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Search for tidally driven abundance anomalies in Am stars

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Abstract. High S/N, high resolution CCD spectra of 10 Am binaries with different orbital elements, rotation and atmospheric parameters obtained with the 2-m telescope of NAO Rozhen (Bulgaria) were analyzed. We carried out preliminary abundance analyses of these stars and studied the possible dependences of abundance anomalies and [Ca/Fe] on their values of effective temperature, $v \sin i$, orbital period, and eccentricity. There are weak trends of [Ca/Fe] increasing with $v \sin i$ and decreasing with eccentricity and orbital period. [Ca] seems to be increasing with effective temperature, and [Fe] decreasing with $v \sin i$ and increasing with eccentricity. However we need to study more stars to confirm and disentangle the possible trends.

Keywords. Techniques: spectroscopic, stars: abundances, stars: atmospheres, binaries: spectroscopic, stars: chemically peculiar, stars: rotation

1. Introduction

The Am stars are a well known subgroup of chemically peculiar (CP) stars on the upper Main Sequence (MS). They exhibit abnormally strong metallic and unusually weak Ca and Sc lines. This peculiarity seems to be due to microscopic selective diffusion driven mainly by radiation pressure and gravity. The diffusion operates first below the deepest He II convection zone until it disappears because of He settling and then proceeds much higher and more effectively below the H+H I convection zone. An additional superficial iron convection zone may develop on the MS (Michaud 1970, Richard *et al.* 2001). Rotation was found to play a key role in this process as it induces large scale mixing which can disturb the slow diffusion process. More elaborate calculations by Charbonneau & Michaud (1991) indicate that a rotational velocity less than about 90 $\mathrm{km\,s^{-1}}$ is required for diffusion to prevail and the Am phenomenon to occur. A growing amount of recent observational evidence supports the above-mentioned picture and reveals that there exists either a smooth or a step function dependence of Am peculiarity on rotation (Abt 2000, Burkhart & Coupry 2000, Varenne & Monier 1999, Takeda & Sadakane 1997, Abt & Morrell 1995, and Savanov 1995). Abt (2000) and Abt & Morrell (1995) even favour the view that "rotation alone can explain the appearance of an A star as either abnormal or normal." Nevertheless, Am peculiarities seem to depend on the evolutionary status or the age as well. They may (1) develop very quickly soon after the star arrives on the Main

Sequence, or even before that (Burkhart & Coupry 2000), and does not undergo considerable changes during the MS phase or (2) the observable abundances of some elements may significantly depend on age (Alecian 1996). Apart from that, the Am phenomenon is apparently restricted to a well defined region of the MS what further involves its dependence on atmospheric parameters such as effective temperature and gravity (Künzli & North 1998, Hui-Bon-Hoa 2000). However, it is usually difficult to distinguish evolution and temperature effects since temperature and age strongly correlate. Domingo & Figueras (1999) find that there is no significant difference between the evolutionary status of Am and normal A-type stars while Künzli & North (1998) found a deficit of young Am stars.

Tidal effects might play a unique role in driving the CP phenomenon. The stellar companion induces additional large scale motions, flows, oscillations, and such inside and/or on the surface of the star which may mix the medium. We will refer to these processes as tidal mixing. On the other hand, tidal effects may also act as a stabilizing agent suppressing other mixing processes (e.g., rotationally induced mixing), evidence of which is that some late-type tidally locked binaries possess higher Li surface abundances (Ryan & Deliyannis 1995). One of us (Budaj 1996) has suggested an empirical 'tidal mixing + stabilization' hypothesis to account for the behaviour of some of the below mentioned observations in Am stars. Can these hypothetical processes find a more physical footing among the known theoretical processes operating in binary stars. Theoretical analyses of the tidal effects are concerned with mainly synchronization and circularization mechanisms. There are two competing but not mutually exclusive (Tassoul 1995) views of this problem in early type binaries.

In the dynamical tide theory of Zahn (1977), a variety of gravity modes (g-modes) are induced by the tidal potential mainly if eccentric orbits are involved. In stars with radiative envelopes, radiative damping retards the dynamical tide which results in spin-orbit synchronization and circularization. The theory predicts that synchronization prevails within orbital periods of about 2 days and circularization within about 1 day for an A type binary. An observational search for forced oscillations in early type binaries was started by Harmanec *et al.* (1997). Recently, Eggleton *et al.* (1998) suggested that turbulent viscosity dissipation acting on the equilibrium tide can also operate on the upper Main Sequence. This mechanism was originally proposed by Zahn (1977) for stars with convective envelopes. It assumes that the star is in hydrostatic equilibrium, a nonzero viscosity causes the tidal bulge to lag (or to lead) the secondary star. This induces a tidal torque and subsequent spin-orbit synchronization and circularization.

In the hydrodynamical mechanism of Tassoul & Tassoul (1992), the lack of axial symmetry in a nonsynchronously rotating tidally distorted star produces large-scale meridional currents via Ekman pumping. These currents exchange mass and angular momentum. This mechanism can remain operative for larger orbital periods, up to $P_{\rm orb} \approx 100\,$d. However, pseudo-synchronization beyond $P_{\rm orb} \approx 15 - 25\,$d might be only marginal. The circularization is effective up to $P_{\rm orb} \approx 10\,$d. The geometry of such currents is similar to rotationally induced meridional circulation as they rise (sink) at the equator and sink (rise) at the poles if the rotational period is shorter (longer) than the orbital one.

Am peculiarities may depend on the orbital elements in a binary system (Budaj 1996, 1997, Iliev *et al.* 1998). They seem more pronounced in eccentric orbits and possibly also with longer orbital periods provided that the binary components are relatively close with orbital periods, $P_{\rm orb} < 180$ days. Since Am stars are often found in binaries (Abt 1961, 1965, Abt & Bidelman 1969, North *et al.* 1998, Debernardi *et al.* 2000) they offer a unique chance to study the influence of a companion on the stellar hydrodynamics. The main purpose of this paper will be to continue a systematic spectroscopic investigation of Am binaries and concentrate also on the possible dependence of Am peculiarities on the orbital elements.

2. Observations and sample stars

We searched the region $\lambda\lambda$5000-9000 for sufficiently weak but still detectable unblended lines of the most peculiar and deficient elements in Am stars (Ca, Sc, C, Mg, etc.) so that the lines were not strongly affected by microturbulence. However, we required that the lines could still be seen even if the elements were underabundant in sharp line stars or normal in broad line A type stars and that the lines were not blended even at high rotation. Finally, we chose two spectral regions $\lambda\lambda$6400-6500 and $\lambda\lambda$6660-6760 and concentrated on Ca I λ6439 and the rich spectrum of Fe lines.

Our spectroscopic observations were carried out with the 2-m RCC telescope of the Bulgarian National Astronomical Observatory as part of our observational programme on Am stars in binary systems. A Photometrics AT200 camera with a SITe SI003AB 1024 × 1024 CCD chip (24 μm pixels) was used in the Third camera of the Coudé spectrograph to provide spectra with a typical $R = 32000$ and S/N ratio of about 300. The instrumental profile was checked and adjusted during the instrumental set-up using the comparison line spectrum so that its FWHM was about 0.2 Å and never exceeded this value. IRAF standard procedures were used for bias subtracting, flat-fielding and wavelength calibration. Telluric lines were removed using the spectra of hot, fast rotating stars. The wavelength calibration has the r.m.s. error of 0.005 Å. The EQWREC2 code of Budaj & Komžík (2000) was also used for some tasks such as continuum rectification. A few tens of Am binaries from the sample of Budaj (1996) were chosen with V brighter than 7 and declinations $\delta > -10^\circ$. Only stars with orbital periods $10 < P_{\rm orb} < 180$ d were considered initially. This assured a full range of original eccentricities which did not undergo circularization on the MS. We put no constraint on the rotational velocity.

3. Atmospheric parameters and atomic data

The $uvby\beta$ indices (dereddened with the UVBYBETA code of Moon & Dworetsky 1985) are taken from Renson (1991). Geneva and UBV photometry are from Rufener (1980) and Mermilliod *et al.* (1997), respectively. The atmospheric parameters were derived using the TEFFLOGG code of Moon & Dworetsky (1985, see also Smalley & Dworetsky 1995) from $uvby\beta$ photometry, and independently with the Kobi & North (1990) calibration of Geneva photometry. If both estimates were available we accepted their rounded mean as the best choice for model atmosphere parameters. All the Am stars studied here are either SB1 binaries or have a very weak secondary spectrum, hence the possible influence of their companions on photometry was neglected. A detailed spectrum synthesis of the spectral regions was accomplished using the code SYNSPEC (Hubeny *et al.* 1994, Krtička 1998). Model atmospheres were interpolated from Kurucz (1993). The VALD atomic line database (Kupka *et al.* 1999) also containing Kurucz (1990) data, complemented by the data from Budaj & Iliev (2003), was used to create a line list for the spectrum synthesis. Over 2000 lines were used in each spectral region. The Fe abundance was determined first from weak Fe lines and the microturbulent velocity was used as a free parameter to obtain a fit for stronger Fe lines. The computed spectra were convolved with the instrumental profile (Gaussian of 0.2 Å FWHM) and rotationally broadened to fit with the observed spectra.

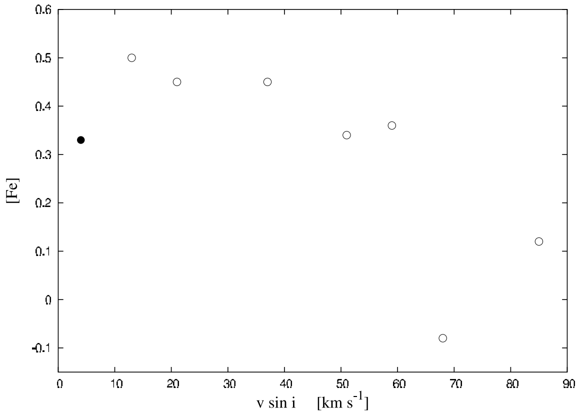

Figure 1. Iron abundance versus the projected rotational velocity. The full circle is an outstanding hot Am star.

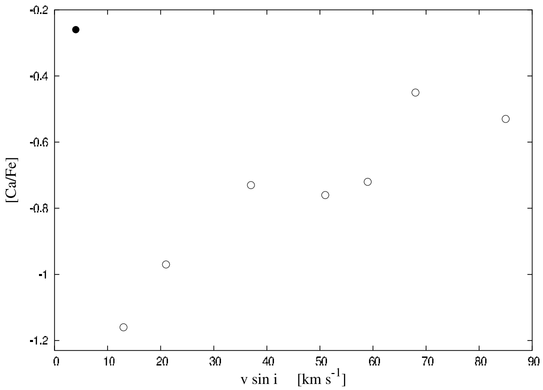

Figure 2. [Ca/Fe] versus the projected rotational velocity.

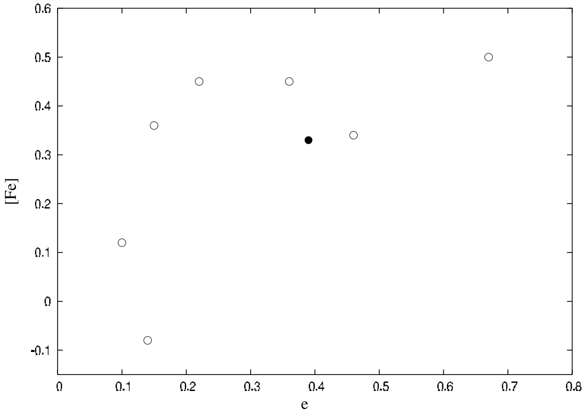

Figure 3. Iron abundance versus the eccentricity of the orbit.

4. Results

Based on what was summarized in the introduction, we could expect that the Am anomalies (or iron abundances) in such a sample of Am binaries (specified by the selection rules mentioned above) should decrease with rotational velocity and increase with

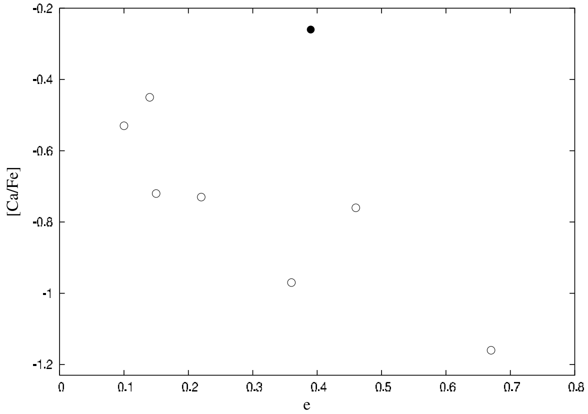

Figure 4. [Ca/Fe] versus the eccentricity of the orbit.

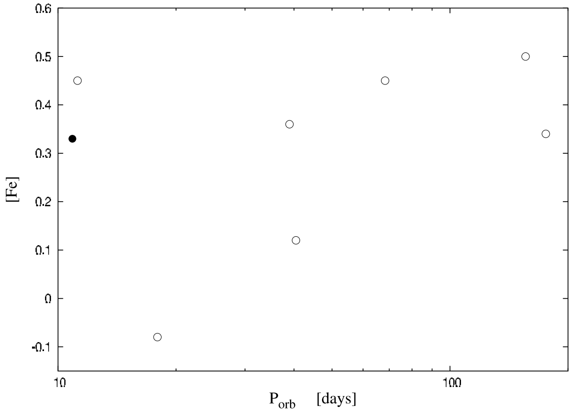

Figure 5. Iron versus the orbital period.

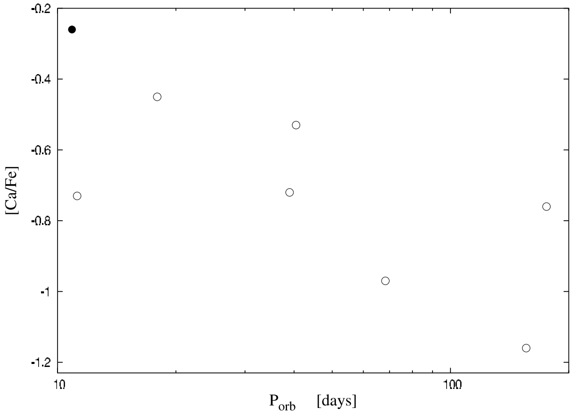

Figure 6. [Ca/Fe] versus the orbital period.

eccentricity and orbital period. Just the opposite should hold for the calcium abundances since, contrary to iron, calcium is mostly underabundant in Am stars. Thus [Ca/Fe] should behave like calcium and should be a much more reliable tracer of the above effects since the Ca and Fe abnormalities multiply. Moreover, [Ca/Fe] should be much

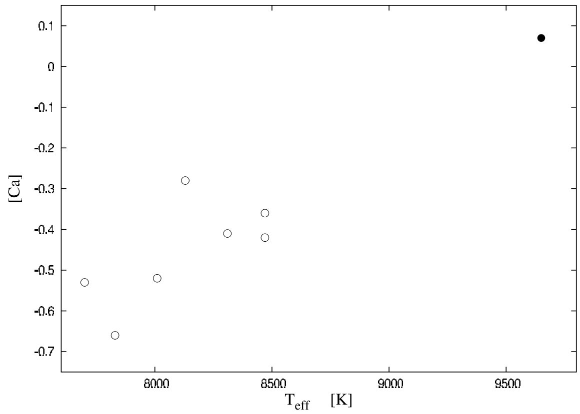

Figure 7. Calcium abundance versus the effective temperature of the star.

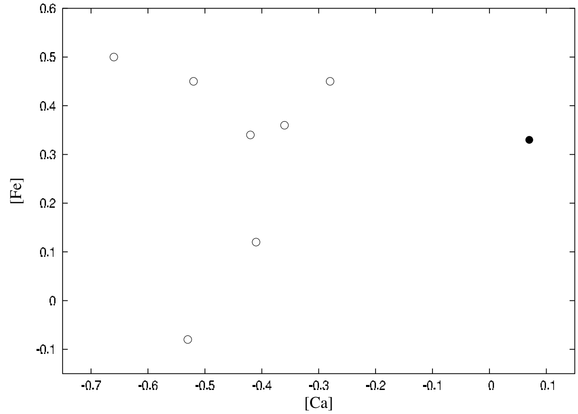

Figure 8. Iron versus calcium abundances.

less sensitive to the uncertainty in the effective temperatures since both Ca and Fe lines observed behave in the same manner, namely, get weaker with increasing temperature.

Now, let us look at real data to see if it conforms to the picture outlined above. Two out of the ten Am stars studied turned out not to be Am stars since their [Ca/Fe] ratio was greater than 1, so they were excluded from the figures. Figures 1 and 2 illustrate the behaviour of the iron abundance and of [Ca/Fe] on the projected rotational velocity. There is a weak trend, as expected, namely a decrease of iron with rotation and an increase of [Ca/Fe] with rotation which means that the Am peculiarity increases towards slower rotation. Figures 3 and 4 depict the behaviour of iron and [Ca/Fe], respectively, versus the eccentricity and again, as expected, there is a weak tendency of Fe to increase with eccentricity while the opposite seems to hold for [Ca/Fe]. Figures 5 and 6 illustrate the behaviour of iron and [Ca/Fe], respectively, with the orbital period. Again the possible dependences are very weak, but iron seems to increase while [Ca/Fe] seems to decline with orbital period. Figure 7 illustrates that the calcium abundance also has a tendency to increase with the effective temperature of the star. Stars with higher temperatures are more normal, i.e., have lower calcium underabundances. Finally, Figure 8 plots the Fe versus Ca abundance. There is no apparent anticorrelation between the two. One point is outstanding in many of the figures. This outlier is marked by a black dot. It represents a hot Am star which does not seem to fit into the general scheme.

All the possible dependences are very weak. Nevertheless, it is apparent that Fe and

[Ca/Fe] behave in exactly the opposite manner. This is not a pure consequence of a Ca - Fe anticorrelation or a random scatter in the figures and is well over the precision of such abundance analysis. Thus, we can confirm the anti-correlation of the Am peculiarities with rotation and effective temperature. More interestingly, Fe and [Ca/Fe] seem to depend on the eccentricity and orbital period what indicates the influence of a companion on the mixing and hydrodynamics of the Am component which conforms to the tidal mixing + stabilization hypothesis of Budaj (1996). A larger sample of Am binaries must be studied for abundances to disentangle the possible dependence of the Am phenomenon on mass, age (or temperature), rotation, orbital elements, and mass ratio, and to permit a more definite conclusions about the tidal effects.

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