Detection of High-Degree Nonradial Pulsations in Gamma Bootis

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ABSTRACT. The line-profile variations of the rapidly rotating δ Scuti star γ Boo can be explained by high-degree (|m| ~ 10) nonradial pulsations (NRPs) with an apparent period of Δt ~ 0.047 days. This same period was derived from two data sets taken three months apart wherein the amplitude increased by 30%. Such high-degree NRP cannot explain the apparent reversals previously observed by Auvergne et al. for this star in the cores of the hydrogen Balmer lines and Ca II K line. Our radial-velocity variations can be reconciled with their 0.25 day spectroscopic period if an amplitude of ~ 1 km s^{-1} is adopted, an order of magnitude less than previous measurements. We demonstrate that the presence of line-profile variations from high-degree modes probably limits the accuracy of radial-velocity measurements and may appear as bumps in the radial-velocity curve.

1. INTRODUCTION

The δ Scuti variables are A-F type stars which pulsate with periods of ~2 hr. The amplitudes of the light variations are ~0.02 mag and radial-velocity (RV) variations are typically less than 10 km s^{-1}. The characteristic short periods and small RV amplitudes have made spectroscopic observations of δ Scuti stars difficult, except with the largest telescopes. As a consequence, most studies of the δ Scuti variables have been photometric.

The presence of both radial and (low-degree) nonradial modes of oscillation has been well established in δ Scuti stars (Yang 1991) and often the stars are found to be multiperiodic. Mode identification can be derived from Q values, m-mode splitting, velocity-to-light ratios, and profile fitting. Campos and Smith (1980) and Smith (1982) compared model profiles to observations to identify radial and low-degree nonradial modes for a selection of δ Scuti stars. They found roughly equal numbers of pure radial oscillators, pure (multiperiodic) nonradial oscillators, and mixed-mode oscillators.

The first report of high-degree NRPs in δ Scuti stars was made by Yang and Walker (1986) for the F2 II-III star Ω Eri. Walker et al. (1987) followed this discovery with the observation of four rapidly rotating stars (κ^2 Boo, 21 Mon, ν Uma, and Ω Eri) at higher resolution (0.035-A per pixel). All of the stars displayed high-degree NRP with modes ranging from |m| = 8 to 16 and apparent periods from Δt = 0.045 to 0.104 days. Further analysis by Kennelly et al. (1990) has demonstrated that low-degree modes are also present. The line-profile variations of the star κ^2 Boo were successfully reproduced with a geometrical NRP model by Kennelly et al. (1991). Their model indicates a single high-degree mode (m = -12) with a period of oscillation in the corotating frame of P_{osc} = 0.071 days, consistent with p-mode oscillations.

2. LINE-PROFILE VARIATIONS OF γ Boo

Auvergne et al. (1979) described γ Boo (A7 III) as a classical, evolved δ Scuti star with v sin i = 145 km s^{-1}, M_v = 0.93, and T_{eff} = 8000 K which belongs to an intermediate group of stars that bridge the gap between the main sequence variables and the Cepheid variables. Photometric variations with a period of P = 0.29 days have been reported (e.g., Auvergne et al. 1977), but often the star appears constant. The interpretation of this star was based on the occurrence of variations (or “reversals”) in the core of the Ca II K and hydrogen Balmer lines. Earlier observations (Baglin et al. 1968; Le Contel et al. 1970) had also reported this effect. The model devised by Karp (1975) to describe line splitting in Cepheid variables was adopted to explain the variations. According to this model, the variation arise from a pressure-wave induced temperature inversion in the upper layers of the atmosphere resulting from the nearly resonant pulsation of the photosphere and chromosphere.

Radial-velocity variations at two epochs were measured by Auvergne et al. (1979) using two techniques: taking the mean velocity shift of the red and blue sides of the profiles, and fitting the cores of the profiles with a Voigt function. They estimated the amplitude of the radial-velocity curve to be 10–20 km s^{-1} and found it to display “bumps” which were apparently correlated with the passage of a reversal in

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Observations of $\gamma$ Boo

<table>
<thead>
<tr>
<th>Julian Date</th>
<th>JD 2448138</th>
<th>JD 2448255</th>
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<td>Series length (days)</td>
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<td>0.128</td>
</tr>
<tr>
<td>No. of observations</td>
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<td>Exposure time (s)</td>
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<td>S/N per diode</td>
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The period of the RV variations was reported to be $P_{RV} = 0.25$ days and was not considered to be significantly different from the photometric period.

The behavior of the reversals as described by Auvergne et al. (1979) is reminiscent of the variations that can arise from nonradial pulsations. This mechanism might serve as an alternative explanation for the variations. Unfortunately both the signal to noise and the time sampling in Auvergne et al. (1979) are inadequate to establish this idea with certainty. High signal-to-noise data obtained using modern detectors with good time resolution should provide some answers.

3. OBSERVATION AND ANALYSIS OF $\gamma$ Boo

We have begun a survey of spectroscopic variability among $\delta$ Scuti stars to investigate the properties of high-degree variations within the $\delta$ Scuti instability strip.

Gamma Boo was among the stars selected. Time series observations were made with the Dominion Astrophysical Observatory 1.22-m telescope coudé spectrograph and 1872 Reticon detector (Walker et al. 1985) on 1990 September 4 and December 29. The reciprocal dispersion of these observations was $10 \text{ A mm}^{-1} (0.15 \text{ A pixel}^{-1})$ with spectral coverage of 284 A centered at $\lambda \sim 4500$ A. The spectrograph resolution was $\sim 2$ pixels. Details of the two runs can be found in Table 1. The data reduction program RETICENT (Pritchet et al. 1982) was used to process the data. This package was designed to reduce and analyze spectroscopic data recorded specifically with a Reticon detector. Rectification of the data was accomplished by computing the mean spectrum for each series and fitting a third degree polynomial to the continuum level of this spectrum. After dividing each spectrum in the series by the rectified mean, the function by which the individual spectra would be rectified was calculated by fitting a cubic spline to the large scale variations in the spectra. No smoothing was applied to the data. A portion of the observed spectral region centered on the unblended lines of Ti II $\lambda 4501.3$, Fe II $\lambda 4508.3$, and Fe II $\lambda 4515.3$ is shown in Figs. 1 (a) and 1 (b) for each run. Residuals were generated by subtracting the mean spectrum from each spectrum in the series [Figs. 2(a) and 2(b)]. Despite the noise, features traveling from blue to red with an amplitude of $\sim 0.5\%$ of the continuum can be easily distinguished. The moving features are more

![Fig. 1](image-url)
NONRADIAL PULSATIONS IN $\gamma$ BOOYIS

Fig. 2—Residuals were constructed by subtracting from each spectrum of Fig. 1 the mean for the series to reveal the variations within the absorption lines. (a) BJD 2448138 and (b) BJD 2448255.

apparent by viewing with the eye close to the plane of the page.

A more sensitive indication of line-profile variations is provided by the absolute mean deviation of the residuals (i.e., the sum of the absolute values of the residual variations, normalized by the number of spectra in the series). Figures 3(a) and 3(b) illustrate the mean deviation for the lines in the selected spectral region. The inverted mean spectrum is superimposed for comparison for each set of observations. The depth of the strongest line has been normalized to coincide with the maximum of the mean deviation. These plots indicate an amplitude of the line-profile variations that is approximately 2-3 times the noise level.

A 30% increase in the amplitude of the variations was detected in the December data relative to that obtained in September.

The pattern of the variation from any individual line is too contaminated by noise to perform an analysis of the variations. Because of the limited dispersion (14.5 pixels per line profile), it was not possible to smooth the data without removing the signature of the variations. The signature could be clarified by averaging a number of lines to improve the signal to noise. However, because the star is rotating rapidly, the lines are very broad and there are very few which are unblended. On the assumption that by averaging many lines the effect of both the noise and the blends would cancel, portions of the residual spectra centered around the positions of the strongest lines (from $\lambda 4460$ to $\lambda 4520$) were summed. A polynomial interpolation routine was used to map each portion of the spectra from the wavelength scale to a velocity scale before summation. Enough points were used in the interpolation so as to not introduce smoothing to the data. All lines were given equal weight regardless of the line strength. The mean residuals are illustrated in Figs. 4(a) and 4(b). A mean deviation plot of these variations reveals an increase in the effective S/N of a factor of 2 to 3. Further averaging did not improve upon this value.

The pattern of traveling features seen in the mean residuals of $\gamma$ Boo is similar to that identified in the four stars observed by Walker et al. (1987) for which the existence of high-degree NRP has been firmly established. We have analyzed the variations of the mean residuals in terms of the NRP model to determine the mode and period of the oscillation.

According to theory the moving bumps arise from the velocity (and temperature) variations of a wave traveling around the star. The apparent period of the variations, $\Delta t$, is the time for the pattern to repeat itself and is related to both the phase velocity of the wave and the rotational velocity of the star. To determine $\Delta t$ the variations in the intensity of the residuals were sampled at 10 km s$^{-1}$ intervals and transformed into amplitude spectra in the Fourier domain, a technique applied by Gies and Kullavanijaya (1988). The amplitude spectra were averaged and the value of $\Delta t$ corresponding to the maximum amplitude was
The observed period of oscillation for a rotating star is dependent on the true frequency of pulsation and the frequency of rotation. Lee and Saio (1990) have noted that unless the ratio of pulsation frequency to rotation frequency is large, high order terms introduced by the Coriolis force cannot be neglected. Although γ Boo is rapidly rotating, the requirement is satisfied because the star pulsates at frequencies corresponding to ρ modes. The first-order equation is sufficient to describe the pulsations:

$$\frac{1}{P_{\text{osc}}} = \frac{1}{\Delta t} + \frac{mv \sin i}{R \sin i} (1-C),$$

(3)

where \(P_{\text{osc}}\) is the period of oscillation in days in the corotating frame, \(\Delta t\) is the observed period in days, \(m\) is the mode, \(v \sin i\) is the projected rotational broadening width in \(\text{km s}^{-1}\), \(R\) is the stellar radius in \(R_{\odot}\) and \(C\) is the Coriolis correction term. Assuming \(i=90^\circ\), \(R=3.1\) and \(m = -10\) and letting \(C=0\), we estimate that \(P_{\text{osc}} = 0.073\) days for γ Boo.

The amplitude of the variations is a reflection of the velocity amplitude on the stellar surface (Kennelly et al. 1991) and can be used to estimate the velocity amplitude if resolution effects are taken into account. The amplitude of the variations within a line is also proportional to the strength of the line and depends on the intrinsic width of the line. Figure 8 shows the mean deviation and mean spectrum for the entire spectral region for the September data. It is clear that the amplitude of the variations increases at the position of the lines as was illustrated in Fig. 3. However, for the intrinsically broad H\(\alpha\) line no variation above the noise level is apparent despite its strength. We assume that the intrinsic resolution, determined by the width of the line, is too poor to reveal the presence of the variations at the S/N of these spectra. (The H\(\beta\) line was not included in the spectral region of the December observations.)

Radial-velocity variations can indicate the presence of low-degree modes of oscillation. Variations in line position on the order of \(~1\, \text{km s}^{-1}\) are difficult to measure for a...
single line especially at high dispersion and large rotational broadening; however by using the entire spectral region very accurate measurements are possible. We applied the Fahlman–Glaspey difference method (Fahlman and Glaspey 1973) which is equivalent to a cross correlation technique to the time series of spectra obtained for γ Boo using the mean spectrum as the reference template. The results are indicated in Figs. 9(a) and 9(b). Neither series was long enough to cover a full cycle but a fit to the data with the published period of 0.25 days is shown. In this case, an amplitude of ~1 km s$^{-1}$ is derived which differs from the observations of Auvergne et al. (1979) by an order of magnitude. The December observations suggest an additional variation reminiscent of the “bumps” observed in the radial-velocity curve by Auvergne et al. (1979). Imposing a sinusoidal fit to these variations gives a period of 0.050 ± 0.002 days which is approximately equal to that of the line-profile variations and is in phase with the passage of bumps in the residuals [Fig. 4(b)]. Maxima in the RV curve occur when a subfeature (absorption feature) is positioned immediately to the red side of the line center. The absence of a similar variation in the September RV curve may be attributed to the slightly smaller amplitude of the line-profile variations at that time.

4. DISCUSSION

We shall consider the idea that the intensity variations reported by Baglin et al. (1968) and the reversals observed by Le Contel et al. (1970) and Auvergne et al. (1979) were in fact line-profile variations caused by high-degree modes of oscillation. The apparent confinement of the variations to the cores of the lines is understandable considering the degradation of the resolution of subfeatures toward the wings of the line. However, although obtained at a comparable dispersion, our observations of the Hγ line of γ Boo show no indication of the variations reported by Auvergne et al. (1979) in the hydrogen Balmer lines (as well as Ca ii K). If the line-profile variations observed in both cases do have the same origin, this absence suggests that the amplitude of the oscillations must have decreased quite significantly.

With a computer simulation of nonradial pulsations we have attempted to reproduce the variations reported in Hγ. The model, discussed in Kennelly et al. (1991), uses spherical harmonics to describe the velocity perturbations introduced by the surface oscillations. A synthetic spectrum centered around Hγ (generated using the model atmosphere code of Hubeny 1988) is used as input to the model. Although the radial-velocity variations of Hγ could be re-

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**Fig. 4—** A time series of mean residuals constructed by averaging portions of the spectra centered around the strongest lines. (a) BJD 2448138 and (b) BJD 2448255.
produced by a radial mode of pulsation, we could not reproduce the line-profile variations by imposing high-degree modes with amplitudes even as high as 30 km s\(^{-1}\). The intrinsic width of the hydrogen line, even broader than \(\nu \sin i\), prevents these modes from appearing as variations.

**Fig. 5**—The amplitude spectrum of the line-profile variations was used to derive the apparent periods (a) 0.045 days at BJD 2448138 and (b) 0.047 days at BJD 2448255. The dashed line is the window function generated at these periods.

**Fig. 6**—The projected rotational broadening \(\nu \sin i = 120\) km s\(^{-1}\) was determined by fitting rotationally broadened synthetic line profiles (dashed) to the unblended Fe \(\Pi\ 44508\) line.

**Fig. 7**—A fit to the combined radial-velocity curves of the bumps [described by Eq. (1)] provides an estimate of the mode (\(|m| = 10\)) and period of variation. The dashed curves represent the fits to the data for \(|m| = 9\) (short dash) and \(|m| = 11\) (long dash). (a) BJD 2448138 and (b) BJD 2448255.

**Fig. 8**—The mean deviation and mean spectrum for the September time series which demonstrates the concentration of variations at the positions of the lines and the marked absence of any variations associated with the core of the \(\eta\) line at 44340.
in the rotationally broadened profile. The poor resolving power of Hγ is demonstrated in Fig. 10 where the intrinsic spectrum (top) can be compared with the rotationally broadened spectrum (bottom). Therefore we must conclude that the variations reported by Auvergne et al. (1979), if in fact real, cannot be explained by the presence of high-order nonradial pulsations.

The bumps seen in the radial-velocity curves of Auvergne et al. (1979) and Le Contel et al. (1970) likely result from the sensitivity of the measurements to the apparent passage of features in the line profiles. The presence of line-profile variations set a limit on the accuracy of radial-velocity measurements regardless of the method of measurement and those obtained from the cores of the lines where the amplitude of the line-profile variations is largest will be influenced to the greatest extent. Although in this study (with $v \sin i = 120$ km s$^{-1}$), Hγ proved to be insensitive to line-profile variations of high-degree modes, the metallic lines show a clear indication of high-degree variation. The variation seen in the RV curve is correlated to the passage of features observed in these lines.

Our observations indicate that γ Boo can be described as a multiperiodic pulsating star with a single high-degree on radial mode ($|m| \approx 10$) with period, $\Delta t = 0.047$ days (or $P_{osc} = 0.073$ days in the corotating frame) and a single radial or low-degree nonradial mode of pulsation. In fact, this interpretation is analogous to the results determined for κ$^2$ Boo, which shares some of the same physical properties with γ Boo. The spectral types are A7 III and A8 IV, respectively, and the $v \sin i$ values are 120 and 115 km s$^{-1}$, respectively. The apparent period of line-profile variations measured for κ$^2$ Boo was $\Delta t = 0.045$ days ($P_{osc} = 0.071$ days) in close agreement with that obtained here for γ Boo. The twin stars differ in one important respect however: the period of the low-degree variations. The radial-velocity variations of κ$^2$ Boo have a period of $P_{RV} = 0.071$ days, which is significantly shorter than the variations of γ Boo.

Although these two stars may be very similar, stars distributed throughout the δ Scuti instability strip possess a variety of pulsational properties. Why are some stars in the δ Scuti instability strip multiperiodic while others seem to pulsate with a single period or not at all? Photometric studies are only sensitive to low-degree modes, so what fraction of the δ Scuti stars pulsate with high-degree modes? Is there evidence for a dependence of variability on evolutionary position in the H–R diagram? Our continuing survey of spectroscopic variability should provide answers to many of these questions.

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REFERENCES

Hubeny, I. 1988, Comp. Phys. Commun., 52, 103