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Fundamental Parameters of Intermediate and High Mass Stars

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Abstract. Knowledge of the fundamental stellar properties: mass, radius, effective temperature and wind mass-loss rate are essential for constraining models of the late stages of evolution. The only accurate, fundamental method is to determine these parameters from binary stars but this has been done for few binaries — and no red supergiants — to the accuracy needed to significantly constrain models. We seek to determine the masses of red supergiant (RSG) stars in massive binaries accurate to 1%. In detached RSG binaries, the component stars evolve independently and the (lower mass) companions are still on the main sequence as B or A stars. To determine accurate orbits of the supergiant primaries, radial velocity observations of $\sim$50 detached RSG binaries have been carried out at the DAO 1.2m McKellar Telescope over the past decade. The early-type spectra of the companions are nearly featureless in the optical, and furthermore, these spectra must be separated from those of the brighter RSG primary. Therefore, it is advantageous to use the companion's spectrum in the ultraviolet (UV) to determine radial velocity shifts. Eclipsing binaries are especially useful because stellar masses can be found from analyses of the eclipse light curve and spectroscopy alone. We present preliminary analyses of fundamental parameters of three red supergiant eclipsing binary systems for which HST/GHRS and STIS high-resolution UV spectroscopy is available: ζ Aur, HR 2554, and VV Cep.

1. Introduction

The only fundamental way to determine stellar masses is by using binaries but, to date, no red supergiants (or bright giants) have masses determined to the 1% accuracy needed to significantly constrain evolutionary models. To address this situation, PDB has carried out radial velocity observations of $\sim$50 RSGs in binaries at the DAO 1.2m McKellar Telescope over the past decade. These

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binaries are primarily high-declination, detached G-M bright giant or supergiant systems with B or A-type main-sequence companions. Typical orbital periods are 1–10 years. Currently, about 10,000 stellar spectra of the program stars have been obtained in the red near Hα. Phase coverage over at least one orbital period is available for most of the DAO binaries. The spectral region was chosen to use O_2 telluric lines near 6300 Å as a velocity fiducial, giving a radial velocity precision of $\sim$100 m s^{-1} per observation, and K_1 accurate to $\sim$30 m s^{-1}. Orbital inclinations can not be found spectroscopically, and additional information, usually from interferometry or astrometry, is required. Observations with the Navy Prototype Optical Interferometer (NPOI) are planned to determine orbital inclinations. A few of the DAO binaries eclipse, and for these favored systems, orbital inclinations can be found from analysis of the eclipse light curve and spectroscopic orbits alone (primary orbit plus K_2 of the secondary orbit). With the primary spectroscopic orbit known, a small number of observations of the secondary's radial velocity, precise to $\sim$1 km s^{-1}, and well-separated in orbital phase, suffice to yield the desired solution. This velocity precision is attainable with HST/GHRS or STIS echelle spectroscopy, provided interstellar lines are used as velocity fiducials.

Analysis of the full DAO dataset is not yet complete. In this paper, we report on preliminary analyses incorporating HST/GHRS and STIS UV spectroscopy[2] for the three RSG binaries ζ Aur, HR 2554, and VV Cep.

2. ζ Aurigae

This eclipsing binary (K4 Ib + B5 V, $P = 2.66$ yr) is the brightest eclipsing K supergiant ($V = 3.75$) in the sky, and the binary which we have studied most intensively. The mass loss rate is $\dot{M} \sim 10^{-8} M_\odot$ yr^{-1}, and wind accretion effects are minimal in the UV spectrum. Therefore, the observed UV spectrum is essentially that of the B star's photosphere with spectral line absorption along the line of sight to the hot star, and scattering of hot star photons back into the line of sight by the primary RSG's wind, superimposed on the stellar spectrum. This binary is an excellent candidate for accurate mass determination, and several useful observation epochs exist in the HST archives. These HST data were used by Bennett et al. (1996), along with a revised primary orbit from Griffin (1995), and an analysis of the eclipse light curve to determine stellar masses accurate to 3–4%. The radial velocity semi-amplitudes used in this analysis were: $K_1 = 23.35 \pm 0.14$ km s^{-1} (Griffin 1995) and $K_2 = 28.2 \pm 0.6$ km s^{-1} (Bennett et al. 1996).

Archival UV observations using HST/GHRS, along with proposed observations with HST/STIS, will determine K_2 to 200 m s^{-1}. Analysis of the full DAO dataset will yield K_1 to 50 m s^{-1}. Combined, these analyses will determine masses accurate to 1%.

[2]Based on observations with the NASA/ESA Hubble Space Telescope obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Incorporated, under NASA contract NAS5-26555

3. HR 2554

This southern binary (G6 II + A1 V, $P = 195\,\mathrm{d}$), with an orbital solution dating from Wilson & Huffer (1918), was only recently discovered to be eclipsing by Ake & Parsons (1987). Although one of the few, bright eclipsing RSG binaries in the sky, it has received surprisingly little attention in recent years. The analysis of Brown et al. (2001) yielded an accurate primary orbit with $K_1 = 24.29 \pm 0.03$ km s^{-1} from precise radial velocity observations of the optical spectrum, and $K_2 = 38.6 \pm 1.1$ km s^{-1} from HST/GHRS observations of the UV spectrum. The resulting stellar mass determinations of $M_1 = 3.14 \pm 0.17\,M_\odot$ and $M_2 = 1.98 \pm 0.11\,M_\odot$ are accurate to 5%. Since essentially all of the error in these determinations arises from uncertainties in the secondary's radial velocity amplitude, reducing the uncertainty in K_2 to 200 m s^{-1}, as planned from proposed HST/STIS observations, will yield masses accurate to 1%.

4. VV Cephei

VV Cephei (M2 Iab + B0.5V, $P = 20.3$ yr) is the brightest ($V = 4.90$), eclipsing M supergiant binary in the sky. We have obtained extensive HST/STIS observations of the UV spectrum of VV Cep extending over 1/3 of an orbital period from mid-eclipse in late 1997 through quadrature in 2003 and beyond. VV Cep is of particular interest because: (i) the supergiant primary is a close spectral proxy to that of the well-studied α Ori, and (ii) as a binary, the fundamental stellar parameters, in principle, may be accurately determined. However, the high mass loss rate of $1.5 \times 10^{-6} M_\odot$ yr^{-1} makes such determinations difficult because of absorption of the companion's B-type spectrum by the RSG's massive stellar wind. Furthermore, there appears to a significant, and variable, source of UV continuum flux in addition to that of the B star. Because the secondary's spectrum can not be cleanly separated from the observed UV spectrum, direct radial velocity analyses of the companion are not feasible.

The optical spectrum of VV Cep is that of a normal M2 supergiant but with the Balmer lines in emission. The primary has a well-established radial velocity semi-amplitude of $K_1 = 19.4$ km s^{-1} (Wright 1970). The emission at Hα is extremely prominent, with a peak flux several times that of the surrounding continuum. The Hα emission does not follow the velocity of the supergiant primary, but moves in an opposite sense, suggesting the emission originates from or near the B star. Assuming the Hα emission traces the motion of the hot companion, Wright (1977) found a radial velocity semi-amplitude of $K_2 = 19.1$ km s^{-1} for the B star. The Balmer emission, with the exception of Hα, vanishes during eclipse. The Hα emission decreases but remains present throughout total eclipse, with the (emission) equivalent width at mid-eclipse being an order of magnitude less than the out-of-eclipse value. The Balmer emission must originate from a region immediately around the B star; for Hα, this emission region is sufficiently extended that part of it remains weakly visible at mid-eclipse.

The spectral energy distribution (SED) of the supergiant, corrected for interstellar extinction of $A_V = 1.24$, is fitted by models of Lejeune, Cuisinier, & Buser (1997) to obtain the effective temperature and angular diameter: $T_{\mathrm{eff}} = 3830$ K, and $\theta_D = 6.38$ mas. The times of ingress and egress establish the size of the angular orbit, since then the separation of stellar centers equals the supergiant's angular radius. A single degree of freedom remains: the unknown value of the orbital inclination. An inclination of $i = 90°$ gives central eclipses and the largest orbit: $a = 21.7$ mas. Decreasing inclination results in projected orbits that eventually graze the supergiant's pole while closely following the stellar limb. These rather pathological orbits have smaller a and shallow central eclipse depths. The disappearance of the higher Balmer lines, and the sharp reduction in Hα emission at mid-eclipse, implies that the eclipse is not grazing and must have significant depth at mid-eclipse. Assuming a minimum mid-eclipse depth of $0.10\,R_1$ (R_1 = supergiant radius) implies a minimum orbit size of $a \sim 10$ mas for $i \sim 77°$. Therefore, Wright's (1977) value of $i = 76.7°$, from Hutchings & Wright's (1971) analysis of the Hα emission profiles, lies at the low end of the probable range of inclinations. Lacking any further information on the inclination, we adopt a value near the mid-point of the allowed range: $i = 84° \pm 4°$, which implies an angular semi-major axis of $a = 16 \pm 4$ mas.

Then, the mass ratio $M_2/M_1 = 1.02$, with individual stellar masses of $M_1 = 18.2\,M_\odot$ and $M_2 = 18.6\,M_\odot$, and an orbit size of $a = 24.8$ A.U. Comparison of the linear and angular orbits gives a distance of 1.5 ± 0.4 kpc, and a supergiant radius of $R_1 \sim 1000\,R_\odot$. While useful, these values are hardly accurate determinations. Better results are badly needed for the secondary orbit and the orbital inclination.

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