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Multiplicity in 5 $M_\odot$ Stars

Nancy Remage Evans[1]

[1] Smithsonian Astrophysical Observatory

Abstract: Multiwavelength opportunities have provided important new insights into the properties of binary/multiple 5 $M_\odot$ stars. The combination of cool evolved primaries and hot secondaries in Cepheids (geriatric B stars) has yielded detailed information about the distribution of mass ratios. It has also provided a surprisingly high fraction of triple systems. Ground-based radial velocity orbits combined with satellite data from Hubble, FUSE, IUE, and Chandra can provide full information about the systems, including the masses. In particular, X-ray observations can identify low mass companions which are young enough to be physical companions. These multiwavelength observations provide important tests for star formation scenarios including differences between high and low mass results and differences between close and wide binaries.

1 Introduction

The multiplicity of stars provides important clues to star formation processes, and in some cases is the most important determinant of their future. For 5 $M_\odot$ stars, multiwavelength observations have provided detailed information about their multiplicity and also their binary/multiple properties. Specifically Cepheids (post-main sequence He burning stars in the "blue loop" phase of evolutionary tracks) can be used to provide such information in novel ways.

1.1 Multiplicity

Because these cool supergiants often have hot main sequence companions, ultraviolet spectra (HST and IUE) provide a spectrum of the companion uncontaminated by the light of the primary (Evans 1995). This has been used to determine Cepheid masses (Evans et al. 2005, and references therein). It has also been a particularly valuable way to identify systems which are not simply binaries, but triple systems (Evans, et al. 2005). In fact, without some direct information about the secondary, one cannot be confident in general that a system contains only two stars.

Triple systems among Cepheids have been identified in many ways (see Evans, et al. 2005). W Sgr provides one example. It was known both to be a binary system with an orbit (Babel et al. 1989) and to have a hot companion (Böhm-Vitense & Proffitt 1985; Evans 1991). However, the combination was not consistent with a reasonable mass for the Cepheid (see Evans, Massa & Proffitt 2009). The solution came from an HST STIS (Space Telescope Imaging Spectrograph) spectrum (Fig 1). The hottest star in the system is resolved from the Cepheid and its spectroscopic binary companion. This new insight results in a reasonable upper limit to the Cepheid mass from the astrometric orbit of the Cepheid (Benedict et al. 2007).

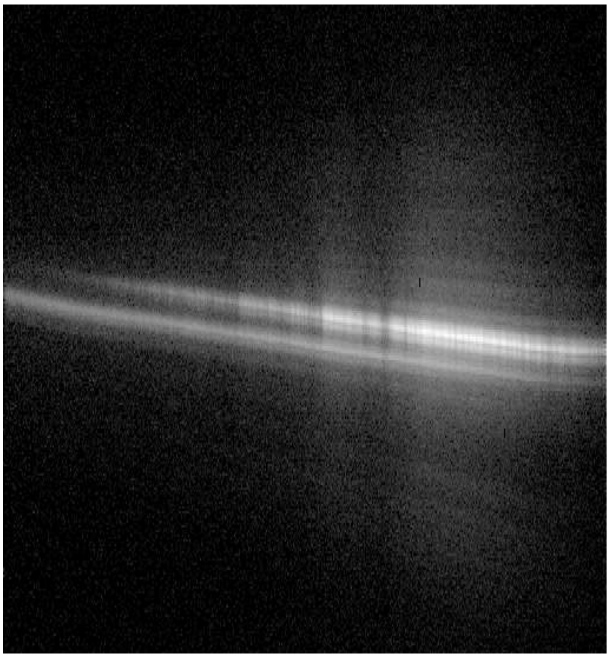

Figure 1: The flat-fielded HST STIS image of W Sgr. Wavelength increases to the right from about 1796 to 3382 Å. The cooler component (Cepheid + spectroscopic binary companion) is the upper one in the image and clearly separated from the hotter component below which extends much further toward shorter wavelengths. The spectrum flux is on a log scale. The strongest feature in the Cepheid spectrum is Mg II 2800Å. Reprinted from Evans, et al. (2009).

Another example of the detection of a third star from a spectrum of the secondary is provided by SU Cyg. The hot companion of the Cepheid is known to be a binary from ultraviolet velocities. However, in addition, it has a strong Ga II feature at 1414 Å, indicating that it is a HgMn star (Wahlgren & Evans 1998). Since these chemically peculiar stars require very slow rotation to facilitate element diffusion, they are found in short period binaries, whose orbit and rotation have been tidally locked. The Ga II feature is easily identifiable on a low resolution spectrum, indicating that the companion is itself a binary.

In order to determine the fraction of well-studied binary Cepheid systems which are in fact triple, we (Evans et al. 2005) have compiled a list of 18 Cepheids with orbits which have an ultraviolet spectrum of the companion. Of these, 44% (possibly 50%) are triples, a very high fraction for 5 $M_{\odot}$ stars.

1.2 Mass Ratio Distribution

Ultraviolet spectra also provide very precise spectral types of the companion, from which masses can be inferred. The mass ratios from the companion mass and a mass inferred for the Cepheids are shown in Fig. 2. (See Evans (1995) for a full discussion of Cepheid mass ratios and completeness.) Note that the Cepheid sample includes only systems with orbital periods longer than a year, since shorter period systems would have undergone Roche lobe overflow before the primary became a supergiant. For comparison, the mass ratio distribution of solar mass stars from Duquennoy and Mayor (1991, hereafter referred to as DM) is shown. The distributions are very similar, despite the fact that the Cepheid primaries are 5 times as massive as the DM primaries. For comparison, the mass ratio distribution of O stars from recent studies is shown (Rauw et al. 2009; Sana et al. 2008; Sana, Gosset & Evans 2009; Kiminki et al. 2009). It contains a population of equal mass binaries and falls off for low mass companions. This poses the question of whether the mass ratio (q) distribution is a function of separation and/or mass, and also the role of incompleteness. That is, one explanation for the difference in Fig. 2 between Cepheids and O stars may be that short period binaries in the O star sample are more likely to have equal mass binaries than the remaining longer period (wider separation) binaries in the Cepheid sample.

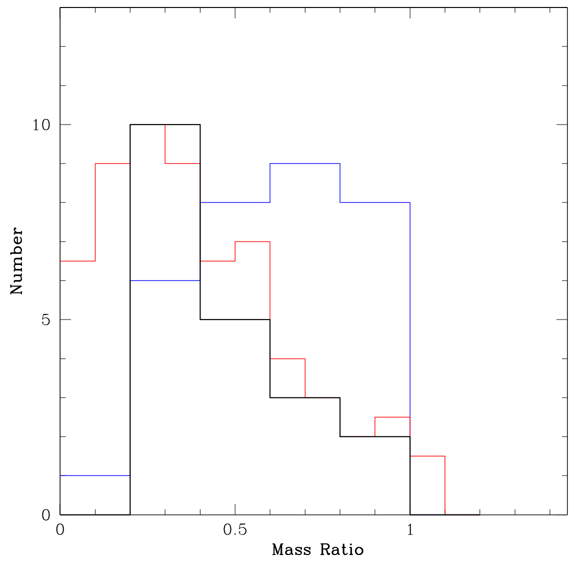

Figure 2: The distribution of mass ratios q = M_2/ M_1. The black line is the Cepheid sample (Evans 1995); the red line is the solar mass sample from DM; the blue line is the O star sample.

1.3 Low Mass Companions

One important aspect of binary properties is the prevalence of low mass companions for 5 $M_\odot$ primaries. These are, of course, the most difficult to detect both by photometric and spectroscopic (radial velocity) techniques. We are exploring the use of X-rays to improve this situation. Comparable mass main sequence stars (late B stars) do not in general produce X-rays. Low mass stars (spectral types mid F through K) young enough to be Cepheid/late B star companions (typically 50 Myr old) produce copious X-rays. M stars are weaker X-ray sources; older field stars are also much weaker X-ray sources. A list was drawn up of B3 to A0 stars in Tr 16 with proper motions indicating cluster membership (Cudworth, Martin & DeGioia-Eastwood 1993). Fig. 3 shows the sample with X-ray detections from a Chandra image (Evans et al. 2011; Townsley et al. 2011; Albacete-Colombo et al. 2008). Lines show the ZAMS for 2.3 kpc with E(B-V) = 0.45, 0.55, and 0.65 mag. 39% of the late B stars are detected as X-ray sources, indicating that they have low mass companions. See Evans, et al. (2011) for a complete discussion, including the X-ray detection fraction.

1.4 Discussion

As shown in the previous sections, multiwavelength observations have provided considerable new insight into the binary/multiple properties of 5 $M_\odot$ stars. Here we discuss some remaining issues about multiplicity.

Direct observations of companions, provided particularly in ultraviolet studies by HST and IUE, find a high fraction of triple systems (at least 44%). Even this, however, may not be the total count of

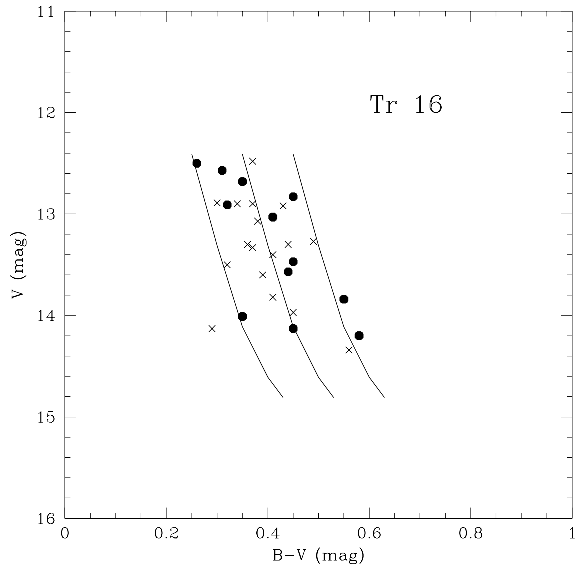

Figure 3: Late B stars in Tr 16 (from Evans, et al. 2011). Dots are detected in X-rays; x's are not detected. The lines are the ZAMS for 2.3 kpc and an appropriate range of B-V corresponding to E(B-V) = 0.45, 0.55, and 0.65 mag.

system members. For instance, in some systems with low mass companions, the low mass companion might itself be a binary.

The distribution of mass ratios (Fig. 2) strongly favors unequal mass companions. This pertains, however, only to Cepheids with separations ($a \sin i$) larger than about 0.4 AU and periods longer than a year (Sugars & Evans 1996). This is at least part of the reason for the difference between Cepheid mass ratios and those of O stars in Fig. 2.

A way to identify low mass companions of late B stars (comparable in mass to Cepheids) using X-ray images is shown in Fig. 3. How complete is our knowledge of the total binary/multiple fraction for 5 $M_\odot$ stars? The fraction Cepheids with companions hotter than mid A spectral type is known from an IUE survey of the 76 Cepheids brighter than 8^{th} mag (Evans 1992). 21% were found to have companions (which rises to 34% after a statistical correction was included based on stars with known orbital motion). The "Chandra fraction" of low mass companions and the "IUE fraction" should have relatively little overlap, and hence are approximately additive. Furthermore, the results tentatively suggest that the steep rise in secondary mass frequency seen in the DM solar mass stars from 1 to 0.2 $M_\odot$ stars is mimiced in the $5M_\odot$ mass ratio distribution. However, a drop off at the lowest mass ratios for the O stars (if confirmed) would imply only a very small fraction companions of 1 $M_\odot$ or less, as compared to a very large fraction for solar mass stars. That is, the *mass ratio* not the *mass* may be the important parameter at the time in star formation scenarios when the q distribution is determined.

For comparison, the recent study by Mason et al. (2009) of combined spectroscopic binary velocity results with interferometry for O and B stars[1]. They find a binary fraction of 66% for O stars. Their lists, of course, are not likely to contain low mass companions since small mass ratios and large magnitude differences make these companions very difficult to detect.

[1]X-ray identification of young companions cannot be used, since O and early B stars in this sample are intrinsic X-ray producers.

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