Radial Velocities for Four δ Sct Variable Stars

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Received February 27, 2019; revised April 23, 2019; accepted May 6, 2019

Abstract We report 124 radial velocities for the δ Sct variable stars VZ Cnc, AD CMi, DE Lac, and V474 Mon, covering full pulsation cycles. Although we also obtained data on KZ Hya, the signal-to-noise ratios of those spectra were too low to determine meaningful velocities. We confirm the multi-periodic behavior of both VZ Cnc and V474 Mon. However, our data do not cover a long enough baseline to address the multi-periodic nature of AD CMi claimed by Derekas *et al.* (2009). Our velocities, added to those in the literature for DE Lac, suggest discordant center-of-mass velocities, but the data are few.

1. Introduction

Delta Scuti variable stars are intrinsic pulsators of spectral type A to F, with short pulsation periods (usually less than 0.3 day). They lie on the H-R Diagram at the intersection of the Main Sequence and the classical instability strip. These stars can be either Population I or Population II, the latter also known as SX Phoenicis stars. Many δ Scuti stars are radial pulsators, while others pulsate nonradially. Breger (2000) points out that these stars represent a transition between the large amplitude radial pulsation of the classical instability strip (e.g., Cepheids) and the nonradial pulsations that occur in the hot side of the H-R Diagram.

Precise radial velocities are useful in several aspects of δ Scuti studies. For example, radial velocities are needed when employing the Baade-Wesselink method for determining distances, which has been applied to δ Scutis by Guiglion *et al.* (2013) and Burki and Meylan (1986), among others.

In this paper we present new radial velocity observations of four δ Scuti stars: VZ Cnc, AD CMi, DE Lac, and V474 Mon. We attempted velocities for the Pop II star KZ Hya, but were unsuccessful due to the required short integration time of the observations and the low metallicity of the star. For each star we have radial velocities for the complete pulsation cycle. Basic information about each star is given in Table 1, taken from the *General Catalogue of Variable Stars* (GCVS; Samus *et al.* 2017).

2. Observations

The observations were taken in 1996 (DE Lac) and 2003 (VZ Cnc, AD CMi, KZ Hya, V474 Mon, see Table 1) at the McDonald Observatory 2.1-meter Struve telescope at the f/13.5 Cassegrain focus with the Sandiford Échelle Spectrometer (McCarthy *et al.* 1993). All observations were taken at resolving power $R = 60{,}000$ per 2 pixels with a 1 arcsecond slit fixed in orientation. Two wavelength setups were used: the first, corresponding to observations taken 25 Jul 1996–26 Sep 1996, covered 5500–6900 Å in 27–28 orders (hereafter, the red region); the second set, taken 13 Dec 2003–18 Dec 2003, was observed using a bluer setup, 4280–4750 Å in 18 orders (hereafter, the blue region). Immediately following each stellar observation and prior to a telescope move, a Th-Ar emission spectrum was obtained for wavelength calibration. Internal flat field and bias frames were observed nightly for calibration of the Reticon 1200 × 400 CCD.

Each night we observed a spectrum of at least one radial velocity standard star chosen from the Geneva list of CORAVEL

Table 1. Observed δ Scuti stars.

Star	*R.A. (2000)* *h m s*	*Dec. (2000)* *° ′ ″*	*V* *(mag.)*	*Spectral Class*	*Integration* *(seconds)*	*Principal Period* *(days)*
VZ Cnc	08 40 52.1	+09 49 27	7.18–7.91	A7 III-F2 III	240	0.17836356
AD CMi	07 52 47.2	+01 35 50	9.21–9.51	F0 III-F3 III	210	0.122974458
KZ Hya	10 50 54.1	–25 21 15	9.46–10.26	A0	120,180	0.059510388
DE Lac	22 10 07.8	+40 55 11	10.08–10.43	F5-F8	see Table 5	0.253692580
V474 Mon	05 59 01.1	–09 22 56	5.93–6.36	F2 IV	240	0.1361258

Table 2. Adopted radial velocity standard stars.

Star	R.A. (2000) h m s	Dec. (2000) ° ′ ″	V (mag.)	Spectral Class	Radial Velocity (km s^{-1})
HD65934	08 02 11	+26 38 16	7.70	G8 III	35.8
HD102870	11 50 42	+01 45 53	3.59	F8 V	4.3
HD136202	15 19 19	+01 45 55	5.04	F8 III-IV	54.3
HD187691	19 51 02	+10 24 57	5.12	F8 V	–0.0
HD222368	23 39 57	+05 37 35	4.13	F7 V	5.6

standard stars (http://obswww.unige.ch/~udry/std/stdcor.dat) to set the velocity zero point. The standard stars used for these observations are listed in Table 2.

3. Data reduction

The CCD frames were reduced using standard IRAF procedures (Tody 1993) (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.). The IRAF task FXCOR determines a velocity for every échelle order. Because of instrumental effects or telluric features, seven of the red region orders always produced erroneous velocities; these were rejected for all spectra. For each spectrum (blue and red regions) we rejected any anomalous velocities in the remaining orders using an iterative Chauvenet's criterion (Chauvenet 1864; Taylor 1997). To apply Chauvenet's criterion we computed the mean and standard deviation of the ensemble of velocities in a spectrum. We determined the distance of each velocity from the mean in units of the standard deviation and computed the probability that this deviation would occur for a sample of our size. If this probability is less than 50%, that value is rejected. The criterion is iterated until no rejections occur. The mean and standard deviation of the velocities from the remaining orders were then computed. For the red region (DE Lac only), the typical number of orders retained was 9, and for the blue region, 17. The red region had few lines for these hot stars, hence the paucity of orders retained.

A more extensive description of our reduction process from raw CCD frames to radial velocities is given in Barnes *et al.* (2005, Paper I).

The median standard-error-of-the-mean in an individual radial velocity is ± 0.05 km s^{-1} for the red region and ± 0.22 km s^{-1} for the blue region, computed from the scatter in the velocities from the multiple échelle orders. This internal scatter underestimates the actual uncertainty in the measured radial velocity of the star. The order-to-order scatter does not include uncertainty due to error in the adopted radial velocities of the standard stars, uncertainty due to motion of the image in the spectrograph slit, uncertainty in the wavelength scale, and uncertainty due to potential differences in the velocity scale between the δ Sct variable stars and the standards used for the velocity zero point.

As in Papers I and II (Jeffery *et al.* 2007) we inferred the likely uncertainty in our observations by looking at the scatter in the radial velocity pulsation curves. For this paper we used AD CMi as it has numerous observations and is not affected by multi-mode behavior. We fit Fourier Series of successively greater order to the velocities given in Table 4. The scatter in fits of order 4–6 was stable at the ± 0.30 km s^{-1} level. We interpret this as a reasonable estimate of the uncertainties in the radial velocities presented here. In Papers I and II we obtained estimated uncertainties of ± 0.40 km s^{-1} (Cepheids) and ± 0.50 km s^{-1} (RR Lyrae) from the same instrumentation and reduction process.

4. Radial velocity results

We list individual radial velocities in Tables 3–6 together with the mid-point Heliocentric Julian Dates and pulsation phases. The data we obtained for KZ Hya were too low in signal-to-noise, given the short integration time required for its pulsation period (Kim *et al.* 2007) and the low metallicity of the star ([Me/H] = -0.99 ± 0.1, Fu *et al.* 2008), to obtain radial velocities. McNamara and Budge (1985) and Przybylski and Bessell (1979) both observed spectra of KZ Hya, but note that no lines except those of H and Ca II H and K were visible. The latter are too blue for our observations. Although we see Hγ on some (but not all) of the spectra, the low SNR of our observations prevents reliable radial velocities from being measured. We therefore disregard this star in our remaining analysis.

With the exception of DE Lac (see below) integration times were set not to exceed 2% of the pulsation period to avoid smearing the velocities.

4.1. VZ Cnc

VZ Cnc is a double-mode δ Sct. Boonyarak *et al.* (2009) did a study of times of maximum for VZ Cnc to determine its period change, correcting for the double-mode behavior. They deduced, based on 194 times of maximum, that the period is increasing at the rate of 1.4×10^{-8} per year. We inverted their quadratic ephemeris of times of maximum light to compute the phases of our observations, where phase is the fractional part of the epoch, E:

$$HJD_{obs} = 2431550.7197\ (\pm 0.002) + 0.17836356\ (\pm 0.00000002)E + 0.7\ (\pm 0.15) \times 10^{-8}E^2. \quad (1)$$

Our radial velocities are presented in Table 3 and shown in Figure 1. We have used different symbols to represent the different dates of observation: triangles, dots, and crosses represent (UT) 15 Dec, 16 Dec, and 17 Dec 2003, respectively. Its multimodal behavior is clearly seen in this figure. Uncertainties in the velocities are ± 0.30 km/s.

4.2. AD CMi

Boonyarak *et al.* (2011) analyzed times of maximum for AD CMi based on 100 maxima. They found a very small quadratic variation in the times of maximum, too small to be of significance across the dates of our observations, nonetheless we adopted their quadratic period variation for computation of the phases, as described above, to be consistent with previous studies:

$$HJD_{obs} = 2436601.8215 + 0.122974458E + 2.7 \times 10^{-13}E^2. \quad (2)$$

Table 3. Radial velocities of VZ Cnc.

UT Date	*HJD–2450000 (days)*	*Phase*	*V_r (km s^{-1})*
15 Dec 2003	2988.8682	0.8688	22.93
	2988.8752	0.9077	27.00
	2988.8795	0.9316	29.20
16 Dec 2003	2989.8343	0.2349	30.44
	2989.8376	0.2532	22.65
	2989.8429	0.2827	11.69
	2989.8429	0.2827	11.69
	2989.8517	0.3315	1.89
	2989.8550	0.3499	1.10
	2989.8604	0.3799	0.52
	2989.8637	0.3982	1.16
16 Dec 2003	2989.8687	0.426	3.26
	2989.8721	0.4448	4.44
	2989.8779	0.4771	7.02
	2989.8823	0.5015	9.56
	2989.8873	0.5293	12.33
	2989.8910	0.5498	14.56
	2989.8963	0.5793	16.91
	2989.8996	0.5976	19.43
	2989.9059	0.6326	22.89
	2989.9376	0.8087	35.96
	2989.9432	0.8398	39.01
	2989.9466	0.8586	39.67
	2989.9525	0.8914	41.07
	2989.9561	0.9114	42.45
	2989.9615	0.9414	42.81
	2989.9649	0.9603	43.04
	2989.9706	0.9920	43.91
	2989.9741	0.0114	43.25
	2989.9791	0.0392	43.08
	2989.9825	0.0581	42.94
	2989.9877	0.0869	43.02
	2989.9912	0.1064	42.63
	2989.9964	0.1353	40.12
	2989.9998	0.1541	38.29
	2990.0049	0.1825	35.28
	2990.0083	0.2014	32.18
	2990.0133	0.2291	24.75
17 Dec 2003	2990.9403	0.3780	10.25
	2990.9457	0.4080	9.92
	2990.9492	0.4275	9.92
	2990.9549	0.4591	10.53
	2990.9583	0.4780	9.62
	2990.9641	0.5102	9.94
	2990.9678	0.5308	10.08
	2990.9732	0.5608	10.69
	2990.9765	0.5791	11.42
17 Dec 2003	2990.9821	0.6102	12.51
	2990.9854	0.6285	13.23
	2990.9907	0.6580	14.57
	2990.9940	0.6763	15.62

Note: Phases are calculated from the ephemeris HJD_{obs} = *2431550.7197 + 0.17836356E + 0.7* × $10^{-8}E^2$.

Table 4. Radial velocities of AD CMi.

UT Date	*HJD–2450000 (days)*	*Phase*	*V_r (km s^{-1})*
14 Dec 2003	2987.8613	0.4862	42.33
	2987.8667	0.5301	44.47
	2987.8696	0.5537	45.81
	2987.8758	0.6042	48.28
	2987.8800	0.6383	49.34
	2987.8853	0.6814	50.36
	2987.8913	0.7302	50.18
	2987.8968	0.775	48.53
	2987.9001	0.8018	47.34
	2987.9076	0.8627	38.70
	2987.9106	0.8872	35.42
15 Dec 2003	2988.8902	0.853	39.93
	2988.8932	0.8774	36.93
	2988.8983	0.9189	31.38
	2988.9013	0.9433	28.49
	2988.9067	0.9872	25.91
	2988.9097	0.0116	25.67
	2988.9150	0.0547	25.78
	2988.9180	0.0791	26.25
	2988.9228	0.1181	27.32
	2988.9259	0.1433	28.70
	2988.9308	0.1832	30.28
	2988.9354	0.2206	31.34
	2988.9405	0.262	32.24
	2988.9435	0.2865	33.68
	2988.9486	0.3279	35.72
	2988.9516	0.3524	35.82
	2988.9568	0.3946	37.06
	2988.9599	0.4198	38.87
	2988.9648	0.4597	41.09
	2988.9678	0.484	41.96
	2988.9728	0.5247	45.41
	2988.9759	0.5499	45.20
17 Dec 2003	2990.9030	0.2207	31.52
	2990.9078	0.2597	33.03
	2990.9110	0.2857	33.87
	2990.9168	0.3329	35.21
	2990.9199	0.3581	35.80

Note: Phases are calculated from the ephemeris HJD_{obs} = *2436601.8215 + 0.122974458*E *+ 2.7* × $10^{-13}E^2$.

Table 5. Radial Velocities of DE Lac.

UT Date	*HJD-2450000 (days)*	*Integration (seconds)*	*Phase*	*Vr (km s^{-1})*
25 Jul 1996	289.8800	1200	0.8475	–0.46
29 Jul 1996	293.8169	1200	0.3658	–9.01
21 Aug 1996	316.7488	900	0.7575	9.12
22 Aug 1996	317.8427	900	0.0694	–23.15
26 Sep 1996	352.6953	1200	0.4494	–4.68

Note: Phases are calculated from the ephemeris HJD_{obs} = *2428807.1385 + 0.253692580*E *+ 1:29* × $10^{-11}E^2$.

Table 6. Radial velocities of V474 Mon

UT Date	*HJD–2450000 (days)*	*Phase*	V_r *(km s^{-1})*
13 Dec 2003	2986.8627	0.7105	21.49
	2986.8727	0.7839	21.56
	2986.8762	0.8096	21.67
	2986.8823	0.8544	21.44
	2986.8859	0.8809	20.51
	2986.8921	0.9264	23.23
	2986.8955	0.9514	22.56
	2986.9015	0.9955	19.70
	2986.9049	0.0205	16.49
	2986.9109	0.0645	15.91
	2986.9149	0.0939	13.84
	2986.9207	0.1365	11.51
	2986.9241	0.1615	10.91
	2986.9299	0.2041	10.50
	2986.9333	0.2291	9.99
	2986.9402	0.2798	9.23
	2986.9435	0.3040	13.48
	2986.9499	0.3510	12.78
	2986.9533	0.3760	12.14
	2986.9593	0.4201	15.05
	2986.9627	0.4451	15.15
	2986.9688	0.4899	16.74
	2986.9721	0.5141	19.52
14 Dec 2003	2987.9205	0.4812	18.08
	2987.9259	0.5209	18.96
	2987.9303	0.5532	20.16
	2987.9362	0.5966	20.96
	2987.9418	0.6377	21.61
	2987.9469	0.6752	22.10
	2987.9502	0.6994	22.25

Note: Phases are calculated from the ephemeris HJD_{obs} *= 2451500.000 + 0.1361258*E.

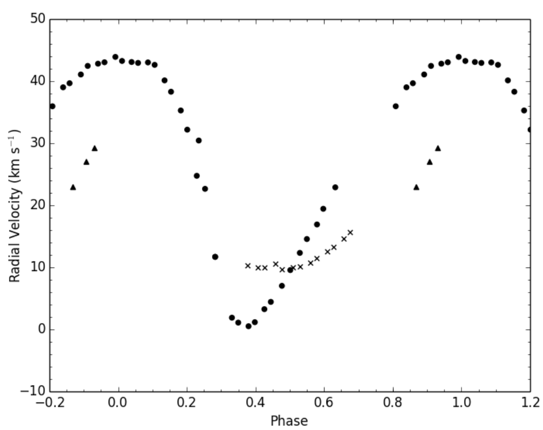

Figure 1. Phased radial velocity curve of VZ Cnc; phases are calculated from the ephemeris $HJD_{obs} = 2431550.7197 + 0.17836356E + 0.7 \times 10^{-8}E^2$. Triangles, dots, and crosses represent UT dates 15 Dec 2003, 16 Dec 2003, and 17 Dec 2003, respectively.

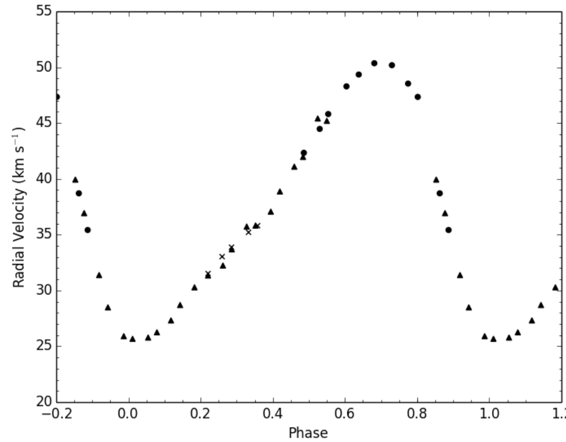

Figure 2. Phased radial velocity curve of AD CMi; phases are calculated from the ephemeris $HJD_{obs} = 2436601.8215 + 0.122974458E + 2.7 \times 10^{-13}E^2$. Dots, triangles, and crosses represent UT dates 14 Dec 2003, 15 Dec 2003, and 17 Dec 2003, respectively.

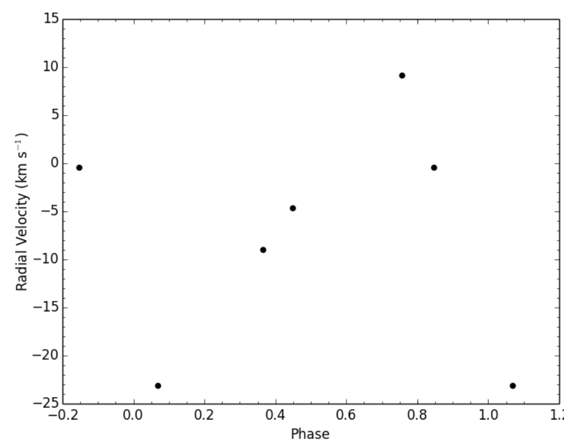

Figure 3. Phased radial velocity curve of DE Lac; phases are calculated from the ephemeris $HJD_{obs} = 2428807.1385 + 0.253692580E + 1.29\ \ 10^{-11}E^2$. Observations were taken on UT dates 25 Jul 1996, 29 Jul 1996, 21 Aug 1996, 22 Aug 1996, and 26 Sep 1996.

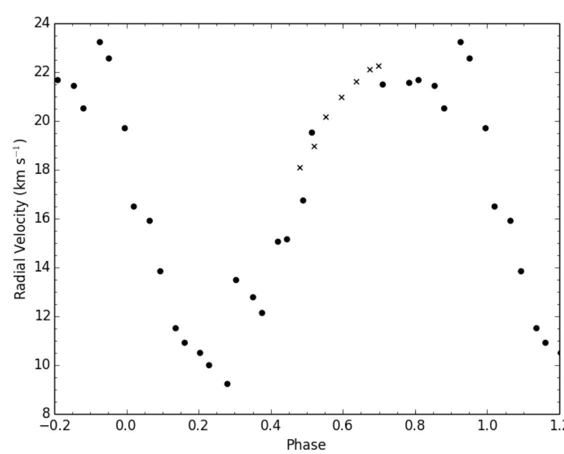

Figure 4. Phased radial velocity curve of V474 Mon; phases are calculated from the ephemeris $HJD_{obs} = 2451500.000 + 0.1361258E$. Dots and crosses represent (UT) 13 Dec 2003 and 14 Dec 2003, respectively.

They give no uncertainties for the ephemeris parameters. Our radial velocities are presented in Table 4 and shown in Figure 2. We have used different symbols to represent the different days of our observations: dots, triangles, and x's represent (UT) 14 Dec, 15 Dec, and 17 Dec, respectively. Uncertainties in the velocities are ± 0.30 km/s.

The mean radial velocity in Table 4 is 37.4 km s^{-1} with an amplitude 24.7 km s^{-1}. This mean velocity agrees nicely with Balona and Stobie (1983), 38.8 km s^{-1}, and with the data in Figure 8 of Derekas *et al.* (2009), ~ 40 km s^{-1}. Abyankhar (1959) gives a value of 34.5 km s^{-1} based on 6 measurements with large scatter.

Derekas *et al.* (2009) find variation in the radial velocity curve ~ 4 km s^{-1} over 4 months that is not seen in our nearly contiguous nights of data. They attribute this to multi-periodic variation. Hurta *et al.* (2007) determined an orbit for the binary based on variation in times of maximum light. They give a period of 42.9 y with an estimated radial velocity amplitude of 2K = 2.2 km s^{-1}. The variation seen in the radial velocities of Derekas *et al.* (2009) greatly exceeds expectation for a 42.9 y orbital period.

4.3. DE Lac

We inadvertently observed DE Lac as part of our RR Lyrae program (Jeffery *et al.* 2007, Paper II) through a typo in our observing list. We should have observed it with an integration time no longer than 435 sec to adhere to our policy of limiting exposure times to 0.02 cycle, instead of the actual times of 900 sec (0.041 cycle) and 1,200 sec (0.055 cycle). Our radial velocities are presented in Table 5 and shown in Figure 3. Uncertainties in the velocities are ± 0.30 km/s.

The effect of the exposure length, t_{exp}, is to smear the underlying signal through boxcar smoothing, so that the amplitude derived from the observations is less than the intrinsic amplitude. For a sinusoidal signal with period P, the reduction in amplitude is $\mathrm{sinc}(\pi\, t_{exp} / P)$ (Murphy 2012). For our 1,200 sec observations this corresponds to a factor of only 0.995.

Wang *et al.* (2014) analyzed times of maximum light and found a variable period. We used their quadratic solution to compute the phases for our observations as described above:

$$HJD_{obs} = 2428807.1385\ (\pm\ 0.0005) + 0.253692580\ (\pm\ 0.000000004)E + 1.29\ (\pm\ 0.16) \times 10^{-11}E^2. \qquad (3)$$

Taking a straight mean of our five velocities we find –5.6 km s^{-1} with an amplitude 32.1 km s^{-1}. Woolley and Aly (1966) obtained +3.6 km s^{-1} and 24.6 km s^{-1}, respectively, based on eight velocities (taken from their Tables VI and VII, Rowland metal values). On the other hand, McNamara and Laney (1976) measured –16.5 km s^{-1} for the gamma velocity and 26.5 km s^{-1} for the amplitude based on 17 velocities. These gamma velocities are discordant with a spread ~ 20 km s^{-1}. Possibly the star is a binary with 2K ~ 20 km s^{-1}; however, analysis of 66 years of times of maximum light by Wang *et al.* (2014) made no mention of an orbital light travel time effect.

4.4. V474 Mon

V474 Mon is known to be a multi-periodic star with at least three periods (Balona *et al.* 2001). For the phases in Table 6 and Figure 4 we adopted the principal radial component from that source. We have used different symbols to represent the different days of our observations: dots and x's represent (UT) 13 Dec and 14 Dec, respectively. We inverted the following to compute phases for our observations:

$$\mathrm{HJDobs} = 2451500.000 + 0.1361258E. \qquad (4)$$

The scatter in our velocities is more than twice the expected uncertainty (± 0.30 km/s), no doubt as a consequence of the multi-periodic variation. Our velocities compare well with those of Jones (1971) and with considerably smaller scatter. Szatmary (1990) lists V474 Mon as a binary with P = 15.492 days. Liakos and Niarchos (2017) list it as ambiguous for binarity.

5. Conclusions

We have presented 124 new radial velocities for the δ Sct variable stars VZ Cnc, AD CMi, DE Lac, and V474 Mon. All radial velocity curves cover complete pulsation cycles. Except for DE Lac integration times were limited to ≤ 2% of the pulsation cycle. The impact of the longer integration times for DE Lac is negligible. We have presented phased radial velocity curves for each star. Our radial velocities confirm the multi-periodic behavior of both VZ Cnc and V474 Mon. However, our data do not cover a long enough baseline to address the multi-periodic nature of AD CMi claimed by Derekas *et al.* (2009). Our velocities, added to those in the literature for DE Lac, suggest discordant center-of-mass velocities, but the data are few. Although we obtained data on KZ Hya, the signal-to-noise ratio of our spectra were too low to determine meaningful velocities for this star.

6. Acknowledgements

Financial support is gratefully acknowledged from National Science Foundation grant AST-9986817 (TGB). Travel support to obtain the observations is acknowledged from McDonald Observatory (EJJ, TGB, TJM). Travel support from the European Space Agency is also gratefully acknowledged (IS). We thank Dr. Michel Breger for helpful comments on the paper.

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