Interferometric and seismic constraints on the roAp star $\alpha$ Cir

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Abstract

We present new constraints on the rapidly oscillating Ap star $\alpha$ Cir, derived from a combination of interferometric and photometric data obtained with the Sydney University Stellar Interferometer (SUSI) and the WIRE satellite. The highlights of our study are:

1. The first determination of the angular diameter of an roAp star.
2. A nearly model-independent determination of the effective temperature of $\alpha$ Cir, which is found to be lower than previously estimated values.
3. Detection of two new oscillation frequencies allowing a determination of the large separation of $\alpha$ Cir.

Based on this new information, we have computed non-magnetic and magnetic models for $\alpha$ Cir. We show that the value of the observed large separation found from the new data agrees well with that derived from theoretical models. Moreover, we also show how the magnetic field may explain some of the anomalies seen in the oscillation spectrum and how these in turn provide constraints on the magnitude and topology of the magnetic field.

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Introduction

$\alpha$ Circini [HR 5463, HD 128898, HIP 71908, $V = 3.2$] is the brightest known rapidly oscillating peculiar A-type (roAp) star. The roAp stars are main-sequence chemically peculiar (CP) pulsators with effective temperatures ranging from 6 500 to 8 500 K. Since CP stars show abnormal flux distributions in their spectra, their effective temperatures are very difficult to determine. Temperatures can be estimated from photometric indices or spectral analysis, but due to the peculiar nature of these stars, values are likely to be affected by systematic effects.

The roAp stars also present the highest oscillation frequencies observed in the main sequence part of the instability strip, with typical values ranging from 1 to 3 mHz. The high frequencies of the oscillations observed in roAp stars indicate that these are high radial order, low degree acoustic modes. Since the oscillations are of high radial order we can, in principle, use the asymptotic theory to study the oscillation spectrum. However, these oscillations are affected by an intense magnetic field that will perturb the frequencies from the asymptotic trend.

$\alpha$ Cir is one of the best studied roAp stars and, as such, both seismic and non-seismic data for this star are available in the literature. However, to date, the large frequency separation (defined as the difference between the frequencies of modes of the same degree and consecutive radial orders) of $\alpha$ Cir cannot be reconciled with that expected from an effective temperature around 8 000 K, suggested by most determinations found in the literature, and the luminosity derived from the Hipparcos parallax (Matthews et al. 1999).

Detection of the large separation

$\alpha$ Cir was observed for 84 d during four runs with the WIRE satellite in the period from 2000–2006 (Bruntt et al., private communication). During the last two runs we collected simultaneous ground-based Johnson $B$ observations on 16 nights with the 0.5-m and 0.75-m telescopes at the South African Astronomical Observatory (SAAO) and 2 hr of high-cadence, high-resolution spectra from the Ultraviolet and Visual Echelle Spectrograph (UVES) on the Very Large Telescope (VLT). The oscillation frequencies detected in the WIRE data are shown in Figure 1. The $f_6$ and $f_7$ frequencies have not been observed before, and are present in both the WIRE and SAAO data sets. The $f_6 + f_1 + f_7$ frequencies have the highest amplitudes and form a triplet with a nearly equidistant frequency spacing of $30.173 \pm 0.004 \mu$Hz. We interpret this spacing as either the large frequency separation or half of that.
Figure 1: Frequencies detected in $\alpha$ Cir from the WIRE data, $f_4$, $f_6$, $f_1$, $f_7$, $f_5$. We have included $f_2$ and $f_3$ from Kurtz et al. (1994). The vertical dashed lines mark half the large separation (the mean of $f_1 - f_6$ and $f_7 - f_1$).

Asteroseismology

Non-magnetic model

Bruntt et al. (2008) determined the effective temperature of $\alpha$ Cir by combining the measured angular diameter of the star obtained with the Sydney University Stellar Interferometer (SUSI) and its bolometric flux, computed from calibrated spectra. They found a nearly model-independent value for the effective temperature of 7420 ± 170 K, which is lower than all previous determinations found in the literature. The new values for the effective temperature and luminosity, derived from the Hipparcos parallax and the interferometric radius, were used to place $\alpha$ Cir in the Hertzsprung-Russell (HR) diagram as shown in Figure 2.

Three CESAM (Morel 1997) evolutionary tracks that go through the 1-$\sigma$ error box are shown in Figure 2. We chose the model that best fitted the position of the star in the HR diagram and its parameters are given in Table 1. We calculated the theoretical oscillation frequencies for that model with the linear adiabatic oscillation code Aarhus Adiabatic Pulsation Package (ADIPLS; Christensen-Dalsgaard 2008). From these theoretical frequencies we calculated the large frequency separation and obtained a value of $\Delta \nu = 60.4 \mu$Hz. Comparing this value with the observed frequency spacing we conclude that this model reproduces well the observed separation between the three principal modes. Moreover, we conclude that the observed large frequency separation of $\alpha$ Cir is 60.346 ± 0.008 $\mu$Hz and, thus, that the frequencies $f_6$, $f_1$ and $f_7$ must
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Figure 2: The position of α Cir in the HR diagram, with three evolutionary tracks for masses of 1.70, 1.715 and 1.73 M⊙. The constraints on the fundamental parameters are indicated by the 1-σ error box (\(T_{\text{eff}}, L/L_\odot\)) and the diagonal lines (radius).

...correspond to modes of alternating even-odd spherical degrees. This new value is significantly larger – and much more secure – than the 50 μHz suggested by Kurtz et al. (1994).

Table 1: Global parameters of the CESAM model used for α Cir. The following input parameters were used: \(X_0 = 0.70, Y_0 = 0.28, \alpha = 1.6\) and no overshooting. \(X_0\) and \(Y_0\) are the initial H and He abundances and \(\alpha\) is the mixing length parameter.

| \(M/M_\odot\) | \(\log(L/L_\odot)\) | \(\log T_{\text{eff}}\) [K] | \(R/R_\odot\) | Age (Myr) |
|-------------|-----------------|----------------|-------------|-----------|
| CESAM model | 1.715           | 1.022          | 3.87        | 2.0       | 900       |

Magnetic models

Inspecting Figure 1, where the spacing between the dashed vertical lines correspond to half of the large separation, we note that only the three principal modes seem to follow the trend expected in the asymptotic regime. In particular, \(f_4\), which was also observed by Kurtz et al. (1994), is separated from \(f_6\) by \(\approx 3/4\) of the large separation (\(f_6 - f_4 = 45.41 \mu\text{Hz}\)). Consequently, the oscillation frequencies computed with the model in Table 1 (here-
Table 2: The values of $\delta \nu_{nl}$ and $(f_6 - f_4)$ for the observations and for the best-fitting non-magnetic and magnetic models. The strength and topology of the magnetic field are given for the three magnetic models.

|               | $B_p$ [kG] | Topology      | $\delta \nu_{nl}$ [\mu Hz] | $(f_6 - f_4)$ [\mu Hz] |
|---------------|------------|---------------|----------------------------|-------------------------|
| Observed      | -          | -             | +0.004                     | 45.41                   |
| Non-magnetic model | -          | -             | +2.5                       | 30.2                    |
| Magn. model 1 | 1.4        | Quadrupolar   | -0.66                      | 44.76                   |
| Magn. model 2 | 1.4        | Quadrupolar   | +0.53                      | 40.57                   |
| Magn. model 3 | 1.4        | Dipolar       | -0.81                      | 50.81                   |

After called the non-magnetic model) do not reproduce well the separation between the principal mode and the frequencies $f_2$, $f_3$, $f_4$ and $f_5$. Moreover, the frequencies of the three principal modes have nearly equal separations: $(f_1 - f_6) = 30.1746 \pm 0.0009 \mu Hz$ and $(f_7 - f_1) = 30.1707 \pm 0.0005 \mu Hz$. In fact, the difference between these two “half separations”, which we will denominate by $\delta \nu_{obs}$, is only $0.004 \pm 0.001 \mu Hz$. After computing theoretical $\delta \nu_{nl}$ values for all combinations of mode degrees with $l \leq 3$ for the non-magnetic model, we found that the minimum absolute value taken by this quantity is $\delta \nu_{nl} = 2.5 \mu Hz$. This value is obtained for combinations of modes of degree $l = 0$ and 2, around the frequency 2450 \mu Hz.

Since $\alpha$ Cir is an roAp star, it has a strong magnetic field. We have therefore speculated if the effect of the magnetic field on the oscillations may explain the small value of $\delta \nu_{obs}$. To investigate this possibility, we used a code (Cunha 2006) to compute the magnetic perturbations to the frequencies obtained for our non-magnetic model. As input parameters we considered modes of degrees $l = 0, 1, 2$ and 3, a magnetic field at the pole, $B_p$, within a range of values appropriate for $\alpha$ Cir, (see Bruntt et al. 2008: Sec. 6.1, for a review) and a dipolar or quadrupolar magnetic field topology. The three magnetic models that best reproduce the features of the oscillation spectra of $\alpha$ Cir are shown in Table 2 and the values of $l$ that correspond to each frequency for these models are given in Table 3.

Conclusions and discussion

We have summarized the main results of an intensive study of the roAp star prototype $\alpha$ Cir, part of which has been published in Bruntt et al. 2008. Our team has made the first interferometrically-based determination of the effective temperature of an roAp star. The new value of $T_{eff} = 7420 \pm 170 K$ is lower than
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Table 3: For each of the three best magnetic models and for the best non-magnetic model we list the values of $l$ for the four frequencies $f_4$, $f_6$, $f_1$, and $f_7$.

|                      | $l_{f_4}$ | $l_{f_6}$ | $l_{f_1}$ | $l_{f_7}$ |
|----------------------|-----------|-----------|-----------|-----------|
| Non-magnetic model   | 1         | 0         | 1         | 0         |
| Magn. model 1        | 3         | 2         | 3         | 2         |
| Magn. model 2        | 1         | 3         | 2         | 3         |
| Magn. model 3        | 0         | 2         | 3         | 2         |

all values found in the literature. Additionally, new seismic data for α Cir were acquired with the WIRE satellite and with the 0.5-m and 0.75-m telescopes at SAAO. Two new frequencies were found in both the WIRE and SAAO data and they form a triplet with the known dominant frequency. The triplet is nearly equally spaced with a separation of $30.173 \pm 0.004 \, \mu$Hz, which we interpret to be half the large separation. Using the new global parameters of the star, we computed a non-magnetic model for α Cir. The large separation of this model is in good agreement with the observed large separation, but the model fails to explain the nearly equidistant spacing as well as the secondary frequencies.

In an attempt to understand these discrepancies we computed magnetic perturbations to the frequencies of the non-magnetic model. We found that the magnetic model that best reproduces the oscillation spectrum has a quadrupolar topology and a magnitude of 1.4 kG. From this model, we identify the largest amplitude mode, $f_1$, as being an $l = 3$ mode. We note that due to the magnetic effect, the eigenfunctions in roAp stars are distorted. Thus, it is possible that modes of degree higher than $l = 2$ may generate lower-degree components near the surface that, in turn, may be observed (e.g. Cunha 2005). Also, we find that the magnitude is rather sensitive to the position where one of the boundary conditions of the magnetic code is applied. To overcome this problem, and test the robustness of our results, we are currently implementing a different atmospheric model in our code. Thus, the results presented here for the magnetic models are still preliminary.

References

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