The roAp star α Cir: A target for MONS?

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ABSTRACT

α Cir is the brightest of the known rapidly oscillating Ap (roAp) stars ($V = 3.2$). Five distinct oscillation modes have been observed with photometric amplitudes above 100 ppm. The principal mode has been observed spectroscopically and the results indicate a node in the atmosphere of the star. I will present recent results and discuss what we could learn by observing this star with MONS.

1. Introduction

The Ap or CP2 stars are a group of chemically peculiar stars that range along the main sequence from about spectral type B8 to F0. They are characterised by spectra with anomalously strong lines of Si, Sr, Cr, other iron peak elements, Eu and other rare earth elements. Ap stars also differ from their normal A-star cousins in having slower rotation rates and stronger magnetic fields (up to ~1 kG). The spectral anomalies are thought to have been caused by chemical diffusion from radiation pressure, which has pushed certain elements to the surface, made possible because their atmospheres are sufficiently stable against turbulent or convective mixing. However, they are not stable against pulsation because rapidly oscillating Ap (roAp) stars are found where the Ap phenomenon overlaps the instability strip (reviews by Kurtz 1990; Shibahashi 1991; Matthews 1991, 1997; Kurtz & Martinez 1993; Martinez & Kurtz 1995a,b).

About thirty percent of main-sequence (normal) A-stars in the instability strip pulsate with photometric amplitudes greater than 10 mmag and with periods in the range 30–360 minutes; these are δ Scuti stars. However, the roAp stars are characterised by photometric amplitudes below 8 mmag and with periods in the range 5–15 minutes. Both δ Scuti and roAp stars, pulsate in low-degree ($\ell \leq 3$) p-modes but while the δ Scuti stars pulsate with low-overtones, the roAp stars vibrate in very high-overtones ($n \sim 25$–50). Explaining why the chemically peculiar roAp stars pulsate in much higher overtones than the normal δ Scuti stars remains one of the exciting challenges in this field. For recent theoretical work on different aspects of roAp stars, see Takata & Shibahashi (1995); Dziembowski & Goode (1996); Audard et al. (1998); Gautschy, Saio & Harzenmoser (1998).

About 30 roAp stars have been detected to date. For many it has been possible to detect more than one pulsation mode and therefore infer a value for the large separation $\Delta\nu$ (high-overtone p-mode frequency spacing between modes of the same degree, see Brown & Gilliland 1994). In Table 1, the 7 known roAp stars brighter than $V = 7$ are listed. All these stars are viable targets for a space-based observing mission but α Cir stands out as the brightest by 1.5 magnitudes.

Table 1: Data for the seven brightest roAp stars. The photometric data are from the Hipparcos catalogue, with the seventh column showing the absolute visual magnitudes calculated using the parallaxes (ESA 1997). The last two columns show the frequency of the highest amplitude mode and the inferred large separation (see Martinez & Kurtz 1995a,b).

name	HR	HD	Coords.	V	$B-V$	M_V	Freq (μHz)	$\Delta\nu$ (μHz)
α Cir	5463	128898	15h −65°	3.18	0.26	2.11±0.02	2400	50
γ Equ	8097	201601	21h +10°	4.70	0.26	1.97±0.07	1300	58
10 Aql	7167	176232	19h +14°	5.91	0.25	1.55±0.11	1400	51
DO Eri	1217	24712	04h −12°	5.99	0.32	2.54±0.09	2700	68
IM Vel	3831	83368	10h −49°	6.18	0.28	1.88±0.12	1400	—
33 Lib	—	137949	15h −17°	6.69	0.40	1.94±0.17	2000	40
UV Lep	—	42659	06h −16°	6.78	0.27	1.11±0.25	1700	52

2. Measurements

Kurtz et al. (1994, hereafter KSMT) showed using Strömgren v photometry that α Cir has one dominant pulsation mode with a frequency of 2442 μHz. They also detected four weaker modes, plus two side-lobes of the principal mode and the first harmonic of the principal mode. Figure 1 shows the identified frequencies except for the first harmonic, which has an amplitude of 180 ppm at 4884 μHz ($2f1$). The question to consider in this paper is, what new information can be determined from observing this star with MONS? A 30 day observing run should produce a noise level in the amplitude spectrum of below 0.5 ppm, which is a factor of 50 improvement in the S/N over the data of KSMT. Additionally, MONS may observe in two colours simultaneously.

KSMT inferred a large separation of 50 μHz from the fact that the frequency spacings between modes in α Cir were all nearly integer multiples of 25μHz. However, Kurtz (1998) pointed out that the parallax of α Cir predicted by asteroseismology was significantly different from the Hipparcos parallax. He suggests that another intensive study of α Cir is called for. MONS could certainly confirm the existence of the weaker modes and detect any additional modes that will be near the expected frequencies, shown in Figure 1, if the value for $\Delta\nu$ is correct. In addition to the probable detection of new modes, MONS will be able to make a number of more specific measurements (for each mode) involving rotational splitting, colour and harmonics.

The side-lobes ($f1_{-r}$ and $f1_{+r}$) are separated from $f1$ by 2.6 μHz which is the rotation frequency of α Cir ($P_{\rm rot} = 4.479$ d). Rotational splitting has been seen in many modes of roAp stars and is successfully explained by the oblique pulsator model (Baldry, Kurtz & Bedding 1998b). In this model, an roAp star pulsates non-radially with its pulsation axis aligned with the magnetic axis, but inclined with respect to the rotation axis. Therefore, different aspects of a non-radial mode are viewed as the star rotates. In the Fourier domain, a mode of degree ℓ is split into $2\ell+1$ frequencies. The frequency spacing is exactly equal to the rotation frequency, and the relative amplitudes are determined by both the inclination of the rotation axis to our line of sight (i) and the angle between the rotation axis and the pulsation axis (β). KSMT determined the principal mode in α Cir to be an $\ell = 1$ mode with $\tan i \tan\beta = 0.21 \pm 0.01$. With data from MONS, these parameters could be determined for modes $f2$–$f5$ and possibly for additional detected modes. If the simple

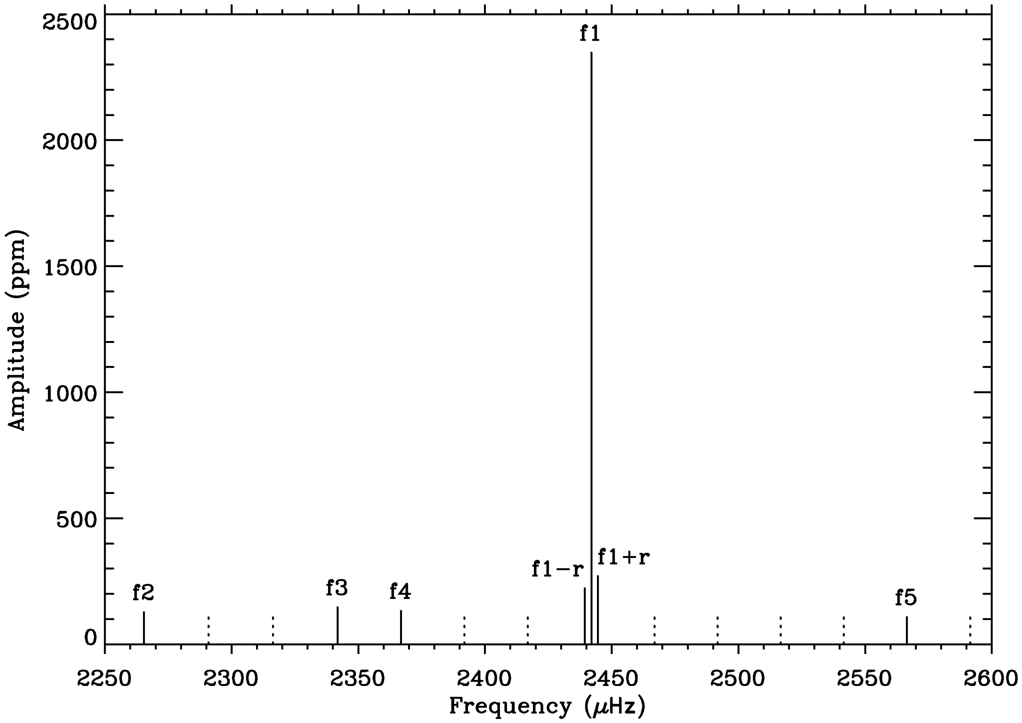

Fig. 1.— Schematic amplitude spectrum of α Cir, from the photometric results of KSMT. The solid lines show the identified frequencies, while the dotted lines show the expected frequencies of other low-degree modes assuming a large separation of 50 μHz. The rms-noise level in the original amplitude spectrum was about 25 ppm (note: 1 mmag = 921 ppm).

oblique pulsator model holds, all the modes should be axisymmetric low-ℓ modes with the same value of β. Perhaps no $\ell = 0$ modes are excited since they have no preferred axis to be aligned with the magnetic field. The identification of the modes that are excited can be used to test models of the excitation mechanism in the star (Gautschy et al. 1998). In reality, the identification may not be so simple, since the best studied roAp star HR 3831 shows a complicated frequency spectrum which can be explained by a distorted dipole mode (Takata & Shibahashi 1995). The same sort of distortions may be discovered in α Cir using the data from MONS.

Recently, the principal mode in α Cir has been studied using spectroscopy and multi-colour photometry. Baldry et al. (1998a) discovered that the velocity amplitude and phase varied significantly between different absorption lines. They attributed this to a radial velocity node in the atmosphere of the star. Medupe & Kurtz (1998) observed that the photometric amplitude dropped by more than expected for a blackbody at longer wavelengths (see Figure 2). One interpretation of their results is that the temperature amplitude of the pulsation changes with atmospheric depth in α Cir, including a node in the atmosphere. This is consistent with Baldry et al.'s spectroscopic results and with the models of Gautschy et al.

W. Dziembowski (discussion) noted that "at ~kG magnetic field intensity, we should have very

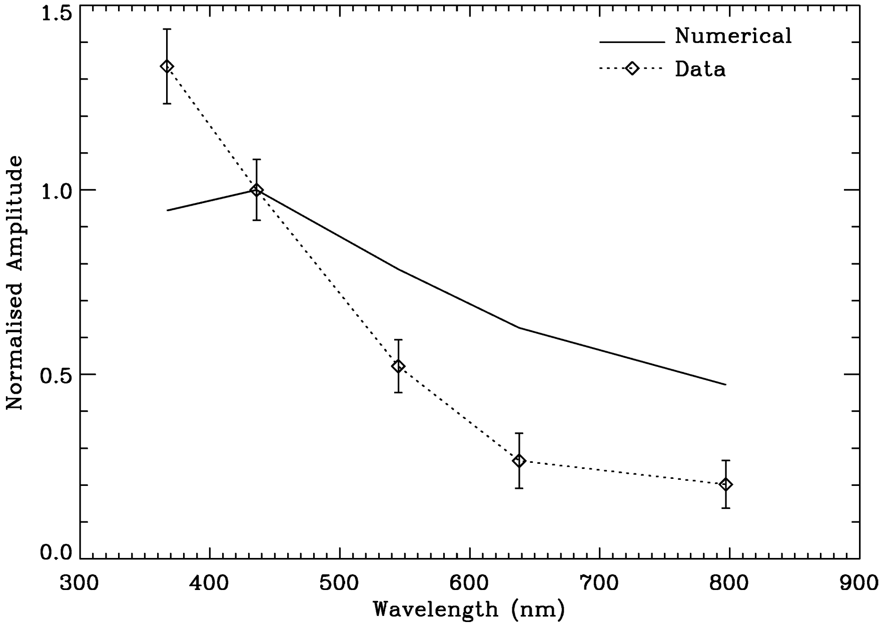

Fig. 2.— Colour photometry of the principal mode in α Cir, from Medupe & Kurtz (1998).

significant effects of the field on the eigenfunction behaviour in the atmosphere. Therefore we should regard localisation of nodes in atmosphere determined with models ignoring those effects as highly uncertain." Indeed, Gautschy et al. recognised that their treatment of the outer regions was far from realistic but their results at least indicate that nodes can be expected in the atmospheres of roAp stars. R. Medupe (discussion) also warned that "our models are still not good enough for us to be able to interpret data correctly. The model I used to deduce the presence of a node in the atmospheres of roAp stars is based on questionable assumptions (Medupe & Kurtz 1998); 1. the opacity increases from B to I, this ignores line opacity, 2. that temperature effects are dominant but Medupe, Christensen-Dalsgaard & Kurtz (1998) have shown that including non-adiabaticity fits the multi-colour photometry well and in this case 'pressure' effects dominate temperature effects." The two colour photometry of MONS could measure the photometric amplitude ratio (between two different wavelengths) for different modes and therefore as a function of n and ℓ. This may determine whether non-adiabatic effects are important or whether the change in amplitude as a function of depth can explain the significantly reduced amplitude at longer wavelengths. In particular, the ratio of the amplitude at longer to shorter wavelengths should decrease as a function of n in the second case.

In addition to the rotational splitting parameters and the colour amplitude ratio, there are other possible diagnostics. For instance, as well as each mode having a photometric amplitude difference between two colours, there will be a phase difference as has been seen in other roAp stars. Also, the first harmonic of non-sinusoidal pulsation has been detected for the principal mode in α Cir. Therefore, with MONS, the amplitude and phase of the first harmonic should be measurable for all the known modes.

3. Conclusions

J. Christensen-Dalsgaard (discussion) noted that “this is clearly a very interesting star, on which we may learn a lot from MONS. However, I worry that the star is so complex that we may not be able to understand what we observe. Thus I suggest to consider it as a secondary target, possibly for an extended mission, but probably not as a primary target.” However, there are several groups working on theoretical aspects of roAp stars (see section 1) and they will benefit greatly from the data from MONS and T. R. Bedding (discussion) pointed out that “α Cir can not be observed by MOST because it is too far south, whereas γ Equ, 10 Aql and HR 1217 can be.” Therefore, including α Cir as a target will complement the data from the MOST satellite mission.

The minimum observation time for α Cir should be 9 days (two rotation periods) in order to resolve the rotational splitting. It should be carefully considered whether it is worth observing for longer than 9 days for the improved frequency resolution and S/N. If not, then a second roAp star could be considered as a target for a similar length of observation (see Table 1).

There is no doubt that much new information can be obtained by observing α Cir with MONS, even if no new modes are discovered (which would seem unlikely). The problem arises with the interpretation of the data because of the complexity of this star and its magnetic field. However, I suggest that α Cir offers one of the best chances for theoreticians to model a star where magnetic fields are important both for its evolution and pulsation. Therefore, the lack of present understanding of this star should not exclude it as a primary target for MONS.

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