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## *Letter to the Editor*

# **The discovery of nonradial pulsation in the $\lambda$ Bootis star HD 111604**

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**Abstract.** Evidence for high order nonradial pulsation (NRP) has been discovered in the  $\lambda$  Boo star HD 111604. Analysis of a limited number of spectra of the Na I D lines indicate that the mode of oscillation,  $|m|$ , is approximately 20 and NRP features circumnavigate the star every 0.71 days. Current models suggest that these objects should be near the ZAMS, and the detection of nonradial pulsation in at least one member of the class presents the exciting possibility of performing a direct measurement of its evolutionary state to test this hypothesis.

**Key words:** stars: oscillations – stars: peculiar A – stars: individual: HD 111604 – stars:  $\delta$  Scuti – stars:  $\lambda$  Boo

## **1. Introduction**

Spectral peculiarities among the A-type stars now appear to be the norm. A collection of A stars with similar temperatures and surface gravities can form a veritable zoo, with no two appearing the same. One may appear to have “normal” abundances, another may show characteristics of the magnetic Ap stars, yet another those of the classical Am stars, and still another may have very weak metal lines. The latter is an example of the  $\lambda$  Bootis class of objects.

The Ap and Am phenomena are now generally thought to be reasonably well understood. Unfortunately, the weak-lined  $\lambda$  Boo stars are proving to be somewhat more difficult to explain. Gray's (1988) definition of this class of about two dozen stars is as follows: they have Ca II K and metallic-line spectral types near A0, weak Mg II  $\lambda 4481$ , and hydrogen lines with cores typical of early to late A-type stars. Relative to the Balmer cores, the K-line and metallic-line types are too early, and the stars

appear metal weak. He also suggests that there may be two distinct subgroups, with one subgroup having peculiar hydrogen profiles. From their small space velocities, surface gravities near the ZAMS, binarity, high  $v \sin i$ , and colours, the  $\lambda$  Boo stars appear to be population I stars with abundances more characteristic of population II objects. Gerbaldi and Faraggiana (1993) provide a recent review and a list of members of the class.

Several ideas have been put forward in the last few years to explain the  $\lambda$  Boo phenomenon. Venn and Lambert's (1990) observation that the abundances of elements in three  $\lambda$  Boo stars are similar to interstellar gas depleted by formation of grains has led to a promising model developed by Charbonneau (1991) and Turcotte and Charbonneau (1993) in which the  $\lambda$  Boo stars are *accreting* mass at a rate on the order of  $10^{-13} M_{\odot} \text{ yr}^{-1}$ . In their scenario, Turcotte and Charbonneau (1993) suggest that the  $\lambda$  Boo stars still possess a remnant of the accretion disc from which they formed and they are able to make several predictions. First, the model successfully shows that underabundances will occur only in stars with a narrow range of temperatures similar to those of the known  $\lambda$  Boo stars. Secondly, the abundance anomalies will disappear in  $10^6$  years because of circulation currents, so all of the  $\lambda$  Boo stars should be essentially on the ZAMS. Finally, given the short lifetime of the abundance peculiarities the accretion must be occurring in the current epoch.

In order to search for direct evidence of circumstellar material associated with the  $\lambda$  Boo stars, we recently completed a high resolution spectroscopic survey of the Na I D lines of all of the  $\lambda$  Bootis stars observable from the Canada-France-Hawaii Telescope (CFHT). During the course of this investigation we have serendipitously discovered one of the first known cases of spectrum variability among the class (Bohlender, in preparation, discusses another example). In what follows below we show that HD 111604 (HR 4875), classified as a  $\lambda$  Boo star by Gerbaldi

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& Faraggiana (1993) based on the appearance of its UV spectrum, is a nonradial pulsator. This first spectroscopic confirmation of pulsation in a  $\lambda$  Boo star presents us with the exciting prospect of a direct method of determining the evolutionary state of at least one member of the class.

## 2. Observations

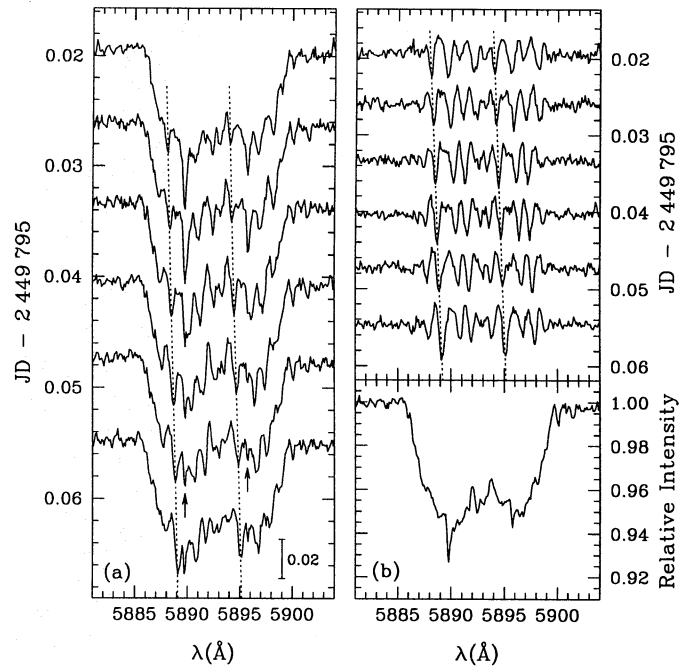
The spectra discussed here were obtained on 1995 March 18 UT with the CFHT and the  $f/8.2$  coude spectrograph. The instrument configuration included the red mirror train, objective, Richardson slicer, and folding flat, the 600 l/mm mosaic in first order, and the front-side illuminated Loral3 2048  $\times$  2048 CCD with 15  $\mu$ m pixels. The central wavelength was approximately 5892  $\text{\AA}$ . The stellar data have been reduced in a conventional manner with IRAF<sup>1</sup>. A gaussian fit to several lines in Th/Ar wavelength calibration exposures obtained before and after the stellar exposures give FWHM corresponding to a spectral resolution of about 0.22  $\text{\AA}$ . Because the relative humidity was near 0% there is essentially no contamination of this spectral region by telluric features.

The first 8 min exposure of HD 111604 suggested the presence of several interstellar features in the Na I D lines of the star, but this seemed unusual since we estimated the star to have a distance on the order of 100 pc. Given this distance and its high galactic latitude we can expect very little in the way of interstellar absorption, and almost certainly not multiple interstellar absorption features (Welsh et al. 1994). As a result, we took a second exposure and saw evidence for some variability in these “shell” features. A sequence of several exposures taken over an hour is shown in Fig. 1, as well as the residuals which result after subtracting the mean spectrum from the individual exposures. The blue-to-red progression of travelling bumps in the spectra is readily seen.

A closer examination of Fig. 1a shows what appears to be a sharp, stationary component in each of the Na I D lines. The average spectrum shown at the bottom of Fig. 1b tends to smooth out the variable features and the stationary features become much more prominent. They are likely weak interstellar absorption lines, but the possibility exists that HD 111604 may also have a circumstellar shell. A detailed discussion of the complete Na I D line survey will be presented elsewhere (Bohlender & Gonzalez, in preparation), so we will not pursue this question any further in the present paper.

Before proceeding we would like to note that Weiss et al. (1994) have incorrectly identified HD 111604 as the variable star DQ Her. A brief examination of the SIMBAD database will show that HD 111604 is most emphatically **not** related to this nova.

<sup>1</sup> IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.



**Fig. 1.** a) A sequence of spectra of the Na I D lines of the  $\lambda$  Boo star HD 111604. Time advances towards the bottom of the figure and the relative intensity scale is indicated. The dashed lines follow the redward motion of a prominent NRP feature in each component of the doublet. A possible interstellar or circumstellar feature is marked by the arrow. b) Residuals from the mean spectrum, shown at the bottom, of HD 111604. The intensity scale of the residuals is the same as for the mean spectrum. The mean spectrum reduces the visibility of the NRP and shows the presence of an interstellar or circumstellar feature more clearly.

## 3. Discussion

The spectrum variability of HD 111604 is remarkably similar to that seen in rapidly rotating  $\delta$  Scuti stars (e.g., Walker et al. 1987, Kennelly et al. 1991, Kennelly et al. 1992). The  $\delta$  Scuti stars are unstable to nonradial stellar oscillations driven by the  $\kappa$  mechanism and described by the three quantum numbers:  $n$  (the radial order),  $\ell$  (the nonradial degree), and  $m$  (the azimuthal order). The oscillations introduce velocity perturbations of the stellar rotation profile to produce variations in the line profile shapes (Vogt & Penrod 1983), and by analyzing a series of Doppler-broadened line profiles, modes and frequencies can be determined. The line-profile variations of HD 111604 are particularly reminiscent of that of  $\tau$  Peg for which multiple modes with  $\ell$  as high as 16 have been detected using a two-dimensional Fourier analysis (Kennelly et al. 1992). We therefore suggest that HD 111604 displays the first known case of NRP in the  $\lambda$  Boo class. However, with the current limited set of data we can not completely rule out photospheric abundance inhomogeneities as the source of the spectrum variations, or even, as the

referee noted, orbiting inhomogeneities in a possible accretion flow around the star.

For a single hour of data, a two-dimensional Fourier analysis similar to that performed on  $\tau$  Peg would almost certainly be considered an over-interpretation. Instead, we derive a rough estimate for the principle mode of oscillation, assuming  $\ell = |m|$  (i.e., a sectoral mode), and its period using the method of Walker et al. (1987). That is, we calculate the mode  $|m|$  as

$$|m| = 2\pi(v \sin i)/(a_0 \Delta t) \quad (1)$$

where  $v \sin i$  is the projected rotational broadening,  $a_0$  is the average acceleration of the oscillation subfeatures at the line center, and  $\Delta t$  is the average delay between successive subfeatures crossing the line center (i.e., the apparent period of oscillations as measured in the observer's frame). The time necessary for a wave to circumnavigate the star is then

$$P = |m| \Delta t. \quad (2)$$

If the rotational velocity were large compared to the phase velocity of the wave then the period  $P$  would provide an estimate of the rotation period of the star. However, for rapidly rotating  $\delta$  Scuti stars at least, the ratio between the rotation frequency and oscillation frequency is small, typically  $\Omega/\nu = 0.08$  (Kennelly 1995).

In Fig. 1 the passage of one subfeature is followed from frame to frame in each of the Na I D lines of HD 111604. From such features we measure values of  $a_0 = 1650 \text{ kms}^{-1}\text{day}^{-1}$  and  $\Delta t = 0.0354$  days. We have also carried out a spectrum synthesis of the mean Na I D line profiles and find  $v \sin i = 185 \pm 5 \text{ kms}^{-1}$ , in good agreement with the value of  $183 \text{ kms}^{-1}$  given by Gerbaldi and Faraggiana (1993). Equations 1 and 2 then give  $|m| \approx 20$  and  $P \approx 0.71$  days.

The success of the Turcotte and Charbonneau (1993) model requires that the  $\lambda$  Boo stars be on or close to the ZAMS. We can use available *uvby* $\beta$  photometry (Hauck & Mermilliod 1995) to derive the surface gravity and effective temperature of HD 111604. First, we use Crawford's (1979) calibration for A-type stars to determine that HD 111604 has  $\delta c_1 = 0.248$  and  $\delta m_1 = 0.0553$ . This then gives  $(b - y)_0 = 0.123$  and  $E(b - y) = -0.011$ . The star thus appears to be unreddened. Balona's (1994) calibration is then used to find  $T_{\text{eff}} = 7770 \text{ K}$ ,  $\log g = 3.33$ ,  $L/L_\odot = 44$ ,  $M_V = 0.53$ ,  $R = 3.7R_\odot$ , and  $M = 1.1M_\odot$ . These values suggest that HD 111604 is an evolved object, with  $M_V$  close to that expected for a star of spectral type A3 III. Given  $V = 5.896$ , we then find that the distance to the star is  $d \approx 120 \text{ pc}$ .

Some caution should be used before drawing any conclusions about the evolutionary status of HD 111604, and hence the validity of the Turcotte and Charbonneau (1993) model, from the above discussion. Our analysis of the *uvby* $\beta$  photometry of HD 111604 completely ignores

the effects of the star's spectrum peculiarity on its magnitudes and color indices. In the introduction we noted that the  $\lambda$  Boo stars seem to divide into two groups: those with normal hydrogen-line profiles (NHL) and those with peculiar hydrogen-line profiles (PHL) (Gray 1988). The PHL stars in Gray's (1988) list have  $\beta$  values  $0.05 - 0.07 \text{ mag}$  smaller than normal early-A V stars. These objects also tend to have the largest  $(b - y)$  values. The  $(b - y) = 0.112$  of HD 111604 suggests that this star is also likely a PHL  $\lambda$  Boo star, in which case the star's H $\beta$  line index, and hence the derived luminosity, is likely strongly affected by its spectral peculiarity. The rapid rotation of HD 111604 might also be expected to affect the surface gravity and, as a result, the luminosity of the star (Crawford 1979). Clearly there is a great deal of doubt as to the evolutionary status of HD 111604 at the present time.

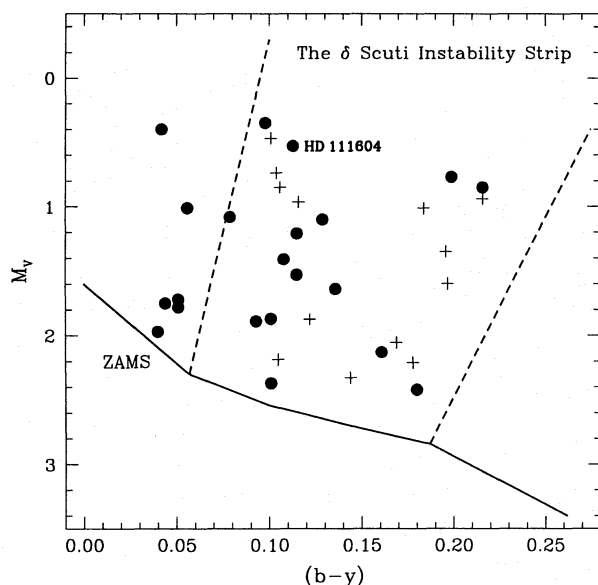
#### 4. Conclusion

In this paper we have reported the first evidence for non-radial pulsation in a  $\lambda$  Bootis star. HD 111604 has high order ( $|m| \approx 20$ ) NRP and the NRP features cross the line centers approximately every 0.0354 days. A simple analysis of the limited set of spectra and *uvby* $\beta$  photometry can not definitively determine the evolutionary state of the star because of uncertainties in its intrinsic colors. A detailed spectrum analysis of the star should help remove some of this uncertainty.

The nonradial pulsation in HD 111604 also could provide us with a direct method of evaluating the evolutionary state of at least one member of the  $\lambda$  Boo class, and as a result, confirm or refute the validity of the Turcotte and Charbonneau (1993) idea of an accretion origin for these stars. This possibility arises because the oscillation properties of a star change as the star evolves. The frequency of the acoustic modes (trapped in the outer envelope) decreases (roughly as  $R^{-1.5}$ ), while numerous gravity modes (trapped in the interior) become free to propagate as a result of the development of a steep gradient in chemical composition outside the stellar core (e.g. Dziembowski [1995]). Although the interaction of the gravity and acoustic modes is thought to introduce difficulties for the identification of low-degree modes, the zone of propagation of the high-degree acoustic modes (i.e., the likely origin of the variations displayed in Fig. 1) is well-separated from the interior, so these modes should remain uncontaminated by gravity mode variations and may lead to easier identification. We therefore encourage more extensive (multi-site) observations in order to determine the complete mode spectrum of HD 111604. Comparison of the measured frequencies with theoretical values expected for a given mass star as a function of age should then give a reasonable indication of the evolutionary status of the star.

HD 111604 is obviously very closely related to the  $\delta$  Scuti stars. The very fact that HD 111604 lies in the  $\delta$  Scuti instability strip and is variable, unlike classical





**Fig. 2.** The location of the  $\lambda$  Boo stars ( $\bullet$ ) in the  $(b-y) - M_V$  color-magnitude diagram. A-type stars for which Kennelly (1994) has detected spectrum variations are also indicated (+). The dashed lines indicate the photometrically determined boundaries of the  $\delta$  Scuti instability strip. The location of HD 111604 is labelled.

Am stars in the same region of the H-R diagram, may also be indirect evidence for the rather exotic accretion origin of these objects. The so-called “parameter free” diffusion model (see Michaud [1991] for a recent review) is quite successful in explaining the peculiarities observed in the classical Am stars. It also explains the mutual exclusion of the  $\delta$  Scuti and Am phenomena. In the latter objects the He II convection zone, which provides the driving mechanism for pulsation in A-type stars, diffuses downward out of the outer envelope shortly after the star’s formation. As a consequence, Am stars are not pulsationally unstable. The fact that HD 111604 is pulsating then indicates that its peculiar abundances can not arise from diffusion processes identical to those occurring in the Am stars.

Could other  $\lambda$  Boo stars be nonradial pulsators? HD 111604 is certainly not the first example of a variable  $\lambda$  Boo star. Gray (1988) draws attention to several members of the class that might be photometric variables and Weiss et al. (1994) have recently reviewed the known photometrically variable  $\lambda$  Boo stars. HD 111604 itself is also a low-amplitude photometric variable (Provin 1953). In Fig. 2 we show the location in the  $(b-y) - M_V$  color-magnitude diagram of all of the  $\lambda$  Boo stars listed by Gerbaldi and Faraggiana (1993) which have published  $uvby\beta$  photometry. Again, we use Crawford’s (1979) calibration to determine  $M_V$ , ignoring any influence the peculiar hydrogen lines of the  $\lambda$  Boo stars might have on  $\beta$ , and hence  $M_V$ . Also indicated are the A-type stars with NRP discovered by Kennelly (1994) as part of his survey of line profile variations in stars in the  $\delta$  Scuti instability strip. A

total of 15 of 21  $\lambda$  Boo stars, including HD 111604, lie in the photometrically determined  $\delta$  Scuti instability strip. A recent but very limited survey we have carried out has resulted in at least four other cases of low-level spectrum variability, most likely caused by NRP, in  $\lambda$  Boo stars. We therefore have the prospect of determining the evolutionary status of a substantial number of the class and hopefully insert one more piece into the peculiar A-star puzzle.

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