurements for Przybylski's star are from two spectrographs. Six objects are rapidly-oscillating Ap stars. The six are grouped together at the end of Table 2. One of the stars in this group, HR 5623 (HD 133972) is not a roAp, and one roAp, 33 Lib, does not show the shift. Two objects thought to be related to the roAp stars because of their core-wing anomaly (Cowley et al. 2001), HD 965 and HR 7575 (HD 188041) also do not have the ^{48}Ca shifts.

Three points fall between the two groups. It is not yet clear to what extent they may be genuine intermediate cases or whether they are due to large errors. We admit the latter might be as large as 0.05 Å.

Figure 2 shows ten spectra in the region of the λ8498 line. The spectra are displaced upward, respectively by 0.0, 0.27, 0.84, 1.2, 1.6, 2.0, 2.4, 2.8, 3.2, and 3.7 in units where the continuum is 1.0. The thin, vertical lines are at 8498.06 (the solar position) and 8498.20 (the wavelength for ^{48}Ca II). The profiles for HD 188041 and HD 965 have double bottoms. We attribute this mostly to the Zeeman effect, and the reported wavelengths in Table 2 are for the *centroids* of these lines. It does appear that the red portion of the profile of both stars is somewhat deeper than the violet, and this indicates blending, quite possibly by ^{48}Ca II.

5. Discussion

Isotopic anomalies have not yet become established in the magnetic sequence of CP stars. Although they are well known to show lines of Hg and Pt, the spectra are more complex than those of HgMn stars, so that subtle wavelength shifts are easily attributed to blends. This confusion is less likely with lines of the Ca II infrared triplet because they are located in a region where blending is less severe, and they are intrinsically strong.

Abundance anomalies in CP stars are generally attributed to chemical fractionations. The papers cited earlier show that this interpretation is not without difficulties. The ^{48}Ca isotope might be explained in some HgMn stars where there is a slight

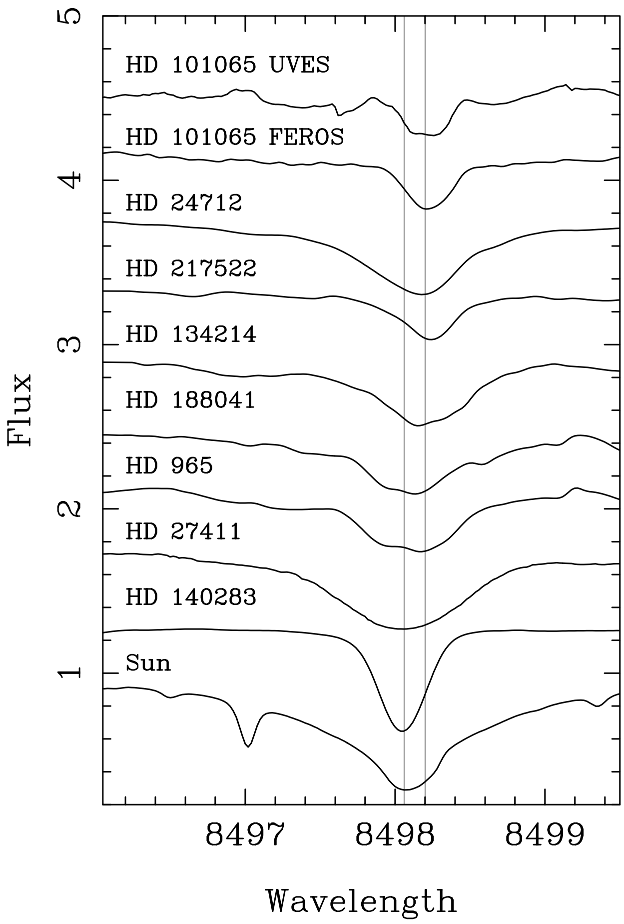

Fig. 2. Spectra of 10 stars in the region of Ca II λ8498. Spectra have been displaced upward for purposes of illustration by amounts given in the text. The upper 7 stars are all magnetic stars. HD 27411 is an Am. HD 140283 is a well-studied subdwarf. The thin vertical lines are at λ8498.06 and 8498.20.

abundance excess of calcium. In this case, the lighter isotopes might be assumed to be pushed out of the photosphere. The magnetic stars studied here, are cool, comparable in temperature to Am stars, where calcium sinks. It is unclear what kind of fractionation scenario might account for an excess of the heavy isotope of calcium in these stars.

Is there a connection between the ^{48}Ca-stars investigated here, and the HgMn objects found by Castelli & Hubrig to show the same anomaly? The only obvious similarity is that both kinds of stars show the most extreme abundances, and, especially isotopic, anomalies.

Nuclear scenarios were once considered in connection with CP stars, but have been widely abandoned. The ^{48}Ca isotope poses a problem for any nucleosynthetic scheme, as discussed for example by Clayton (2003).

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