Fundamental Parameters of Cepheids: Masses and Multiplicity

Nancy Remage Evans

SAO, 60 Garden St., MS 4, Cambridge MA 02138

Abstract. Masses determined from classical Cepheids in binary systems are a primary test of both pulsation and evolutionary calculations. The first step is to determine the orbit from ground-based radial velocities. Complementary satellite data from Hubble, FUSE, IUE, and Chandra provide full information about the system. A summary of recent results on masses is given. Cepheids have also provided copious information about the multiplicity of massive stars, as well as the distribution of mass ratios and separations. This provides some important constraints for star formation scenarios including differences between high and low mass results and differences between close and wide binaries.

Keywords: Cepheids, masses, multiplicity, evolutionary tracks, star formation
PACS: 90

INTRODUCTION

In addition to being primary extragalactic distance calibrators, classical Cepheids provide an accurate luminosity for moderately massive stars evolved beyond the main sequence to the core He burning phase. For this reason, when a mass can be measured, they provide a benchmark to test evolutionary calculations. As was appreciated more than 4 decades ago the masses inferred from hydrodynamic pulsation calculations disagreed with the evolutionary track predictions, though the discrepancy ("the Cepheid mass problem") has been greatly reduced with revised opacity values.

In a related topic, Cepheids have provided us with a wealth of information about the binary/multiple properties of intermediate mass stars, which are important to check against the predictions of star formation calculations. Among these diagnostics are the fraction of binary or multiple systems, the distribution of mass ratios, the maximum separation of systems, and the difference in any of these between massive systems and low mass systems.

BINARY PARAMETERS

Mass Ratios

One area where Cepheid systems provide particularly well defined characteristics is the mass ratios. Because Cepheids are cool evolved stars, when they have hot companions (late B or A spectral type), the companions completely dominate at ultraviolet wavelengths. A survey of 76 of the brightest Cepheids (Evans 1992) with the International Ultraviolet Explorer (IUE) satellite identified *all* such hot companions. Because the spectral region 1200 to 2000 Å is very temperature sensitive in this spectral range, a very acurate temperature or spectral type can be determined from these spectra. A standard zero-age main sequence (ZAMS) relation provides an accurate mass of the secondary (M_2) from these spectral types. A theoretical Cepheid mass-luminosity relation provides the mass of the primary (M_1). Fig. 1 shows the distribution of mass ratios determined in this way. In Fig. 1, the Cepheid mass assumes no main sequence core convective overshoot (as discussed in Evans, 1995). This is an upper limit to the predicted mass of the Cepheid, and it is likely that they are somewhat smaller. This should not change the shape of the distribution, however. It only means that the mass ratios are a little underestimated.

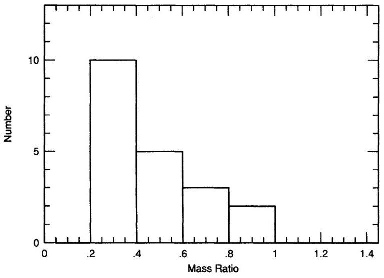

FIGURE 1. The mass ratio M_2/M_1 frequency histogram. The Cepheid mass (M_1) assumes no main sequence core convective overshoot, which is an upper limit to the primary mass. Taken from Evans, 1995.

The preference for low mass companions in Fig. 1 is clear. There is an important caveat to this diagram. All Cepheids with known orbits have periods longer than a year. This makes sense since stars in closer orbits would have overflowed their Roche lobes (and presumably coalesced) in their previous evolution through the red giant phase. Figure 1, however, provides a strong contrast in the distribution of mass ratios between these systems and systems with periods less that 40 days which have a preference for equal mass pairs (Tokovinin 2000).

Selection Effects/ Completeness

In discussions of binary parameters, it is always important to assess the completeness the of the information available, in particular which companions would be detected. Cepheids provide unusually complete information because the spectra of hot companions can be observed uncontaminated by the spectrum of the primary (the Cepheid). As discussed by Evans, et al. (2005), we now have a list of 18 Cepheids which have ground-based orbits and an observation of the secondary spectrum with IUE. In addition 8 of these have been observed in high resolution with either the Hubble Space Telescope (HST) or IUE, which allows a definitive answer to whether the secondary it itself a binary. For this well-observed sample of 18 stars, 8 and possibly 9 (44%, possibly 50%) are triple systems. That is, there is a very high fraction of triple systems among the known binary systems.

Low Mass Companions

What about low mass companions? Do we have any information about them? Because Cepheids are young stars, their companions must also be young. Young stars of types late F, G, K, and M are prolific X-ray producers because their coronae are much more active than those of older field stars. An optical image of a field within 0.1 pc of a Cepheid (the commonly accepted radius outside which binary systems are thought to be disrupted by the galactic star field) will show numerous red stars. An X-ray image will typically indicate a very small number which are young, and hence possible physical companions. We (Evans, Guinan, et al. 2009) have recently observed Polaris with the ACIS camera on the Chandra X-ray satellite. This image showed that two cool stars suggested to be companions (Polaris C and D) are not young stars. However, it identified one and possibly two stars which might be. The recent detections of three Cepheids on XMM X-ray images (Engle et al. 2009) means that it is likely that the Cepheid contributes to the X-ray source at the location of Polaris A =Aa + Ab, although the spectroscopic companion Ab has a suitable spectral type (F6 V) to produce X-rays also.

MASSES

Several new results have been added to the list of Cepheid masses in recent years. Currently masses have been determined in three ways. In some cases the high resolution ultraviolet spectra of the companion have provided an orbital amplitude for the secondary. This can be combined with the orbital velocity amplitude of the primary and the mass of the secondary from IUE spectra to obtain the mass of the Cepheid (primary). Second, recently Benedict, et al. (2007) have observed astrometric motion in Hubble Fine Guidance Sensor (FGS) observations for two Cepheids. Combining this with the orbit of the Cepheid and the mass of the companion also produces a Cepheid mass. Finally, the 30 year orbit of Polaris has been resolved with the Hubble Advanced Camera for Surveys (ACS), and the companion has been detected. This results in the first purely dynamical determination of the mass of a Cepheid.

S Mus

We will now discuss three recent results on Cepheid masses. The Cepheid S Mus has the hottest known companion. The high ultraviolet flux of S Mus B means that it could be observed with the high resolution echelle mode of the HST Goddard High Resolution Spectrograph (GHRS, Böhm-Vitense, et al. 1997), and hence it has the most accurately measured orbital velocity amplitude of a secondary. Unfortunately, because of the high temperature of the companion there is a degeneracy between the energy distribution and the reddening in the IUE spectral region, and the temperature cannot be as well determined as for cooler companions. For this reason, we (Evans, et al. 2006) obtained a FUSE spectrum, and identified regions which are relatively free of H_2 absorption but particularly temperature sensitive. Comparison with appropriate standard star spectra in these areas resulted in an improved temperature for the companion, and hence an improved Cepheid mass.

W Sgr

W Sgr is a system for which Benedict, et al. (2007) measured astrometric motion. It has a small orbital velocity amplitude, and a spectral type for the companion W Sgr B of A0 V from IUE spectra. Fig. 2 shows a Hubble Space Telescope Imaging Spectrograph (STIS) spectrum of the system (Evans, et al. 2009) which changed our understanding completely. The spectroscopic binary Aa + Ab would not be resolved in the image, and is the top spectrum with the Cepheid dominating the spec-

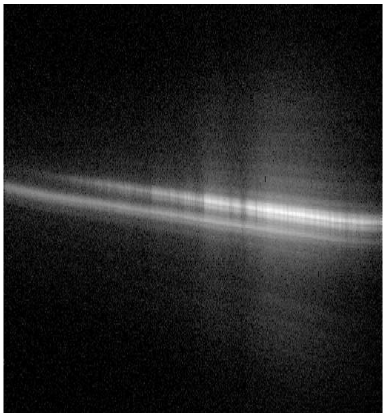

FIGURE 2. An HST STIS spectrum of the W Sgr system. Wavelength increases from left to right from approximately 1792 to 3382 Å. The system is spatially resolved in the approximately vertical direction. The hottest component in system is the lower one. The upper spectrum is the combined Cepheid plus the cooler companion, the component in the spectroscopic binary. Taken from Evans, et al. 2009.

trum at the long wavelength (right) side. The hottest star (which would dominate the IUE spectrum from 1200 to 2000 Å) is clearly resolved as the third star in the system. The spectroscopic binary (upper spectrum) was carefully extracted. Comparison with supergiant spectra comparable in temperature to the Cepheid Aa showed that no flux from the companion Ab was identified. An upper limit to the mass (spectral type) of the companion Ab was obtained, resulting in an upper limit to the Cepheid mass.

Polaris

Finally, Polaris is a low amplitude Cepheid which has long been known to be a member of a 30 year spectroscopic binary system (Kamper 1996). Recently, Wielen et al. (2000) used the proper motion of Polaris from *Hipparcos* observations to determine the inclination of the system. As the final piece of the puzzle we (Evans, et al. 2008) used the High Resolution Channel (HRC) of the Advanced Camera for Surveys (ACS) on Hubble to detect the faint companion and hence measure the separation between the primary and the secondary (Fig. 3). A second observation a year later detected orbital motion of the companion. The right hand image in Fig. 3 shows that the image of Polaris B taken at the during the 2006 observations, which was used to determine the point spread function (PSF) of the Polaris A image. Note that the PSF of Polaris B has an asymmetry similar to that of Polaris A, but with no sign of an artifact at the location of Ab in the left and middle images, confirming the detection of Polaris Aa.

Combining all these data we (Evans, et al. 2008) determined a mass of the Cepheid, Polaris Aa of $4.5^{+2.2}_{-1.4} M_{\odot}$, the first purely dynamical mass of a Cepheid.

We also determined the properties of the close companion Ab. It is 5.4 mag fainter than the Cepheid at 2255 Å, with an inferred spectral type of F6 V. This is consistent with the mass $1.26^{+0.14}_{-0.07} M_{\odot}$ found from the mass solution.

Polaris B (18” from the Cepheid) has a flux at 2255 Å consistent with a spectral type of F3 V – F4 V at the distance of Polaris. It also has a proper motion very close to that of Aa + Ab, consistent with orbital motion in a long-period bound system.

FUTURE WORK

We can expect improvements from future work, particularly in two ways. First, we should be able to improve the error bars on the masses of several of the systems. For Polaris, for instance, continued measurement of the motion of the companion Ab will improve the mass determination. In addition, future X-ray observations should improve our knowledge of the occurrence of low mass companions.

ACKNOWLEDGMENTS

Acknowledgments: Many people contributed to these projects including Ed Guinan, Scott Engle, Howard Bond, Gail Schaefer, Derek Massa, Charles Proffitt, Scott Wolk, Massimo Marengo, Margarita Karovska, Ken Carpenter, Erika Böhm-Vitense, and Giuseppe Bono. Funding for this work was provided by Chandra X-ray Center NASA Contract NAS8-39073 and STScI grant GO-10891.

REFERENCES

1. Benedict, G. F., McArthur, B. E., Feast, M. W., Barnes, T. G., Harrison, T. E., Patterson, R. J., Menzies, J. W., Bean, J. L., Freedman, W. L. 2007, AJ, 133, 1810
2. Böhm-Vitense, E., Evans, N. R., Carpenter, K., Beck-Winchatz, B., and Robinson, R. 1997, ApJ, 477, 916
3. Engle, S. G., Guinan, E. F., DePasquale, J., and Evans, N. 2009, in the proceedings of "Future Directions in Ultraviolet Spectroscopy”, in press
4. Evans, N. R. 1992, ApJ, 384, 220

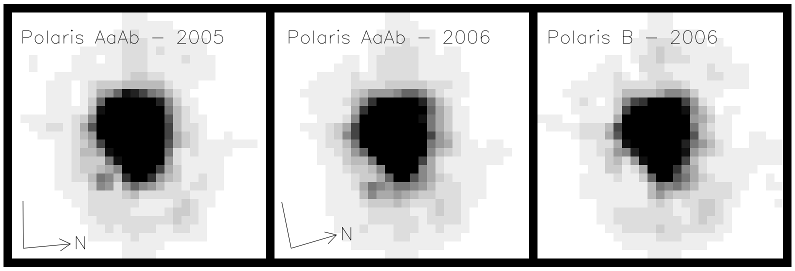

FIGURE 3. Co-added ACS HRC images of Polaris Aa (primary, Cepheid) and Ab (companion) taken in 2005 (left) and 2006 (middle) in 0.85” x 0.85” images at 2255 Å. Ab is at the “7 o’clock” position. The right image shows the distant companion Polaris B taken during the 2006 observations. Taken from Evans et al. 2008.

5. Evans, N. R. 1995, ApJ, 445, 393.
6. Evans, N. R., Carpenter, K. G., Robinson, R., Kienzle, F., and Dekas, A. E. 2005, AJ, 130, 789
7. Evans, N. R., Massa, D., Fullerton, A., Sonneborn, G., and Iping, R. 2006, ApJ, 647, 1387
8. Evans, N. R., Schaefer, G. H., Bond, H. E., Bono, G., Karovska, M., Nelan, E., Sasselov, D., and Mason, B. D. 2008, AJ, 136, 1137
9. Evans, N. R., Massa, D., and Proffitt, C. 2009, AJ, 137, 3700
10. Evans, N. R., Guinan, E., Engle, S., Wolk, S. J., Schlegel, E., Mason, B. D., and Karovska, M. 2009, AJ, submitted
11. Kamper, K. W. 1996, JRASC, 90, 140
12. Wielen, R., Jahreiss, H., Dettbarn, C., Lenhardt, H., and Schwan, H. 2000, A&Ap, 360, 399