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A SPECTROSCOPIC ORBIT FOR REGULUS

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ABSTRACT

We present a radial velocity study of the rapidly rotating B star Regulus that indicates the star is a single-lined spectroscopic binary. The orbital period (40.11 days) and probable semimajor axis (0.35 AU) are large enough that the system is not interacting at present. However, the mass function suggests that the secondary has a low mass ($M_2 > 0.30\ M_\odot$), and we argue that the companion may be a white dwarf. Such a star would be the remnant of a former mass donor that was the source of the large spin angular momentum of Regulus itself.

Subject headings: binaries: spectroscopic — stars: early-type — stars: individual (Regulus, α Leonis)

Online material: machine-readable table

1. INTRODUCTION

Regulus (α Leo; HD 87901; HR 3982; HIP 49669) is a nearby ($d = 24.3 \pm 0.2$ pc; van Leeuwen 2007) intermediate-mass star of spectral type B7 V (Johnson & Morgan 1953) or B8 IVn (Gray et al. 2003). It is one of a number of nearby B- and A-type stars exhibiting extremely fast rotation. The very broad shape of its photospheric absorption lines indicates a projected rotational velocity of $V \sin i = 317 \pm 3$ km s^{-1} (McAlister et al. 2005). The full picture of its fast spin came with the first interferometric observations of Regulus with the CHARA Array optical long baseline interferometer (McAlister et al. 2005). These observations showed that the star is rotationally flattened and gravity darkened at its equator. Models of the spectrum and interferometry demonstrate that the star has a rotation period of 15.9 hr, with an equatorial velocity equal to 86% of the critical velocity, where centripetal acceleration balances gravity.

The fast spin of Regulus is puzzling given its probable age (≈150 Myr; Gerbaldi et al. 2001). Stars born as fast rotators are expected to slow down relatively quickly after birth, and only again achieve rapid rotation at the conclusion of core H-burning through a redistribution of angular momentum (Ekström et al. 2008). Thus, it is surprising to find rapid rotation in Regulus, a star which is still in the middle of its core H-burning stage. On the other hand, stars that are members of interacting binaries can experience large changes in spin due to tidal interactions and mass exchange. Langer et al. (2008) discuss how mass transfer may lead to the spin up of the mass gainer in a large fraction of these binaries. Depending on the initial separation and mass ratio, the system may merge or it may widen following mass ratio inversion, leaving the donor remnant in a large orbit that shuts down mass transfer once the donor's envelope is lost. We know of several examples of such post-mass-transfer binaries with rapid rotators, including the Be X-ray binaries with neutron star companions (Coe 2000) and Be binaries with He-star companions (Gies et al. 1998; Maintz et al. 2005; Peters et al. 2008).

Regulus does have a known wide companion (α Leo B at a separation of ≈175″, which is itself a binary consisting of K2 V and M4 V pair; McAlister et al. 2005), but this companion has far too great a separation to have ever interacted directly with Regulus. There are no known closer companions, but the last significant radial velocity investigation was made in 1912–1913 by Mellor (1923). The scatter in the results introduced by the broad and shallow appearance of the spectral lines may have discouraged other investigators, but this early work and others (Maunder 1892; Frost et al. 1926; Campbell 1928; Palmer et al. 1968) suggest that any velocity variations present are relatively small. However, a low-mass donor remnant would probably create only a modest reflex motion in Regulus, so the lack of demonstrated variability is not unexpected. We have made spectroscopic observations of Regulus on many occasions over the last few years, and here we present a summary of the velocities measured in these spectra. We find that Regulus is in fact a low-amplitude, single-lined, spectroscopic binary, and we discuss the possible nature of the companion.

2. OBSERVATIONS AND RADIAL VELOCITIES

Table 1 lists the sources and properties of the spectra of Regulus we used to measure radial velocity. The spectra from run numbers 1–8 were made by us and have moderate resolving power and good S/N (usually better than 100 per pixel). These include spectra obtained with the Kitt Peak National Observatory Coudé Feed Telescope (Valdes et al. 2004), the Czech Academy of Sciences Ondrejov Observatory telescope and HEROS spectrograph (Štefl et al. 2000), and the Multiple-Telescope Telescope at the Georgia State University Hard Labor Creek Observatory (Barry et al. 2002). We have also obtained a number of spectra from online archives including the ESO La Silla 50 cm telescope and HEROS spectrograph, University of Toledo Ritter Observatory echelle spectrograph (Morrison et al. 1997), the ELODIE spectrograph of the Observatoire de Haute Provence (Moultaka et al. 2004), the ESO VLT and

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TABLE 1
Journal of Spectroscopy

Run Number	Dates (Besselian Year)	Range (Å)	Resolving Power (λ/Δλ)	N	Observatory/Telescope/ Spectrograph
1	1989.3	4453–4597	6280	6	KPNO/0.9 m/Coudé
2	2000.9	6445–6700	12100	30	KPNO/0.9 m/Coudé
3	2004.8	6466–6700	9500	16	KPNO/0.9 m/Coudé
4	2005.9	4240–4580	10300	2	KPNO/0.9 m/Coudé
5	2006.8	6434–6700	7600	2	KPNO/0.9 m/Coudé
6	2006.8	4240–4580	10200	2	KPNO/0.9 m/Coudé
7	2000.9–2002.4	3780–5700, 5832–8483	20000	46	Ondřejov/2 m/HEROS
8	1999.1–2000.3	6500–6700	14000	6	HLCO/MTT 1 m/Ebert-Fastie
9	1999.4	5832–8483	20000	1	La Silla/0.5 m/HEROS
10	2004.2–2007.1	6527–6596	26000	37	Ritter/1 m/Echelle
11	1996.3	4000–5000	34100	2	OHP/1.9 m/ELODIE
12	2003.0	3760–4500, 4800–5100	80000	1	VLT/8 m/UVES
13	2004.0	3800–5000	120000	2	La Silla/3.6 m/HARPS
14	2006.1–2007.1	3750–5150	48000	3	La Silla/2.2 m/FEROS
15	1979.0–1995.3	1200–1900	10000	12	*IUE*/0.45 m/Echelle (SWP)

UVES (UVES Paranal Observatory Project, ESO DDT Program ID 266.D-5655; Bagnulo et al. 2003), La Silla 3.6 m telescope and HARPS spectrograph (Mayor et al. 2003), and La Silla 2.2 m telescope and FEROS spectrograph (Kaufer et al. 1999; Weselak et al. 2008). In many cases, the archival spectra included a series made within a few minutes' time, and we report here the average velocity of such groups. Finally, we also collected a series of 12 UV high-dispersion spectra from the archive of the *International Ultraviolet Explorer* (*IUE*). All these spectra were reduced to a rectified continuum format using standard routines in IRAF,[6] and then each group was transformed onto a uniform, heliocentric wavelength grid in increments of log λ. Many of these observations record the red spectrum in the vicinity of Hα, and we usually removed the atmospheric telluric lines in this part of the spectrum using contemporaneous spectra of rapidly rotating A-type stars or using the atlas of atmospheric transmission[7] made by L. Wallace, W. Livingston, and K. Hinckle (KPNO). The *IUE* spectra were similarly transformed to a uniform log λ grid (Penny et al. 1997). In prior studies of more distant O stars, we have checked the wavelength calibration by registering the positions of interstellar lines with those in the average spectrum. Regulus, however, is so close that most of the interstellar lines are too weak, and in the end we relied on the measurement of a single feature, O I λ1302, for registration, which introduces some additional scatter into our radial velocities from the *IUE* spectra.

All the radial velocities were measured using the cross-correlation method with errors estimated according to the scheme described by Zucker (2003). All the optical spectra were cross-correlated with a synthetic model spectrum taken from the work of Martins et al. (2005). This spectrum is based on a Kurucz model atmosphere for solar abundances, interpolated to $T_{\rm eff} = 12{,}200$ K and $\log g = 3.5$, which are close to average values over the visible hemisphere (McAlister et al. 2005). The model template was smoothed with a rotational broadening function to better match the actual spectrum, and in each case the model was transformed to the observed wavelength grid. Unfortunately, the models of Martins et al. (2005) do not extend to UV wavelengths, so for the *IUE* spectra we used a model UV template from the TLUSTY/Synspec models of Lanz & Hubeny (2007) for $T_{\rm eff} = 15{,}000$ K (the lowest temperature in their grid) and $\log g = 3.75$. The use of a different template for the UV spectra may introduce systematic differences from those obtained from the optical spectra, but these errors are probably comparable to the measurement errors (see § 3).

Our 168 measurements are gathered in Table 2, which lists the heliocentric Julian date of midobservation, the orbital phase (§ 3), the radial velocity and its internal error, the observed minus calculated residual (§ 3), and the run number corresponding to the observational journal in Table 1.

[6] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

[7] Available at ftp://ftp.noao.edu/catalogs/atmospheric_transmission/.

TABLE 2
Radial Velocity Measurements

Date (HJD − 2,400,000)	Orbital Phase	V_r (km s^{-1})	ΔV_r (km s^{-1})	$(O - C)$ (km s^{-1})	Run Number
43881.848	0.933	15.3	3.2	4.0	15
44333.437	0.191	9.9	2.8	2.9	15
44333.458	0.191	17.4	3.5	10.4	15
44529.050	0.068	26.1	3.7	14.8	15
45360.745	0.802	11.1	2.9	4.4	15

Note.—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.

3. ORBITAL ELEMENTS

The range in the radial velocities is larger than that expected from measurement errors, so we searched for evidence of periodic variations using the discrete Fourier transform and CLEAN method (Roberts et al. 1987) and phase dispersion minimization (Stellingwerf 1978). Both procedures identified the presence of one significant period at $P = 40.11 \pm 0.02$ days, with a power indicating a false-alarm probability of $\sim 10^{-22}$ that the peak results from random errors (Scargle 1982). This period is too long to be related to rotational or pulsational variations, so we assume that it results from orbital motion in a binary. We then derived the remaining orbit elements using the nonlinear, least-squares fitting program of Morbey & Brosterhus (1974) by keeping the orbital period fixed at the value given above. Each measurement was assigned a weight proportional to the inverse square of the larger of the measurement error or 1 km s^{-1} (to account for possible systematic errors between results from different groups of observations). Trials with other weighting schemes gave similar results. Elliptical solutions made no significant improvement in the residuals

TABLE 3
CIRCULAR ORBITAL ELEMENTS

Element	Value
P (days)	40.11 (2)[a]
T_0 (HJD − 2,400,000)	44526.3 (3)
K_1 (km s^{-1})	7.7 (3)
V_0 (km s^{-1})	4.3 (2)
$a_1 \sin i$ ($R_\odot$)	6.1 (3)
$f(M)$ ($M_\odot$)	0.0019 (2)
$(M_2 \sin i)/(1 + M_2/M_1)^{2/3}$ ($M_\odot$)	0.279 (14)
rms (km s^{-1})	2.8

NOTE.—Numbers in parentheses give the error in the last digit quoted.
[a] Fixed.

from the fit (Lucy & Sweeney 1971), so we adopted a circular fit. We present in Table 3 the standard orbital elements where T_0 is the epoch of the ascending node. Note that the error in T_0 increases to ± 3.9 days when the full range in acceptable period is considered. The derived systemic velocity V_0 is similar to the radial velocity of α Leo B of 6.56 ± 0.22 km s^{-1} (Tokovinin & Smekhov 2002), which strengthens the case for a physical connection in this common proper motion pair.

The radial velocity curve and measurements are illustrated in Figure 1. The *IUE* measurements (*open circles*) show the largest scatter around the curve, which we think derives from errors related to registering the wavelength scale with a single interstellar line (§ 2). Most of the residuals for the optical spectra have a size comparable to the measurement errors and are mainly free from systematic trends. However, several of the runs that recorded the red spectrum around Hα do have residuals that are systematically low (see run 3). We suspect that these trends are due to subtle differences in data treatment, but because these specific runs cover only a limited part of the orbital cycle, we did not apply any corrections for systematic differences.

4. DISCUSSION

The orbital variation has a small semiamplitude that eluded detection in earlier studies. Consequently, the derived mass function is also small (Table 3), and we show in Figure 2 the constraints on the possible masses from the mass function. McAlister et al. (2005) used model fits to derive a probable mass of the primary star of $M_1 = 3.4 \pm 0.2\ M_\odot$, and the boundaries of this range are indicated by the vertical dotted lines. Larger orbital inclinations are favored for random orientations, and it is possible that the orbital inclination is comparable to the spin inclination of Regulus, $i \approx 90°$ (McAlister et al. 2005). Thus, the mass of the companion may be close to the minimum mass shown (for $i = 90°$) of $M_2 > 0.30 \pm 0.01\ M_\odot$.

A companion this small may be a low-mass white dwarf or main-sequence star. If Regulus was spun up by mass transfer in an interacting binary, then the remnant of the donor star is probably a low-mass white dwarf (Raguzova 2001; Willems & Kolb 2004). Indeed, the lowest mass white dwarfs are usually found in binary systems (Marsh et al. 1995) where they lost a significant fraction of their mass, and some reach masses as low as 0.17 $M_\odot$ (Kilic et al. 2007). Models by Willems & Kolb (2004) for mass transfer during H-shell burning (their "evolutionary channel 1") often lead to remnant and gainer masses and orbital periods similar to the case of Regulus. Since Regulus and its wider companion α Leo B are not too old (<150 Myr; Gerbaldi et al. 2001), a white dwarf companion would

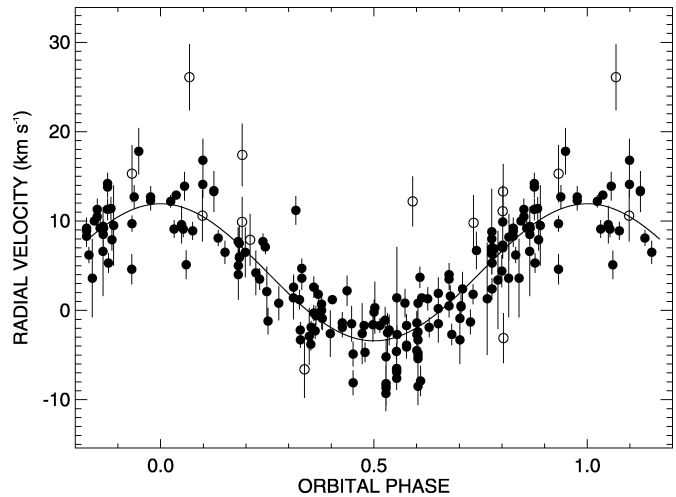

FIG. 1.—Observed and derived radial velocity curves. The open circles indicate the *IUE* UV measurements while the filled circles represent the optical spectra measurements.

not have progressed too far along its cooling track and would probably have an effective temperature >16,000 K (Althaus et al. 2001), much higher than that of the primary B7 V star. Consequently, we might expect to observe a modest FUV flux excess if the companion is a white dwarf, and, in fact, Morales et al. (2001) find that the spectral energy distribution of Regulus is about a factor of 2 brighter in the 1000–1200 Å range than predicted by model atmospheres for a single B7 V star. We note for completeness that a neutron star companion is probably ruled out because it would require a very small inclination (see Fig. 2) and an unlikely evolutionary scenario in which only a modest amount of mass transfer occurred before the supernova explosion (no more than the present mass of the primary).

On the other hand, the companion could be a low-mass, main-sequence star (making Regulus one of the most extreme mass ratio binaries among the massive stars after exclusion of the massive X-ray binaries). Adopting the minimum mass, the companion would be an M4 V star that would be too faint to alter significantly the spectral energy distribution from that for the primary alone (see Fig. 4 in McAlister et al. 2005). It is very unlikely that the companion is the outer component of a

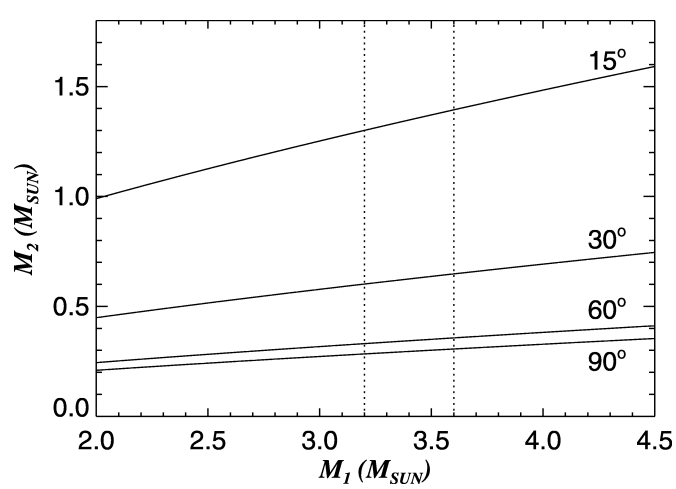

FIG. 2.—Mass diagram constraints for the mass of Regulus (M_1) and its faint companion (M_2). Each solid line gives the relation from the mass function for the orbital inclination indicated on the right-hand side. The vertical dotted lines show the probable mass range for Regulus (McAlister et al. 2005).

once compact triple system. If the fast spin of Regulus is the result of prior mass transfer, then an M4 V star in the orbit we find would have been too close to the central binary for orbital stability (and would have likely been ejected or become a merger product). Thus, in binary models for rapid rotation, the companion cannot be a low-mass main-sequence star but must be the remnant of the donor.

The angular separation of the binary is probably small. If we assume masses of $M_1 = 3.4\ M_\odot$ and $M_2 = 0.3\ M_\odot$, then according to Kepler's third law, the semimajor axis is 0.35 AU. Thus, for a distance of 24.3 pc, the maximum angular separation will be approximately 15 mas, too small for detection by speckle interferometric or adaptive optics techniques. The binary could be resolved in principle by lunar occultation methods or optical long baseline interferometry, but the fact that there is no evidence of a binary from these methods is consistent with the expected faintness of the companion (Hanbury Brown et al. 1974; Radick 1981; Ridgway et al. 1982; McAlister et al. 2005). For example, the magnitude difference in the K-band is probably close to $\Delta m \approx 10$ and 6 mag for the cases of a white dwarf and an M4 V star companion, respectively. Thus, the flux of the companion has no influence on the analysis of the interferometry presented by McAlister et al. (2005).

Our study has led to the discovery of a binary companion to the 22nd brightest star in the sky, and it may, like Sirius, offer another example of a bright star that is orbited by a faint white dwarf. If the companion is a white dwarf, then it may be the closest case of a star stripped to its core by mass transfer in a close binary. The best opportunity to test the white dwarf hypothesis will come from very short wavelength observations where a hot companion may outshine the B7 V primary.

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