Fundamental Parameters from O-Type Binaries

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Abstract. We describe the methods and results of a study of O-type binaries, undertaken with the goal of determining their fundamental parameters and evolutionary states. Cross-correlation analysis is used to determine improved orbital parameters, to constrain the flux ratio, and to determine the projected rotational velocities. Doppler tomography is used to separate the individual component's spectra from a collection of composite spectra distributed in orbital phase. These spectra are then classified to enable estimates of effective temperatures and gravities . The binaries chosen for this study are members of clusters, and cluster photometry is used (along with $T_{\rm eff}$, $\log g$, and the flux ratio) to place the individual stars on an HR diagram and to compare with evolutionary-track predictions. Further work is required to incorporate information from any light variations the systems show. This work provides much-needed constraints on the masses of the individual stars.

1. Introduction

The most basic parameter of a star is its mass, and to determine this parameter the most direct observational means is through the study of binaries. This is particularly important at this time in terms of resolving the 'mass discrepancy', where masses determined from evolutionary tracks and those from atmospheric analyses seem to differ by possibly a factor of 2 or more for Of type stars (Hererro et al. 1992; Puls et al. 1996). To determine the masses in a binary system is not so easy, however.

The advantage of close spectroscopic binaries is their relative speed in orbiting one another, allowing for complete observation of their orbital motion. Also, the spectra can allow the determination of the individual spectral classifications. However, the best spectroscopic oribit will still not give the actual masses of the stars. For this, some other observations constraining the inclination of the orbit is needed. The chance coincidence of a close binary's orbital plane with the line of sight, so that eclipses will occur, is rare. This is a particular problem for massive stars, as massive stars are themselves rare. If we must also have a rare orientation in the sky, we find ourselves with a limited sample.

The study of close spectroscopic binaries is, in practice, problematic. Double-lined spectra are often plagued by line-blending problems and distortion from circumstellar emission (Popper 1980). This can make the determination of orbital velocities, individual spectral classes, and the flux ratio extremely difficult. Although most of these spectroscopic binaries do not exhibit eclipses, many are tidally distorted by their companions. These distortions can lead to photometric variations ('ellipsoidal' variations) that are dependent on their orbital inclination (as well as radii). The range of inclinations that will allow for these small variations is often quite large, however. The most disturbing point about these variations is that they indicate distortions of the stars within their Roche surfaces. This creates the possibility that one or both of the stars is in Roche-lobe overflow (RLOF). Since the observationally-determined masses are needed to test the accuracy of single-star theory, this possibility can make these hard-fought-for masses hard to interpret.

Here we describe a project which has the goal of determining the fundamental parameters and evolutionary status of O-type binaries. We advocate the use of a Doppler-tomography algorithm which shows great promise as a means of extracting the individual component's spectra from a collection of IUE spectra, distributed in orbital phase. The analysis of these individual component's spectra allows the derivation of spectral types for the primary and secondary without the blending effects present in the composite spectra. The ratio of the intensity in cross-correlation functions of the system allows us to place limits on the UV intensity ratio of the two stars.

Cross-correlation techniques also minimize the line-blending effect in determining the orbital velocities. Through these we obtain individual spectral types, UV intensity ratios, and data on the projected rotational velocities of each star. As the binaries are also members of star clusters, these types of data can be combined with the total absolute magnitude to derive radii, and, with the derived individual radii and temperatures, it is then possible to make a critical comparison of theoretical models for binary evolution with observed positions in a Hertzprung-Russell diagram (HRD) of luminosity and temperature. We also advocate the use of photometric variations as a critical constraint on the individual masses and evolutionary status.

2. Tools

2.1. Cross-Correlation

Cross-correlation of a double-lined composite spectrum with a narrow-lined template spectrum will result in a double-peaked cross-correlation function (ccf). The peaks of the function will be shifted in radial velocity with respect to the radial velocity of the template star. To measure these shifts, the locations and widths of the cross-correlation peaks, and their intensity ratio, are determined. If the radial velocity of the template star is known, absolute radial velocities of the individual stars are obtained. This technique can be utilized for all the composite spectra of a binary system. Stickland and collaborators (Stickland & Lloyd 1988 and references therein) have shown that IUE spectra can be used to provide better-defined velocity curves of spectroscopic-binary systems, since many of the UV photospheric lines are high-energy transitions formed deep in the atmosphere and are relatively immune to contamination by circumstellar emission.

The widths of the cross-correlation peaks can also be used to determine the projected rotational velocities of the two stars. This is done by analyzing the cross-correlation peak widths of stars with known projected rotational velocities and determining a calibration of ccf peak width to $v_e \sin i$ (Penny 1996). Furthermore, the relative strengths of the two peaks in the ccfs can be related to the UV flux ratio by using numerical experiments.

2.2. Doppler Tomography

Doppler tomography is an iterative algorithm developed to solve for the individual spectra of a double-lined spectroscopic binary from an ensemble of composite spectra. Tomography is used in medical applications for imaging a 3-D object by moving around the object and gathering 'slices' at many different view angles. For the purpose of separating a double-lined spectroscopic binary spectrum, the object can be imagined to be a luminous 'object' two pixels thick by n pixels long, where n is the number of pixels per spectrum (or two $1 \times n$ spectral 'objects' bonded together). Due to the radial-velocity differences of the stars, a number of viewing angles are generated for tomography, in which parallel rays traverse the object and impinge on a detector, producing the observed spectra at a given orbital phase. Bagnuolo et al. (1992) have shown that good spectral separations can occur provided that the binary has an adequate radial-velocity shift (roughly 30% of the FWHM of the photospheric lines, even with the poor S/N inherent to IUE spectra). The 'first-guess' spectra are usually taken to be featureless, and a satisfactory convergence is typically reached after 40 iterations. Thaller et al. (1995) have commented on some limitations of the algorithm previously, but we note here that strong wind features, such as the P-Cygni lines, may be reconstructed incorrectly, since their radial-velocity curves can be very different from those associated with the stars themselves. For example, Gies (1995) has shown that the blue absorption edge of P-Cygni lines in the spectra of many O binaries remains approximately constant throughout the orbital cycle. Since the tomographic reconstruction is based on orbital Doppler shifts, the reconstruction will be ambiguous in the vicinity of such wind features.

2.3. Spectral Classification

The method adopted for estimating the spectral types and luminosity classes of the individual components of the binary is presented by Penny et al. (1996). Basically, we use the equivalent widths of photospheric lines to estimate the spectral type (7 lines and 2 line ratios) and luminosity class (1 line) based on calibrations that rely on optical spectral classifications. In classifying a spectrum, the spectral line for each criterion is inspected interactively to assure an accurate measurement of equivalent width (by checking the local rectification and the integration limits). Not all the criteria can be applied in every case, because some lines become too weak at the temperature extrema found in the earliest and latest O-type stars and because in some cases the lines are too blended for reliable measurement. An additional luminosity criterion is based on the appearance of the Si IV $\lambda\lambda$1394, 1403 doublet in the composite spectrum. Walborn & Panek (1984) show how this feature ranges from strong absorption in main-sequence stars to strong P-Cygni emission in the supergiants, and thus the appearance of this feature is a sensitive indicator of luminosity class. However, as noted above, the tomographic reconstructions may be poor in the vicinity of the P-Cygni lines because of their non-orbital radial-velocity behavior. This difficulty does not exist in the composite spectra, where the appearance of the combined Si IV profile can be used to test for the presence of a luminous star as at least one member of the binary.

3. Placement in the HRD

In this section we will show three examples of systems once they have been placed on a HR diagram, but which do not yet have an inclination estimate. We will show that, although some analysis can be accomplished, many questions remained unanswered at this stage.

3.1. HD 93205

The spectral types (O3 V + O8 V), along with upper and lower estimates, correspond to temperatures (from Howarth & Prinja 1989) of $T_{\rm eff}({\rm p}) = 49{\pm}2.0$ kK and $T_{\rm eff}({\rm s}) = 36.5 \pm 2.5$ kK. HD 93205 is a member of the cluster Tr 16 (Humphreys 1978); Massey & Johnson (1993) obtained UBV photometry of this cluster and its neighbour Tr 14, and found distance moduli for both of $12.55^{\rm m}$, $E(B-V) = 0.40$, and a composite V magnitude of 7.76 for HD 93205. Walborn (1995) reinterpreted their observations for the case of the two clusters having differing distances, and gives a distance modulus for Tr 16 of $12.135^{\rm m}$. Adopting Walborn's distance, and Massey & Johnson's V magnitude and reddening, we find individual luminosities of $\log{(L/L_\odot)} = 5.85 \pm 0.12$ and 4.74 ± 0.35 for the primary and secondary, respectively. The calculated radii of the two stars are $R_{\rm p} = 11.7 \pm 2.1$ and $R_{\rm s} = 5.9 \pm 3.7 R_\odot$. Masses from the evolutionary tracks are 69.4 ± 6.0 and $22.0 \pm 2.5 M_\odot$.

The anomaly in the system is the mass ratio. The spectroscopic orbit of Stickland & Lloyd (1993) results in a mass ratio $q = M_2/M_1 = 0.44 \pm 0.02$. Stickland & Lloyd note that a secondary spectral type of O8 V would imply a more extreme (lower) mass ratio than given by their spectroscopic results. They suggest that a secondary spectral type of O6.5 V would be more consistent with the observed mass ratio. However, we have confirmed the secondary spectral type of O8 V (from Conti & Walborn 1976), and the resulting evolutionary mass ratio suggests $q = 0.31 \pm 0.04$. The secondary could be appearing both underluminous and cooler than its mass would imply, due to some pre-main-sequence effect. Alternatively, the theoretical predictions for the most massive stars may be in error, and the mass of the primary obtained from the evolutionary tracks may be too large. Without an estimate of the inclination, it is difficult to determine the cause of this discrepancy.

3.2. HD 149404

The spectral types (O8 I + O6.5 III), along with upper and lower estimates, correspond to temperatures of $T_{\rm eff}({\rm p}) = 32 \pm 1.0$ kK and $T_{\rm eff}({\rm s}) = 39 \pm 3.0$ kK. HD 149404 is a member of the cluster Ara OB1. Humphreys (1975) quotes UBV photometry of this cluster and gives a distance modulus of $10.7^{\rm m}$, $E(B-V) = 0.59$, and a composite V magnitude of 5.50 for HD 149404. Using Humphrey's magnitudes, we find individual luminosities of $\log(L/L_\odot) = 5.73 \pm 0.09$ and 5.74 ± 0.15. The radii of the two stars are then $R_\mathrm{p} = 23.8 \pm 3.1$ and $R_\mathrm{s} = 16.2 \pm 4.2 R_\odot$. Comparison with the single-star evolutionary tracks by Schaller et al. (1992) leads to $M_\mathrm{p} = 43.7 \pm 5.3$ and $M_\mathrm{s} = 49.3 \pm 12.0 M_\odot$. Massey & Conti (1979) suggested that the primary (which is less massive) was filling its Roche lobe and hence losing mass, becoming less massive than its companion. The primary appears to be further evolved than its companion (evolutionary ages of 3.4 ± 0.2 Myr and 2.6 ± 0.6 Myr, respectively, as well as the spectral classifications). It is also lying on an evolutionary track of lower ZAMS mass than the secondary (implying that it has always been the less massive). This seems improbable; the primary is more evolved, so it must have started as the more massive star (barring tidal capture). This situation seems to suggest that the primary is in RLOF; however, without an estimate of inclination, the true separation of the two stars is not known. It is not possible to determine if the evolutionary masses are the correct masses, or if one or both of the stars in currently in RLOF.

3.3. HD 152248

The spectral types (O7 I + O7 I), along with upper and lower estimates, correspond to temperatures of $T_\mathrm{eff}(\mathrm{p,s}) = 36 \pm 1.5$ kK. HD 152248 is a member of Sco OB1 (NGC 6231); Perry, Hill & Christodoulou (1991) performed UBV photometry of this cluster and found a distance modulus of 11.55^m, $E(B-V) = 0.44$, and a composite absolute V_0 magnitude of 4.75 for HD 152248. From this we find individual luminosities of $\log(L/L_\odot) = 5.72 \pm 0.08$ and 5.71 ± 0.08, and radii of 18.5 ± 2.4 and $18.3 \pm 2.4 R_\odot$. The two stars have almost identical positions in the HRD. The masses from the evolutionary tracks are $M_\mathrm{p} = 45.7 \pm 5.5$ and $M_\mathrm{s} = 45.2 \pm 5.5 M_\odot$, with ages of 3.0 ± 0.3 Myr each. These ages are in good agreement with the cluster age noted by Stickland et al. (1996; $\sim$3 Myr). The spectroscopic mass ratio, 1.063 ± 0.025, sets the primary as the less massive star, while the evolutionary tracks imply $q = 0.99 \pm 0.13$, with the secondary less massive, although the disagreement is not significant.

This does not, however, form substantial proof that the masses predicted by the theoretical tracks are correct. The two stars are almost identical (with a spectroscopic mass ratio of approximately unity), and their placement anywhere in the HRD will always result in a predicted mass ratio close to one. As we shall see later, the observational masses of these stars are much different from those predicted by the evolutionary tracks.

4. Light-Curves

Light-curves showing even small ellipsoidal variations provide an important constraint on the individual masses and separation. These variations are dependent on the inclination of the orbit to the plane of the sky. However they are also very sensitive to the radii of the stars and the effective temperatures. Because of this it is crucial to use all possible constraints when fitting the light-curve. These include the flux ratio, the effective temperatures, and any cluster photometry and distance modulus (which provides a constraint to the radii of the stars). All of these contain errors, of course, but any possible solution should take these constraints in mind.

4.1. DH Cephei

Small ($\sim 0.05^{\rm m}$) variations were observed by Hill, Hilditch & Pfannenschmidt (1976); Lines et al. (1986) defined a light-curve. Their preliminary fit gave an inclination in the range 45°–55°. This system has recently become very popular, being studied by Sturm & Simon (1993), Hilditch, Harries & Bell (1996), Penny, Gies & Bagnuolo (1997), and Burkholder, Massey & Morrell (1997) within the last 4 years. The orbital solutions and spectral classifications (or effective temperatures) from these studies are essentially in agreement. However, the three groups who attempted a light-curve analysis reached disparate results for the inclination and therefore masses. Both Sturm & Simon (1994) and Hilditch et al. (1996) modelled the photometric variations published by Lines et al. (1986), and both arrive at an inclination of $i = 47° \pm 1°$. However, neither of these groups used the constraint of the cluster photometry and distance modulus. In our study, although we found a satisfactory fits of the Lines et al. (1986) V-band light-curve for inclinations 39°–51°, we found that inclinations 39°–43° satisfy all the constraints from spectroscopy, photometry, and cluster distance modulus. The resultant masses are then 39–50$M_\odot$ and 35–45$M_\odot$ for the primary and secondary, respectively. These masses are in good agreement also with those from evolutionary tracks, suggesting no 'mass discrepancy'.

4.2. HD 152248

One of the systems discussed above, HD 152248, was shown by Mayer, Lorenz, & Drechsel (1992) to be an eclipsing binary with unequal minima and unequally spaced eclipses. Both of these characteristics are probably related to the eccentricity of the orbit: the minima are different because of the differing orbital separations at the two conjunctions, and the eclipse spacing is unequal because of the changing orbital velocity of the stars. The shapes of the eclipses and tidally-related ellipsoidal variation in the observed light-curve are key clues to the stellar radii and orbital inclination, and a preliminary light-curve solution is given by Penny, Gies, & Bagnuolo (ApJ, in preparation). Our results give $i \simeq 71°$, and masses of 25 ± 3 and $26 \pm 3M_\odot$, for the primary and secondary. Our analysis also indicates that both stars are essentially filling their Roche surfaces.

In Section 3.3. we stated that evolutionary tracks give masses of 45.7 ± 5.5 and $45.2 \pm 5.5M_\odot$; these evolutionary masses are too high. This indicates that some additional mass has been lost due to RLOF of both stars. Where this mass has gone is not clear. There doesn't appear to be any observational evidence of either star having a circumstellar shell or disk.

4.3. HD 93205

Photometric variations of $\sim 0.02^{\rm m}$ are currently under analysis by Antonkhina et al. (1997). An inclination estimate for this system would provide the first observational estimate for the mass of an O3 star.

4.4. HD 149404

Notes to a symposium paper by Massey & Conti (1979) indicate variations of 0.03^{m} observed by Morrison, but this work was apparently never published. Analysis of this variation would provide a means to test the current evolutionary state of this system.

5. Conclusion

Although observationally determined masses of O-type stars are problematic and difficult to obtain, they provide the best means of testing theory. The efforts made in the past 10–20 years have greatly enhanced the orbital parameters of many of the O-type binaries. However, to determine the masses light-curves must be found and modelled for these systems. In modelling these data, all constraints on the system must be utilized, including the flux ratio, the effective temperatures, synchronous rotation, cluster photometry, and distance modulii. Also, we must attempt new observations to find more early-type close binaries.

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Discussion

Langer: In HD 152248, the mass lost was as much as some tens of solar masses. I wanted to pick up Stan's argument here [p. 83], that it's not always easy to drive matter to infinity, at least with radiation (and we don't have any other mechanism); so my question is, is there any evidence for circumstellar matter here? If you can't drive it to infinity the lost mass might still be around.

Penny: Well, this is an eccentric orbit; I don't really know, but I guess it's pretty hard for the star to 'catch' this material when it's moving away from it...

Owocki: The basic point is, what is the total potential out of which you have to move the material? You have the potential of both stars here, and it's not an easy problem. You have to ask where's the energy to get the material out to infinity, compared to the binding energy of the system.

Penny: Okay... these are both O7 supergiants, so there's tremendous radiation pressure.

Hilditch: In binary-evolution models there's a parameter 'β', unrelated to the usual velocity-law exponent, which is the fraction of mass that is conserved in mass transfer, with the remainder lost from the system. A typical guesstimate is $\beta \simeq 0.5$, and we can get agreement between observations and models with that value. Of course, an unknown is the initial mass ratio, which you don't know.

Schaerer: For the system where you have the O3+O8 dwarfs [HD 93205], and a discrepancy with the mass ratio, do you also have rotational velocities?

Penny: I have $v_{\rm e} \sin i$, but not the rotation; $v_{\rm e} \sin i = 107$ and 46 km s^{-1} for the primary and secondary, respectively.
Harries: I just wanted to clarify the DH Cephei situation – I only saw your paper [Penny, Gies & Bagnuolo 1997] the day before coming to the meeting. We had another look at our light-curve, and I've plotted χ^2 as a function of inclination [showing viewgraph]; I think you'll agree there's a clear minimum there at 47°, although I admit that the errors we gave in our MN paper were too small [see p. 401].
Penny: The main difference between our inclinations arises because we've put some weight into the absolute magnitude from the cluster membership, which, with the reddening, gives a radius that you need to match.
Harries: Well, even if membership were certain, the cluster distance might well have an uncertainty of half a magnitude.