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ORBITS AND PULSATIONS OF THE CLASSICAL ζ AURIGAE BINARIES

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ABSTRACT

We have derived new orbits for ζ Aur, 32 Cyg, and 31 Cyg with observations from the Tennessee State University (TSU) Automatic Spectroscopic Telescope, and used them to identify nonorbital velocities of the cool supergiant components of these systems. We measure periods in those deviations, identify unexpected long-period changes in the radial velocities, and place upper limits on the rotation of these stars. These radial-velocity variations are not obviously consistent with radial pulsation theory, given what we know about the masses and sizes of the components. Our concurrent photometry detected the *nonradial* pulsations driven by tides (ellipsoidal variation) in both ζ Aur and 32 Cyg, at a level and phasing roughly consistent with simple theory to first order, although they seem to require moderately large gravity darkening. However, the K component of 32 Cyg must be considerably bigger than expected, or have larger gravity darkening than ζ Aur, to fit its amplitude. However, again there is precious little evidence for the normal radial pulsation of cool stars in our photometry. Hα shows some evidence for chromospheric heating by the B component in both ζ Aur and 32 Cyg, and the three stars show among them a meager $\sim$2–3 outbursts in their winds of the sort seen occasionally in cool supergiants. We point out two fundamental questions in the interpretation of these stars: (1) whether it is appropriate to model the surface brightness as gravity darkening and (2) whether much of the nonorbital velocity structure may actually represent changes in the convective flows in the stars' atmospheres.

Subject headings: binaries: spectroscopic — stars: late-type — stars: oscillations

Online material: machine-readable tables

1. INTRODUCTION

Our detailed knowledge of stars in the main sequence comes from analyses of eclipsing double-lined spectroscopic binaries. Solutions to light and velocity curves of such objects can define masses and radii of the component stars well enough to challenge the details of calculated internal structure and evolution. In contrast, defining the basic properties of evolved stars is normally much more difficult. The long periods and correspondingly large separations of binaries containing them make eclipses unlikely, and the existing binaries tend to be only single-lined. The ζ Aur binaries, however, with their eclipses and composite spectra, give us a unique opportunity to determine physical properties of a few massive supergiant stars reliably in the same way we can for many main-sequence stars. A good example of this is the way Bennett et al. (1996) defined the properties of ζ Aur. Wright (1970) discussed these systems, particularly the three classical systems ζ Aur, 31 Cyg, and 32 Cyg, all three of which have supergiant K primaries paired with B stars close to the main sequence. Table 1 gives their fundamental properties.

Most close binaries have circular orbits, although all possible eccentricities seem equally likely among newborn systems, at least those with longer periods (e.g., Abt 2006). The three classical ζ Aur systems all have sizable eccentricities. For this reason, they ought to be subject to certain binary proximity effects in ways other stars are not. For instance, they will be subject to a nonradial pulsation driven by the variable tidal distortion inevitable in an eccentric binary (Cowling 1941; Eaton 2008; Sepinsky et al. 2007). This phenomenon is equivalent to the ellipsoidal variation from the equilibrium tidal distortion in circular, synchronously rotating binaries. Because of the different orientations of their orbits, the two closer systems ζ Aur and 32 Cyg would manifest different phase dependence of this effect in ways giving clues about the internal properties of supergiants. Guinan & McCook (1979) claimed to have detected this phenomenon in 32 Cyg. Wilson (1979) included a theory for it in the Wilson-Devinney code for calculating binary light curves. The other major proximity effect, the so-called reflection effect, might be detectable in these systems as well.

All the cool giants and supergiants seem to be variable, probably through radial pulsations. Henry et al. (2000) argued that all stars to the red of the Linsky-Haisch coronal dividing line are pulsational variables. Even the red giants to the blue of it are variable given precise radial velocities (Walker et al. 1989). The components of ζ Aur binaries would be expected to manifest the pulsations of similar supergiants. Such pulsations would be in addition to the aforementioned proximity effects. Differences in their pulsational periods *might* give us an idea of how mass is distributed in their interiors.

ζ Aur itself is the most interesting of the three classical systems in terms of its binary interactions. It has the shortest period (970 days) and biggest eccentricity ($e \sim 0.4$), and these qualities make it most interesting for looking for the effects of a tidally driven nonradial pulsation. Griffin (2005) discussed the orbit recently, using all the many radial velocities then available. Why, then, should we waste our time redoing his analysis? Our data are several times as precise, cover one orbit continuously, and thereby begin to show coherent deviations of the K star from its orbital velocity.

We will (1) improve the orbital elements for two of the three classical ζ Aur binaries, (2) assess the rotation of these stars, (3) model the ellipsoidal light variations in order to interpret the driven pulsations of the cooler components of these systems, (4) look for the intrinsic (radial) pulsations of these stars and

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TABLE 1

The Classical ζ Aur Systems

Star (1)	Spectrum (2)	Period (days) (3)	a ($R_\odot$) (4)	i (deg) (5)	R_1 ($R_\odot$) (6)	r (R_1/a) (7)	M_1 ($M_\odot$) (8)	M_2 ($M_\odot$) (9)	References (10)
ζ Aur	K4 Ib + B5 V	972	905	87.0	148	0.163	5.8	4.8	Bennett et al. (1996)
HD 32068									
31 Cyg	K4 Ib + B3–4	3784	2710	87.2	197	0.073	11.7	7.1	Eaton (1993b)
HD 192577									Eaton & Bell (1994)
Cyg 32	K4–5 Ib + B6–7	1148	1130	78.6	175	0.155	9.7	4.8	Eaton (1993a)
HD 192909									

Notes.—Spectral types are from Wright (1970). Other quantities are from the cited references in Col. (10).

use them to restrict the radii, and (5) look for evidence of proximity effects and other variation in Hα.

2. OBSERVATIONS

Observations consist of new spectra and photometry for the three classical systems, spanning roughly 3.5 yr since 2004. All these data come from the completely automatic observatory Tennessee State University (TSU) maintains at Fairborn Observatory, a private site in southern Arizona (Eaton et al. 1996).

2.1. *Spectra*

We observed ζ Aur, 31 Cyg, and 32 Cyg between JD 2,452,860 and 2,454,200, obtaining echelle spectra of roughly 30,000 resolution, with the TSU 2 m Automatic Spectroscopic Telescope (AST; Eaton & Williamson 2004, 2007). This set consists of 302, 217, and 348 useful spectra, respectively, for the three stars. We reduced and analyzed them with standard pipeline techniques to derive radial velocities and equivalent widths of Hα. These measurements are available electronically as Table 2. Listed are: (1) HJD, the Heliocentric Julian Date of observation (minus 2,400,000); (2) RV$_{\rm cool}$, the radial velocity of the K star; (3) EW1, an equivalent width of Hα absorption; and (4) EW2, an equivalent width of enhanced absorption in the blue wing of Hα. Column (5) is a tag identifying the star by its HD number. Missing data in this table are identified with a "9.999."

The measured velocities from the AST have a formal external error of 0.10–0.11 km s^{-1} and are 0.35 ± 0.09 km s^{-1} more negative than the IAU radial-velocity system (Eaton & Williamson 2007). The velocities in Table 2 are the raw velocities without the +0.35 km s^{-1} correction to the IAU system. Values of systemic velocities, γ, from our orbital solutions, listed in Table 4, are transformed to the IAU system.

TABLE 2

Sample Spectroscopic Data

HJD (2,400,000+) (1)	RV$_{\rm cool}$ (km s^{-1}) (2)	EW1 (Å) (3)	EW2 (Å) (4)	Star (5)
52,861.9477....................	0.11	1.334	0.113	HD 32068
52,863.8894....................	0.02	1.496	0.152	HD 32068
52,895.9664....................	3.60	1.426	0.167	HD 32068
52,896.9640....................	3.70	1.407	0.149	HD 32068
52,897.9219....................	3.87	1.446	0.161	HD 32068
52,898.9425....................	3.94	1.447	0.162	HD 32068
52,899.9319....................	3.93	1.419	0.154	HD 32068

Notes.—Table 2 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.

Our Hα data consist of observed equivalent widths in a wide band (6561.3–6565.05 Å in the rest frame of the star), EW1, designed to measure the total absorption in the normal profile of such a star, and a narrow band (6559.7–6561.3 Å), EW2, to detect enhancements of the blue wing of the profile that may signal episodic mass ejections in a star's wind. In measuring the spectra, we adjusted the continuum to a common level by defining 13 pseudocontinuum points in the range 6522–6600 Å, automatically measured their levels in the spectra, and renormalizing the spectra to line segments between those points. The EWs depend on the two points at 6559.3 and 6568.1 Å. Several hundred spectra of the K giants α Tau, α Boo, and α Ari, which ought to be ~constant in Hα, give standard deviations per measurement of 0.046 and 0.020 Å, respectively, for EW1 and EW2. We shall use these values as the uncertainties of measurement.

2.2. *Photometry*

We also collected BV observations of the three stars with the TSU 0.4 m Automatic Photometric Telescope (APT), obtaining measurements over complete cycles of both ζ Aur and 32 Cyg and 4.0 yr for 31 Cyg. These measurements consist of nightly means of differential measurements with respect to a comparison star, HD 34412 for ζ Aur and HD 192985 for both 31 and 32 Cyg. The check star for ζ Aur was HD 30834, with 32 Cyg observed as a check star for 31 Cyg. These data should have an external error near 0.004 mag (Henry 1995). They are available electronically as Table 3. Data listed are HJD −2,400,000, $(\Delta U, \Delta B, \Delta V)_{\rm variable}$, $(\Delta U, \Delta B, \Delta V)_{\rm check}$—when available, and HD number of the star. We identify missing data, such as the nonexistent ΔU's, with a "99.999". This arrangement preserves the format of photometric data available on our internet site.

3. ANALYSIS

We shall analyze the three stars to find out how their radial velocities deviate from purely orbital motion and combine these results with photometry to assess what forms the pulsations and proximity effects take in them.

3.1. *Deviations from Orbital Velocities*

The great precision of our AST data lets us solve velocity curves of these three long-period binaries and look for deviations from elliptical orbits. Table 4 gives the results for the three stars, listing the usual spectroscopic elements. For 31 Cyg we have only about one-third of a full orbital cycle of data, so we have combined our data with those listed by Wright & Huffman (1968) and weighted all the data equally. The solution to this combined data set is the same as Wright & Huffman's to within the putative

TABLE 3
SAMPLE PHOTOMETRIC DATA

HJD (2,400,000+) (1)	$\Delta U_{\rm var}$ (2)	$\Delta B_{\rm var}$ (3)	$\Delta V_{\rm var}$ (4)	$\Delta U_{\rm chk}$ (5)	$\Delta B_{\rm chk}$ (6)	$\Delta V_{\rm chk}$ (7)	Star (8)
52,895.9881	99.999	−0.327	−0.942	99.999	0.886	0.085	HD 32068
52,926.0065	99.999	−0.324	−0.934	99.999	0.874	0.079	HD 32068
52,930.0235	99.999	−0.322	−0.933	99.999	0.876	0.081	HD 32068
52,931.0199	99.999	−0.324	−0.939	99.999	0.877	0.077	HD 32068
52,932.0135	99.999	−0.327	−0.939	99.999	0.878	0.079	HD 32068
52,933.0132	99.999	−0.327	−0.940	99.999	0.876	0.080	HD 32068
52,934.0214	99.999	−0.326	−0.938	99.999	0.871	0.069	HD 32068

NOTES.—Table 3 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.

errors. The difference between the spectroscopic period we have derived and the photometric period (1.8 days) corresponds to a shift of +0.21 km $\rm s^{-1}$ of Wright & Huffman's velocities with respect to ours. This shift gives a flavor of the kind of uncertainties that indeterminate zero-point shifts introduce into orbital analyses. The values of the major elements (K, e, and ω) for both ζ Aur and 32 Cyg agree with previous determinations to within the likely errors of those determinations. In particular, they agree with Griffin's (2005) values for ζ Aur to within 2 σ of his formal errors. For 32 Cyg, they should be a significant improvement on the elements of Wright (1970), with which they agree to within the likely errors of that analysis. This excellent agreement means that the shapes and orientations of the orbits of both stars are known well enough to support rigorous analyses of their atmospheric eclipses, driven nonradial pulsations, and eclipse timings.

Figure 1 shows the velocity curves of the three stars. All three are obviously variable, with nonorbital shifts superimposed on the dominant orbital velocities. Figure 2 shows the time dependence of these deviations, which can be rather extreme. The 250 day, 0.75 km $\rm s^{-1}$, deviation of 31 Cyg around 53,700, for instance, if pulsational, would correspond to a 23 $R_\odot$ change in the stellar radius, about 12%, even without any allowance for foreshortening. Alternatively, it could represent some sort of truly global circulation. The variation seen in Figure 2 seems cyclic on timescales of 100–300 days, so one might suspect that some of it could be seasonal observational effects. However, the major effects do not correlate very well in 31 and 32 Cyg, which we observed over the same observing season, occasionally on the same nights, and there is absolutely no hint of such effects in velocities of HD 14214 at levels above 0.05 km $\rm s^{-1}$ (Eaton & Williamson 2007). Three other K supergiants observed over roughly the same time interval, ϵ Peg (K2 Ib), ξ Cyg (K4–5 Ib–II), and 63 Cyg (K4 Ib–IIa), show long-term variations at least as great as the three binaries, although we have far fewer data for these single stars.

We have used two techniques to look for periodicity in the residuals. In the first, using a program written by D. S. Hall, we fit sine curves for a spectrum of periods to the data [$\Delta{\rm RV} = A\sin(2\pi{\rm HJD}/P + \phi)$] and identified minima of χ^2 of these fits as possible periods. In the second, we applied the techniques of Vaníĉek (1971), as we have for the multiperiodic γ Doradus stars (e.g., Kaye et al. 1999; Henry et al. 2001). This second approach lets us reliably find multiple periodicities without "prewhitening," an advantage, especially in the low-frequency domain. We searched for periods in the range 1–1200 days. Both methods identified essentially the same periods, but, because the second method gives more systematic results, we will use them in the following analysis. Table 5 lists the periods found and amplitudes of sinusoids fit to the data for them. If the velocity variation represents a radial pulsation, we may integrate the (sinusoidal) variation over half a cycle to get the total excursion in radius, $\Delta R = \xi AP/\pi$, where $\xi \approx 1.35$ is a correction for the fact that expansion of most of the disk is only partially in the line of sight (e.g., Gray & Stevenson 2007). The periods derived here likely reflect the timescales of some physical phenomena in these stars but not truly coherent long-duration pulsations. This is especially so for the longest periods, those comparable to the ~1200 day duration of our observations. Additional tests for shorter periods (0.03–1.0 days) with the method of Vaníĉek found none, as expected.

3.2. *Rotation*

If the cool components of these binaries were rotating synchronously, they would have significant rotational velocities, $v\sin i = (K_1 + K_2)R_1/a$ for synchronous rotation with the usual assumptions about orientation of the motions. For pseudosynchronous rotation (Hut 1981; Hall 1986), the velocity would be

TABLE 4
SPECTROSCOPIC ORBITS

HD (1)	Period (days) (2)	T[a] (HJD−2,400,000) (3)	K (km $\rm s^{-1}$) (4)	γ[b] (km $\rm s^{-1}$) (5)	e (6)	ω (deg) (7)	References (8)
ζ Aur	(972.162)	53,039.9 ± 0.10	23.17 ± 0.02	10.81 ± 0.01	0.3973 ± 0.0007	328.9 ± 0.13	This paper
31 Cyg	3786.1 ± 0.7	52,372.8 ± 2.2	13.78 ± 0.13	−7.41 ± 0.08	0.224 ± 0.006	206.4 ± 1.4	This paper
32 Cyg	(1147.80)	53,796.9 ± 0.28	16.64 ± 0.03	−7.45 ± 0.02	0.3126 ± 0.0014	222.1 ± 0.3	This paper

NOTES.—Values in parentheses are assumed values taken from the literature. Periods are generally from Batten et al. (1989).

[a] Periastron passage.

[b] Velocity on IAU system.

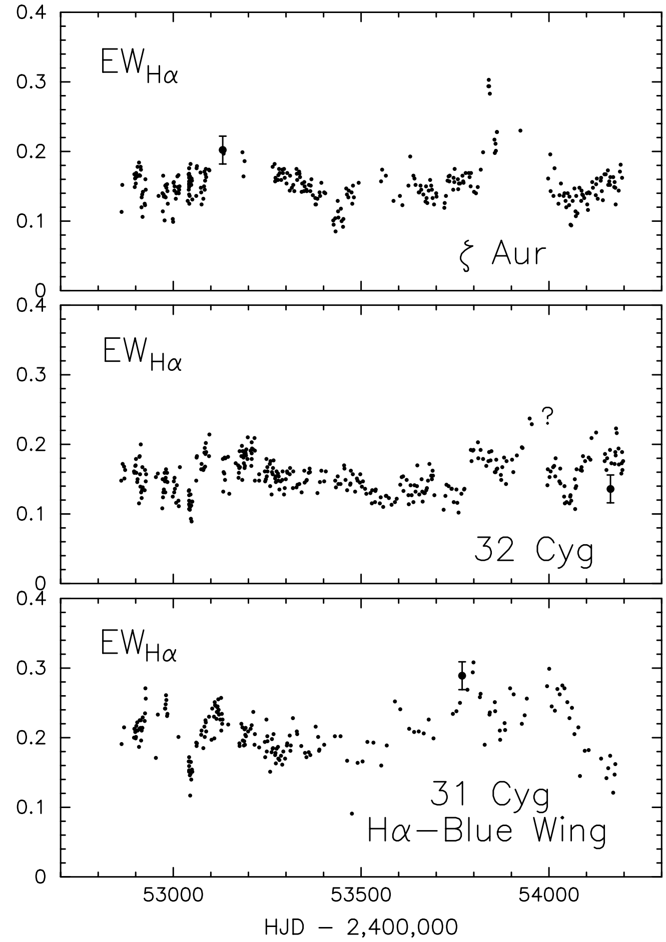

FIG. 5.—Variation of the blue wing of Hα in the three binaries. This is EW2 (in Å), the band that measures enhanced wind absorption in the blue wing of the profile beyond the velocity range of normal chromospheric absorptions. Such enhancements are amply documented in a number of cool supergiants, but there are few of them detected in these data.

very restricted case do we see something like a pulsation in both the brightness and radial velocity of the star. This pulse in 32 Cyg may have been a radial pulsation of the K star, and the same star shows flickering on shorter timescales, at the level of the photometric errors, that may be pulsation in overtones. The roughly coherent variation of 31 Cyg's radial velocity at 125 days may also reflect pulsation, but it is not accompanied by changes in the brightness. Radial pulsation at the 1%–2% level is consistent with eclipse timings in these stars.

The K supergiants in these systems fall in a part of the H-R diagram with rather low pulsation (e.g., Maeder 1980; Henry et al. 2000). Stars with lower masses are generally stable in their lower radial modes but become increasingly susceptible to pulsation in high overtones (Xiong & Deng 2007). Such high overtones are a possible source of the apparently random flickering of the rather stable K giants and supergiants.

One way to get a better idea of the level of any changes in radius from pulsation is to look critically at the timing and duration of eclipses, as we have illustrated with three eclipses of 31 Cyg. We do not think the existing data are good enough to do this in any meaningful way. However, this approach should be possible with photometry from robotic telescopes, but it would take a communal effort over many years.

Other changes in both brightness and velocity are completely inconsistent with the known stability of light variation of these systems and with the expected pulsations of their K components. Especially perplexing is the 200 day drop in velocity of 31 Cyg, corresponding to a 12% change in the star's radius. This kind of change would be accompanied by changes of several days in the eclipse timing. It is much more likely to be a nonpulsational change in the circulation of the star's atmosphere, like the famous star patch in ξ Boo A (Toner & Gray 1988). The range of photospheric velocity caused by granulation or other flows in cooler supergiants (Gray & Toner 1985, 1986a, 1986b, 1987) seems big enough ($\sim$6–10 km s^{-1}) to admit fluctuations at the level we are observing. However, once again we are thus reminded that "there are more things in heaven and earth than are dreamt of in [our] philosophy."

All three of these stars had photometric variations on timescales longer than expected for pulsation. Thirty-one Cyg showed a 1250 day sinusoidal variation in our photometry, covering $\sim$the length of our observations. There is no mechanism for producing this effect, and it may simply reflect variation of the comparison star. Both ζ Aur and 32 Cyg also had variations in brightness beyond their ellipsoidal variation.

Cool components in these three classical systems seem to be rotating no faster than similar single supergiants. In contrast, Griffin et al. (1993) and Eaton & Shaw (2007) found evidence the chromosphere of 22 Vul is rotating *faster* than synchronously. This is a close binary in a circular orbit, which may have been a much closer, interacting system in a previous visit to the giant branch. Likewise, the supergiant component of the relatively close but eccentric binary HR 6902 (G9 II + B8 V) seems to be rotating even faster than pseudosynchronously (Griffin & Griffin 1986). These rotational velocities would seem to be an important clue to the evolutionary history of supergiant binaries once somebody becomes clever enough to interpret them.

We have detected the ellipsoidal variation and its periastron effect in two of the stars and used it to discuss how the driven nonradial pulsations in such a star should change the surface brightness. In this context, we question the use of the concept of gravity darkening in such stars and propose a methodology for determining an effective gravity darkening for such pulsations. We find the light variations of ζ Aur require larger gravity darkening than predicted by Lucy's (1967) diffusive theory. Along these same lines, we may have detected a chromospheric reflection effect in the Hα strength.

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REFERENCES

Abt, H. A. 2006, ApJ, 651, 1151
Batten, A. H., Fletcher, J. M., & MacCarthy, D. G. 1989, Publ. Dom. Astrophys. Obs. Victoria, 17, 1
Bauer, W. H. 1994, PASP, 106, 244
Bennett, P. D., Harper, G. H., Brown, A., & Hummel, C. A. 1996, ApJ, 471, 454
Buta, R. J., & Smith, M. A. 1979, ApJ, 232, 213
Cowling, T. G. 1941, MNRAS, 101, 367
Cram, L. E., & Mullan, D. J. 1979, ApJ, 234, 579
Dziembowski, W. 1971, Acta Astron., 21, 289
Eaton, J. A. 1993a, AJ, 105, 1525
———. 1993b, AJ, 106, 2081
———. 1995, AJ, 109, 1797

Eaton, J. A. 2008, ApJ, in press (arXiv: 0802.2663v1)

Eaton, J. A., & Bell, C. 1994, AJ, 108, 2276

Eaton, J. A., Boyd, L. J., & Henry, G. W. 1996, BAAS, 28, 841

Eaton, J. A., & Henry, G. W. 1996, in IAU Symp. 176, Stellar Surface Structure, ed. K. G. Strassmeier & J. L. Linsky (Dordrecht: Kluwer), 415

Eaton, J. A., & Shaw, F. G. 2007, AJ, 133, 2669

Eaton, J. A., & Williamson, M. H. 2004, Proc. SPIE, 5496, 710

———. 2007, PASP, 119, 886

Fox, M. W., & Wood, P. R. 1982, ApJ, 259, 198

Fredrick, L. W. 1960, AJ, 65, 628

Gray, D. F., & Stevenson, K. B. 2007, PASP, 119, 398

Gray, D. F., & Toner, C. G. 1985, PASP, 97, 543

———. 1986a, ApJ, 310, 277

———. 1986b, PASP, 98, 499

———. 1987, ApJ, 322, 360

Griffin, R., & Griffin, R. 1986, J. Astrophys. Astron., 7, 195

Griffin, R. E. M., Griffin, R. F., Schröder, K.-P., & Reimers, D. 1990, A&A, 234, 284

Griffin, R. E. M., Hünsch, M., Marshall, K. P., Griffin, R. F., & Schröder, K.-P. 1993, A&A, 274, 225

Griffin, R. F. 2005, Observatory, 125, 1

Guinan, E. F., & McCook, G. P. 1979, PASP, 91, 343

Hall, D. S. 1986, ApJ, 309, L83

Henry, G. W. 1995, in ASP Conf. Ser. 79, Robotic Telescopes: Current Capabilities, Present Developments, and Future Prospects for Automated Astronomy, ed. G. W. Henry & J. A. Eaton (San Francisco: ASP), 44

Henry, G. W., Fekel, F. C., Henry, S. M., & Hall, D. S. 2000, ApJS, 130, 201

Henry, G. W., Fekel, F. C., Kaye, A. B., & Kaul, A. 2001, AJ, 122, 3383

Hinkle, K. H., Lebzelter, T., Joyce, R. R., & Fekel, F. C. 2002, AJ, 123, 1002

Hut, P. 1981, A&A, 99, 126

Kaye, A. B., et al. 1999, AJ, 118, 2997

Kubiak, M. 1972, Acta Astron., 22, 11

Lucy, L. B. 1967, Z. Astrophys., 65, 89

Maeder, A. 1980, A&A, 90, 311

Mallik, S. V. 1993, ApJ, 402, 303

McKellar, A., & Butkov, E. 1956, Publ. Dom. Astrophys. Obs. Victoria, 10, 341

McKellar, A., & Petrie, R. M. 1952, MNRAS, 112, 641

Odell, A. P. 1980, Space Sci. Rev., 27, 345

Sepinsky, J. F., Willems, B., & Kalogera, V. 2007, ApJ, 660, 1624

Smith, G. H., & Dupree, A. K. 1988, AJ, 95, 1547

Stamford, P. A., & Watson, R. D. 1976, Proc. Astron. Soc. Australia, 3, 75

———. 1977, MNRAS, 180, 551

Stencel, R. E., Hopkins, J. L., Hagen, W., Fried, R., Schmidtke, P. C., Kondo, Y., & Chapman, R. D. 1984, ApJ, 281, 751

Szabó, R., Buchler, J. R., & Bartee, J. 2007, ApJ, 667, 1150

Toner, C. G., & Gray, D. F. 1988, ApJ, 334, 1008

Townsend, R. H. D. 2003, MNRAS, 343, 863

Vaníĉek, P. 1971, Ap&SS, 12, 10

Walker, G. A. H., Yang, S., Campbell, B., & Irwin, A. W. 1989, ApJ, 343, L21

Wilson, O. C., & Abt, H. A. 1954, ApJS, 1, 1

Wilson, R. E. 1979, ApJ, 234, 1054

Wood, P. R., Olivier, E. A., & Kawaler, S. D. 2004, ApJ, 604, 800

Wright, K. O. 1970, Vistas Astron., 12, 147

Wright, K. O., & Hesse, K. H. 1969, Publ. Dom. Astrophys. Obs. Victoria, 13, 301

Wright, K. O., & Huffman, R. E. 1968, Publ. Dom. Astrophys. Obs. Victoria, 13, 275

Xiong, D. R., & Deng, L. 2007, MNRAS, 378, 1270