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HR 8799: A LINK BETWEEN γ DORADUS VARIABLES AND λ BOOTIS STARS

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ABSTRACT

On the basis of a new classification-resolution spectrum, we find that HR 8799, a known member of the newly discovered γ Doradus variable star class, is a λ Bootis star. Spectral synthesis, in conjunction with fluxes from visible spectrophotometry and the *TD-1* satellite, yields $T_{\rm eff} = 7430$ K, $\log g = 4.35$, microturbulent velocity $\xi_t = 2.7$ km s^{-1}, and metallicity [M/H] $= -0.47$ for HR 8799, confirming its metal-weak nature. HR 8799 is also a "Vega-like" star in that it shows excess flux at 60 μm, probably due to a circumstellar dust shell or disk. Thus, this star links three astrophysically interesting classes of stars and may provide potentially important constraints on the physics of, and the interconnections between, the λ Bootis phenomenon and the γ Doradus pulsation phenomenon.

Key words: stars: abundances — stars: chemically peculiar — stars: individual (HR 8799) — stars: variables: other

1. INTRODUCTION

The number of known types of intrinsically variable and peculiar stars that are associated with the δ Scuti instability strip and are close to the main sequence is remarkable. Only recently have investigations begun to uncover some of the relationships between the objects in this important area of the Hertzsprung-Russell diagram.

The δ Scuti stars, along with their Population II cousins, the SX Phoenicis stars, have spectral types between A3 and F2 and pulsate in both radial and nonradial pressure modes (or modes of mixed pressure- and gravity-mode character). Abundances in many δ Scuti stars are characterized by an overabundance of Fe-peak metals and a slight deficiency in C, N, O, and S. The typical periods of pulsation are of order hours, and amplitudes range from 0.4 mag down to observational limits. Many modes are detected, the current record holder being 4 CVn with 34 frequencies (Breger et al. 1999).

The λ Bootis stars are a spectroscopically defined group of nonmagnetic, chemically peculiar, Population I A-type (typically B9.5–F0) stars that display a mild to pronounced metal deficiency in Fe-peak elements (up to 2 dex below solar abundance) but solar to slightly oversolar abundances of C, N, O, and S. The ages of these stars range from pre–main-sequence to a few times 10^8 years (see Gray & Corbally 1998). A photometric study of λ Bootis stars revealed that roughly 50% of these objects that lie within the δ Scuti instability strip display low-amplitude variations similar to the δ Scuti stars; the remaining 50% are constant at the level of $\sim$0.003 mag (=0.3%; Paunzen et al. 1998).

The γ Doradus variables, found at or just beyond the red (cool) edge of the δ Scuti instability strip, are a newly discovered type of variable star that display high-order (n), low-degree (l), nonradial, photospheric gravity-type oscillations (see, e.g., Kaye et al. 1999b and references therein). The roughly 45 objects that reside on the "master list" of G. Handler & K. Krisciunas (1998, private communication) represent the first evidence of this type of variability within 1500 K of the Sun and are thus astrophysically important. These variable stars were defined based on their observed integrated photometric light and spectroscopic line profile variability, as well as their general physical characteristics defined by Kaye et al. (1999b).

The relationships between the different types of variable stars in this region of the Hertzsprung-Russell diagram are crucial to the physical understanding of stellar structure and evolution of stars at $\sim 2\ M_\odot$, as these stars are among the best candidates for asteroseismological study. An observed connection between λ Bootis stars and the δ Scuti variables is well documented in the literature (see, e.g., Paunzen et al. 1998). To date, no stars have been found that exhibit both δ Scuti and γ Doradus type variations.

In this paper, we present the first evidence of a connection between the λ Bootis stars and the γ Doradus variables. We present a classification-resolution spectrum that clearly shows the λ Bootis nature of the bona fide γ Doradus variable HR 8799 (=V342 Peg = HD 218396). In addition, we comment on how this object fits into the current theoretical schemes attempting to explain the γ Doradus phenomenon.

2. OBSERVATIONS AND CLASSIFICATION

We have obtained a classification-resolution spectrum of HR 8799 using the Gray/Miller Cassegrain spectrograph on the 0.8 m telescope of the Dark Sky Observatory of Appalachian State University. This spectrum was obtained with a 1200 line mm^{-1} grating in the first order and a Texas Instruments 1024 × 1024 thinned, back-illuminated CCD, and it has a spectral range of 3800–4600 Å. The 2 pixel resolution is 1.8 Å, and the spectrum has a signal-to-noise ratio in excess of 300.

The spectrum of HR 8799 was classified on the MK spectral classification system using MK standard stars obtained with the same telescope and spectrograph. Figure 1 shows HR 8799 compared with the standard stars HD 23194 (A5 V) and HD 23585 (F0 V). The Ca II K line and the general metallic line spectrum agree in strength, although not in morphology, with the A5 V standard. The hydrogen line profiles (and thus the effective temperature) are in better agreement with the F0 V standard. This implies that this star is mildly metal deficient. This, combined with the weak

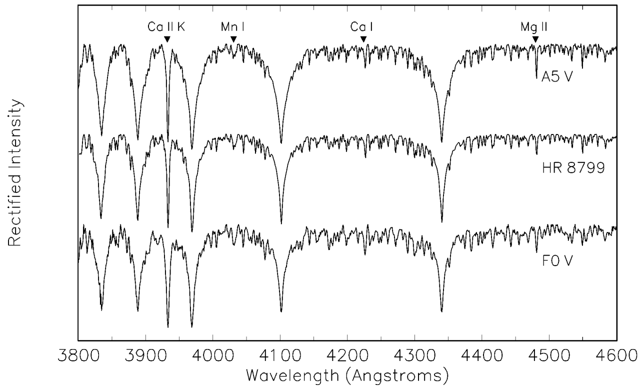

FIG. 1.—Comparison of the spectrum of HR 8799 with the A5 V and the F0 V MK standards. The spectral type of HR 8799 is determined to be kA5 hF0 mA5 v λ Boo. See text for details.

Mg II λ4481 line, suggests that this star is a mild λ Bootis star. Detailed comparison shows that the spectral type of HR 8799 is kA5 hF0 mA5 v λ Boo. The Strömgren photometry available in the literature (see, e.g., Zerbi et al. 1999) agrees with this diagnosis; HR 8799 is found in the "λ Bootis region" of the ($[m_1], b-y$) and ($[m_1], \beta$) photometric diagrams (see Gray 1988; Gray & Corbally 1993) and is well inside the classical δ Scuti instability strip (Breger 1979).

3. THE BASIC PROPERTIES OF HR 8799

The metal-weak nature of HR 8799 may be confirmed using spectral synthesis. One of us (R. O. G.) has devised a technique (see Gray, Graham, & Hoyt 1999 for details) that utilizes a multidimensional downhill simplex method to fit the basic parameters of a star, i.e., the effective temperature ($T_{\rm eff}$), the gravity ($\log g$), the microturbulent velocity (ξ_t), and the metallicity ([M/H]), by iteratively choosing the model that best matches the observed classification spectrum *and* the fluxes from Strömgren *uvby* photometry. The synthetic spectra used in this technique were computed with the program SPECTRUM using the ATLAS9 models of Kurucz (1993). The conversion from *uvby* photometry to fluxes was carried out using the formulae of Gray (1998). The basic parameters so derived are recorded in Table 1; the fit is illustrated in Figures 2 and 3. As can be seen from the fit, HR 8799 has an effective temperature, gravity, and microturbulent velocity in the range expected for an A9/F0 dwarf (cf. Gray & Corbally 1994; Stürenburg 1993) and is mildly metal-weak, with $[\rm M/H] = -0.47$, confirming the results of the spectral classification.

The classification of this star as a λ Bootis star is consistent with its metal-weak nature. That HR 8799 is a Population I star is consistent with its kinematics (space velocity $\sim$24 km s^{-1}), its position just slightly below the zero-age main-sequence (ZAMS), and the observation that it apparently possesses a circumstellar disk or shell similar to that found around Vega (based on its excess flux at 60 μm; see Sadakane & Nishida 1986). Indeed, this is an interesting point, as it reinforces the connection between the λ Bootis phenomenon and the presence of circumstellar material (see Gray & Corbally 1998 and references therein). These characteristics of HR 8799 are compatible with the known properties of both λ Bootis stars and γ Doradus stars. A handful of pre–main-sequence and ZAMS λ Bootis stars are

TABLE 1

HR 8799: BASIC PROPERTIES

Quantity	Value	Reference
Observed Quantities		
$b-y$	0.181 ± 0.007	1
m_1	0.142 ± 0.007	1
c_1	0.678 ± 0.007	1
Hβ	2.745 ± 0.007	1
$V-R$	0.243 ± 0.010	2
$B-V$	0.259 ± 0.010	3
$v \sin i$ (km s^{-1})	37.5 ± 2	4
π (mas)	25.04 ± 0.85	3
Derived Quantities		
$T_{\rm eff}$ (K)	7430 ± 75	5
[M/H]	−0.47 ± 0.10	5
$\log g$	4.35 ± 0.05	5
ξ_t (km s^{-1})	2.7 ± 0.5	5
M_V	2.98 ± 0.08	5
M ($M_\odot$)	1.47 ± 0.30	5
R ($R_\odot$)	1.34 ± 0.05	5
L ($L_\odot$)	4.92 ± 0.41	5

REFERENCES.—(1) Zerbi et al. 1999; (2) Kornilov et al. 1991; (3) ESA 1997; (4) Kaye & Strassmeier 1998; (5) this paper.

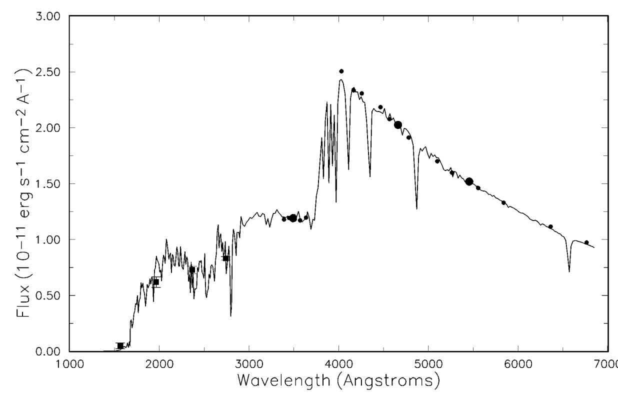

FIG. 2.—Model fit to HR 8799. The fit of the model to observed fluxes is shown. The squares with error bars represent fluxes from the *TD-1* satellite (Thompson et al. 1978). The large circles represent fluxes from Strömgren *uby* photometry, and the small circles represent fluxes from the spectrophotometry of Breger (1976).

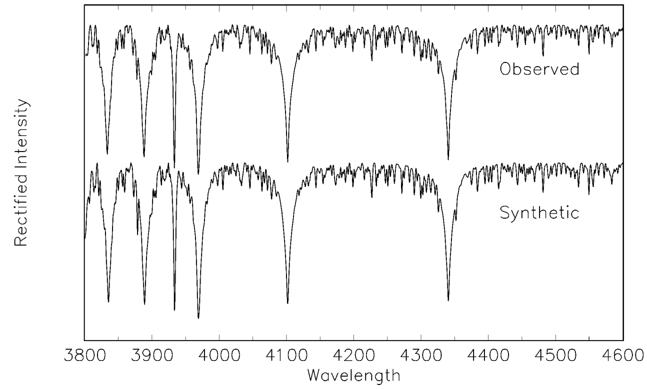

FIG. 3.—Model fit to HR 8799. This figure compares the synthetic spectrum computed from the model and the observed spectrum.

known (see Gray & Corbally 1998), but most seem to scatter up to a magnitude above the main sequence (see Paunzen 1997); similarly, γ Doradus stars apparently range from ZAMS objects to nearly a magnitude above the main sequence (Handler 1999). The λ Bootis stars range in spectral type between A0 and F0; γ Doradus stars range from late A to about F5. The association of circumstellar material with many λ Bootis stars is well known; γ Doradus itself may have a circumstellar shell (Walker & Wolstencroft 1988).

Estimates for the radius of this star may be computed in two ways. First, the $V-R$ and $B-V$ indexes may be used to derive a visual surface brightness parameter that is well correlated with the angular diameter (Barnes, Evans, & Moffett 1978). This angular diameter, combined with the *Hipparcos* parallax of 25.04 ± 0.85 mas (ESA 1997), yields $R = 1.30 \pm 0.19\ R_{\odot}$. On the other hand, the $T_{\rm eff}$ from the model fit may be used in conjunction with the absolute visual magnitude and the bolometric correction (0.04; Flower 1996) to derive $R = 1.35^{+0.05}_{-0.11}\ R_{\odot}$. We adopt the weighted mean of these values as our "final" radius solution: $R = 1.34 \pm 0.05\ R_{\odot}$. This radius yields, using the previously determined $\log g = 4.35 \pm 0.05$ from our model fit, a mass of $M = 1.47 \pm 0.30\ M_{\odot}$. We summarize the basic properties of HR 8799 in Table 1.

4. THE DISCOVERY OF VARIATIONS IN HR 8799

An early note indicated that HR 8799 (=V342 Peg = HD 218396) might be a "candidate for being a slightly metal-poor, low amplitude δ Sct star, with approximate amplitudes of 0.08 in V and 0.05 in c_1" (Schuster & Nissen 1986). Schuster & Nissen (1986) also provided a metallicity calculation ([Fe/H] = −0.55), a spectral classification (A5 V, A5 IV), and an effective temperature (7100 K). Rodríguez & Zerbi (1995) investigated the possible SX Phoenicis nature of HR 8799 and concluded that although there were no periodic signals in their photometry that would indicate the presence of pressure-mode oscillations, there were signals that could be interpreted as gravity-mode pulsations. Results of a detailed, multilongitude photometric campaign that confirmed HR 8799 as a bona fide, multiperiodic γ Doradus variable were recently published by Zerbi et al. (1999).[1] Zerbi et al. (1999) confirmed the findings of Schuster & Nissen (1986) indicating HR 8799 is a low-metallicity object based on their new Strömgren photometry, but their data were not suitable for further analysis along these lines.

5. DISCUSSION AND CONCLUSIONS

HR 8799 is an interesting and important star, as it is not only a λ Bootis star, and γ Doradus star, but also a "Vega-like" star that shows evidence for a circumstellar or protoplanetary disk. As a consequence, it may potentially play an important role in understanding the physical phenomena behind these three types of objects.

For instance, the fact that HR 8799 is both a λ Bootis star *and* a γ Doradus star, but *not* a δ Scuti pulsator even though it lies within the classical δ Scuti instability strip may help to constrain possible pulsation-driving mechanisms for the γ Doradus phenomenon (which involves high-order, low-degree, nonradial, gravity-type oscillations). Our current theoretical model of the λ Bootis phenomenon (see Venn & Lambert 1990; Turcotte & Charbonneau 1993) invokes accretion of metal-depleted gas from a circumstellar shell or the interstellar medium to produce metal deficiencies in the atmospheres of these stars down to the base of the superficial convection zone (consisting of the hydrogen convection zone and the He I partial ionization region [HeCZ]). Many λ Bootis stars are also δ Scuti pulsators, which implies that the deeper He II partial ionization region (HePIZ), which drives δ Scuti type pulsations, is intact in those stars. The absence of δ Scuti pulsations in HR 8799, however, suggests that gravitational settling of helium has occurred to the point that the HePIZ cannot drive pulsations; this is conceivable, as HR 8799 is presumably a slow rotator ($v \sin i = 37.5$ km s^{-1}; Kaye & Strassmeier 1998), and thus meridional circulation would not impede significant helium settling, which occurs when $v_{\rm eq} \lesssim 90$ km s^{-1} (see, e.g., Turcotte & Charbonneau 1993). Unfortunately, this situation implies that chemical separation due to diffusion occurs all the way to the base of the hydrogen convection zone, at which point the chemical separation processes are more efficient, and the star, unless it is experiencing a very high rate of accretion, should then be an Am star (which have overabundances of many iron-peak elements resulting from radiative levitation; see, e.g., Smith 1973) instead of a λ Bootis star! This contradiction suggests, therefore, that the HeCZ is intact in HR 8799 but that the HePIZ is too weak to drive δ Scuti type pulsations. Indeed, no known γ Doradus star shows any evidence of Am tendencies, reinforcing the conclusion that the HeCZ must be intact in these stars.

A possible cause of the pulsations in γ Doradus stars is the presence of an enhancement in the metal abundance (due to diffusive settling and radiative levitation of metals; see discussions in Kaye, Guzik, & Bradley 1999a). The opacity bump resulting from this diffusion and settling of metals may be the same as that found in the recent models of Turcotte, Richer, & Michaud (1998). The fact that HR 8799 is both a λ Bootis star and a γ Doradus variable seems to contradict this theory, since the required opacity bump lies in a region of the atmosphere that is convective (or in a region likely to be affected by convective overshoot), which will spread out the metals forming the opacity bump. However, the dual nature of HR 8799 *is* consistent with the theory that γ Doradus oscillations are driven by a pulsation-convection interaction similar to the "convective driving" mechanism described by Brickhill (1991), in which the observed pulsations are the result of the convection zone modulating the outward energy flow (see Guzik, Kaye, & Bradley 1999).

The additional observation that HR 8799 is a "Vega-like" star is important, as it reinforces the already strong association between the λ Bootis phenomenon and the presence of circumstellar material, probably in the form of a protoplanetary disk.

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[1] $P_1 = 0.5053$ days, $A_1 = 15.98$ mmag; $P_2 = 0.5791$ days, $A_2 = 8.58$ mmag; $P_3 = 0.6061$ days, $A_3 = 5.94$ mmag.

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