Big-Game Hunting: Massive Binaries in 30 Dor

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Abstract. We present results from a search for massive binaries in and around 30 Dor in the LMC, completed using multifibre spectroscopy and complemented by short- exposure photometric monitoring over a ten-day period. We find 21 binaries with $V < 15.0$, consistent with predictions based on Galactic studies of O stars. We also report on our most massive binary system, whose spectral type can be conservatively given as O4 V+O4 V. Spectroscopy, through radial-velocity variations, and photometry, through geometrical considerations of the variable light-curve observed, yield a lower bound for the mass of a O4 V star of $45M_{\odot}$.

1. Introduction

The upper limit of the stellar masses, M_u, is one of the most fundamental, yet elusive, parameters of early-type stars. Because of the dependence of such phenomena as mass loss, luminosity, and chemical enrichment on the mass of a star, particularly at the higher end of the mass spectrum, knowledge of M_u is of fundamental importance to the study of starbursts, stellar population synthesis, the IMF, stellar evolution, and galactic history, through the constraints it puts on evolutionary models of massive stars.

To this day, the most robust, model-independent methods of determining stellar masses remain radial-velocity measurements coupled with either photometric or polarimetric determinations of the inclination of the system's orbital plane to the line of sight. Unfortunately, direct observations of stars with masses above $40M_{\odot}$ are quite rare; in fact, only a single binary system has yet been found with individual masses exceeding $60M_{\odot}$ ($72M_{\odot}$, for the WN7 star HD 92740 in the Carina binary; Rauw et al. 1996). Even HD 93205, which contains an O3 V star, does not include a component whose mass exceeds this value.

If one foregoes the security of newtonian mechanics, it is also possible to determine the mass of early-type stars through methods that avoid the necessity of dealing with binary objects, thus circumventing the difficulty of the small number of very massive binaries found. These methods are:

- Spectral synthesis, as described by Kudritzki (1990), giving $T_{\rm eff}$ and $\log g$, which, when combined with estimates of a star's absolute luminosity and distance, from which R_*, the radius of the star, can be obtained, give *spectroscopic masses;*

- Stellar-wind theory which, by establishing the $\dot{M}$–M relation, allows the determination of the mass of a star through measurement of its mass loss, giving *stellar-wind masses;* and

- Comparison of evolutionary models with observational HR diagrams, which give *evolutionary masses.*

Unfortunately, while spectroscopic and stellar-wind mass predictions agree fairly well with each other, there still exists significant disagreement between those and the predictons of evolutionary masses (Herrero et al. 1992). While this mass discrepancy is more pronounced for evolved stars, it is also seen in some cases of early-type stars on the main sequence.

Furthermore, while for main-sequence stars with masses below $M \simeq 40 M_{\odot}$, stellar evolution theory and observations agree fairly well – the mass–luminosity relation, $L \propto M^{\alpha}$, is well known, with index $\alpha \sim 3$ (e.g., de Jager (1980) – for stars above $40 M_{\odot}$ the situation is unclear; theory suggests that $\alpha \rightarrow 1$ as radiation pressure increasingly dominates the structure of the most massive stars, for which the upper mass limit is claimed to be $M_u \simeq 100$–$120 M_{\odot}$ (e.g., Maeder and Meynet, 1989) or even $200 M_{\odot}$ (e.g., Walborn 1986) based on the theoretical $M \rightarrow L$ conversion, and comparisons with direct mass measurements through radial-velocity observations is hampered by the very small number of very early-type binaries found.

Clearly there is a need to increase the number of known binaries which contain very early-type stars. To reach that goal, we investigated a selection of the brightest, bluest stars of the closest starburst region known in the local group: 30 Dor, in the LMC. The stellar density and young age (but see Walborn & Blades 1997 and Walborn & Barbá 1998 for a discussion of the stellar birth history of this complex) and relative proximity of 30 Dor make it a natural target for the simultaneous observations of large numbers of early-type stars, through either multi-slit or multi-fibre spectroscopy, and a potentially rich niche of massive binaries.

2. Observations

We observed 30 Dor at three epochs from January 1993 to October 1996, using the CTIO Victor Blanco 4-m Telescope and the ARGUS prime-focus multi-fibre spectrograph equipped with the Blue Air Schmidt Camera and 1Kx3K detector. The effective 3-pixel resolution thus reached was 2.8Å. In 1993, during four consecutive nights, we secured typically one spectrum per night of each of our 75 brightest candidates, selected for their brightness and position in the upper-left region of the HR diagram. In January and October 1996, we completed the observations of blue stars with $V < 15$, obtaining in particular several observations each night of the most promising early-type binaries identified during January 1993.

In parallel to the spectroscopic observations, we photometrically monitored our field for ten straight nights in December 1995, mainly for eclipsing variables, using the CTIO 0.9-m telescope equiped with a TeK 2K×2K CCD and 4650-190 blue filter.

3. Results

- In 30 Dor, we have found at least 21, and possibly as many as ∼40, spectroscopic binaries brighter than $V = 15.0$ (the exact number depending on final analysis of the 1996 data), consistent with our previous estimate based on Galactic studies of field O stars (Garmany et al. 1980), where we had expected to find some 34 SB2 systems with periods $P < 10$ days.

- In this paper, we present the most massive binary found in our sample, star 1-98 of Schild & Testor's catalogue of stars in the 30 Dor complex (Schild & Testor (1992)), which they identified as O5 V((f)). Intense monitoring has allowed its reclassification as a very early-type binary exhibiting dramatic radial-velocity changes on timescales of a few hours. Orbital and physical parameters are shown in Tables 1 and 2, respectively. Radial-velocity and differential-magnitude curves, obtained with a 4650-190 filter, are presented in Figs. 1 and 2, respectively.

Table 1. Orbital elements of the early-type binary ST1-98.

	K (km/s)	$P_{\rm orb}$ (days)	T_0 HJD − 2448000	ω °	e
			Individual fits		
Primary	220 ± 4	$1.85554 \pm .00002$	$901.09 \pm .05$	$12.2 \pm .2$	0.07 ± 0.01
Secondary	214 ± 3	$1.85540 \pm .00003$	$901.20 \pm .05$	$10.6 \pm .2$	0.08 ± 0.01
			Combined-data fit		
Primary	217 ± 4	$1.85543 \pm .00002$	$901.140 \pm .03$	11.0 ± 0.2	$0.07 \pm .01$
Secondary	214 ± 4				

Table 2. ST1-98 physical parameters

	$a \sin^3 i$ ($R_\odot$)	$M \sin^3 i$ ($M_\odot$)
Primary	8.1 ± 0.1	7.9 ± 0.1
Secondary	7.9 ± 0.1	8.0 ± 0.1
System	16.0 ± 0.2	15.9 ± 0.2

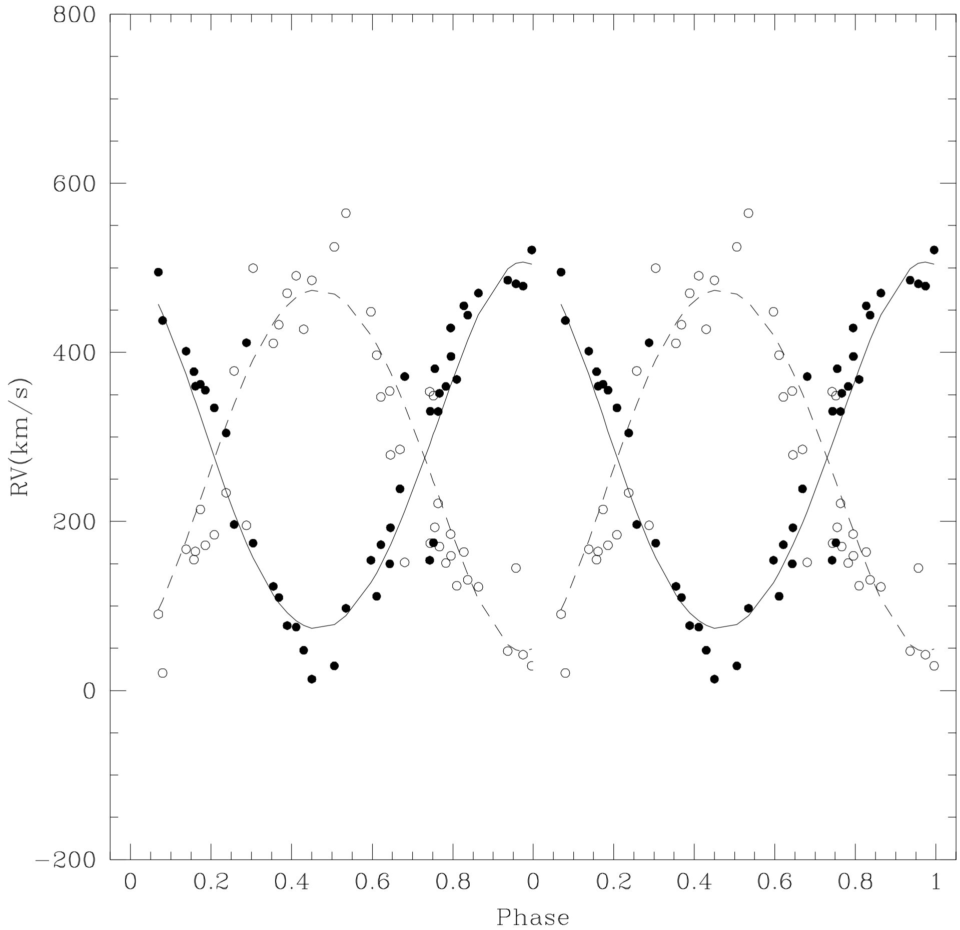

Figure 1. Radial-velocity variations for ST1-98. Phases were computed using the 'combined fit' results from Table 1.

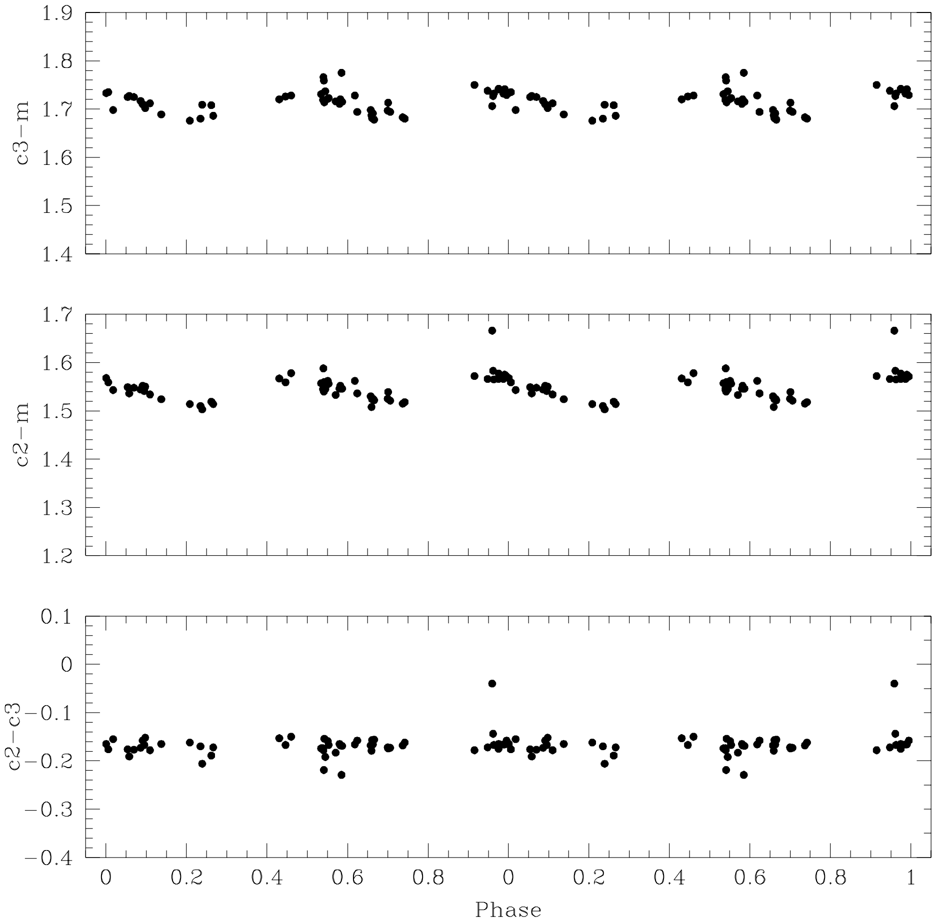

Figure 2. Brightness variations vs. phase, ϕ, computed as in Fig. 1. Notice the very slight double modulation of the brightness of ST1-98 and the fact that light minima occur at $\phi = 0.25$ and $\phi = 0.75$, as expected from the radial-velocity curves. The total brightness variation is 0.06^{m}, which would imply that, if these modulations are due to eclipses, then said eclipses are at best grazing. We can use this result to put an upper bound on i, the inclination of the system, and as a consequence a lower bound on the mass of the system can be determined; conservative assumptions, classifying ST1-98 as a O4 V+O4 V system and allowing for grazing eclipses, would, building on Howarth & Prinja (1989), who give $R = 12R_{\odot}$ for an O4 V object, and taking into account the projected separation between the components, indicate a lower bound for this system's mass of $90M_{\odot}$.

4. Discusssion

We find that ST1-98:

- Shows very slight, but significant, phase-related, modulation in brightness.
- Light minima occur at $\phi = 0.25$ and $\phi = 0.75$, as expected from RV analysis.
- The total brightness variation is 0.06^{m}, which would imply that, if those modulations are due to eclipses, then said eclipses are at best grazing.
- From this fact, combined with classifying ST1-98 as a O4 V+O4 V system and using data from Howarth & Prinja (1989) for R_*, we can put an upper bound on the inclination of the system: $i < 33°$.
- This naturally implies a lower bound for ST1-98's mass of $90 M_\odot$, or $M(\mathrm{O4\,V}) > 45 M_\odot$.

References

de Jager, C., 1980, The Brightest Stars (Reidel, Dordrecht)

Garmany, C. D., Conti, P. S., Massey, P., 1980, ApJ, 242, 1063

Herrero, A., Kudritzki, R. P., Vilchez, J. M., Kunze, D., Butler, K., Haser, S., 1992, A&A, 261, 209

Howarth, I. D., Prinja, R. K., 1989, ApJS, 69, 527

Kudritzky, R. P., 1990, in Properties of Hot Luminous Stars (ASP Conf. Series, Vol. 7, ed. C. D. Garmany (ASP, San Francisco), p. 63

Maeder, A., Meynet, G., 1989, A&A, 210, 155

Rauw, G., Vreux, J.-M., Gosset, E., Hutsemekers, D., Magain, P., Rochowicz, K., 1996, A&A, 306, 771

Schild, H., Testor, G., 1992, A&AS, 72, 729

Walborn, N. R., 1986, in Luminous Stars and Associations in Galaxies (IAU Symp. 116), eds. C. W. H. de Loore, A. J. Willis & P. Laskirides (Kluwer, Dordrecht), p. 185

Walborn, N. R., Blades, J. C., 1997, ApJS, submitted

Walborn, N. R., Barbá, R. H., 1998, in Boulder-Munich II: Properties of Hot, Luminous Stars (ASP Conf. Series, Vol. 131), ed. I. D. Howarth (ASP, San Francisco), p. 336