The calcium isotopic anomaly in magnetic CP stars*

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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 48Ca. 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 λ8498 and 8662 are just those expected if the calcium in the star were nearly pure 48Ca. 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, λλ8498, 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 48Ca and 40Ca.

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 earth 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).
Fig. 1. Wavelengths for the Ca II $\lambda 8662$-line vs. those of the $\lambda 8498$-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 $\lambda 8662$ line was not available. The sunspot was also not plotted because of the complexity of the $\lambda 8662$ 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 10000 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 48000. To reduce the spectrum we used the standard MIDAS pipeline for FEROS. The FEROS spectrum 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 $\lambda 7224$ and Fe I $\lambda 7389$ were useful as a check in such instances, and in a few cases, the O I triplet $\lambda \lambda 7772, 7774, 7775$ 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 $\lambda 8668$ line, but may also be significant for $\lambda 8498$. 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.

<table>
<thead>
<tr>
<th>HD</th>
<th>Other Sp. Type</th>
<th>(B_0) / (B_0)</th>
<th>Ref.</th>
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<tr>
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<td>θ Scl</td>
<td>F4V</td>
<td>–</td>
</tr>
<tr>
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<td>HR 1353</td>
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<td>–</td>
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<td>HR 5340</td>
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<td>CD-45°14901</td>
<td>A5 SrEuCr roAp</td>
<td>–0.7–</td>
</tr>
</tbody>
</table>

(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).

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, λ8452 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 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.

A second group consists of seven stars; measurements for Przybylski’s star are from two spectographs. 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 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 48Ca 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 48Ca 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 48Ca 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 HgMn stars, so that subtle wavelength shifts are easily attributed to blends. Therefore, 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.

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