Variable Stars in the Local Group
ASP Conference Series, Vol. 310, 2004
Donald W. Kurtz & Karen R. Pollard, eds.

Cepheid Masses: FUSE Observations of S Mus

Nancy Remage Evans[1], Derck Massa[2], Alexander Fullerton[3], George Sonneborn[4], Rosina Iping[4]

[1]*Smithsonian Astrophysical Observatory, 60 Garden St., Cambridge, MA 02138, USA*

[2]*NASA's GSFC, SGT, Inc., Code 681.0, Greenbelt, MD 20771, USA*

[3]*University of Victoria, Department of Physics and Astronomy, PO Box 3055, Station CSC, Victoria, BC, V8W 3P6, Canada*

[4]*NASA's GSFC, Code 681, Greenbelt, MD 20771, USA*

Abstract. S Mus is the Cepheid with the hottest known companion. As a benefit, the large ultraviolet flux made it the only Cepheid companion for which the velocity amplitude could be measured with the echelle mode of the HST GHRS. Unfortunately, the high temperature is difficult to constrain at wavelengths longer than 1200 Å because of the degeneracy between temperature and reddening. We have now obtained a FUSE spectrum in order to determine the temperature of the companion better. We have identified two regions which are temperature sensitive near 16 000 K, but are relatively unaffected by H_2 absorption (940 Å, and the Ly β wings). By comparing S Mus B with other FUSE spectra, we have determined a temperature of 17 000 K. The resultant Cepheid mass is $6.0 \pm 0.4\,M_\odot$.

1. Introduction

Measurement of Cepheid masses has been a goal both for a thorough understanding of these primary distance indicators and also as a benchmark for stellar evolution calculations of high mass stars. Specifically, the most important uncertainty in the calculations of evolutionary tracks of massive stars near the main sequence, core convective overshoot, can be constrained by the combination of a measured Cepheid mass and its luminosity.

Ultraviolet high resolution spectroscopy has provided a group of Cepheid double-lined spectroscopic binaries. Specifically, the orbital velocity amplitudes of hot companions can be measured with the Hubble Space Telescope (HST) Space Telescope Imaging Spectrograph (STIS) or Goddard High Resolution Spectrograph (GHRS) and formerly IUE. The ratio of this amplitude with the orbital velocity amplitude of the Cepheid from a ground-based orbit provides the inverse mass ratio. Typically, a very accurate temperature or spectral type for the hot companion can be obtained from IUE low resolution spectra from

https://doi.org/10.1017/S0252921100010976 Published online by Cambridge University Press

1200 to 3200 Å, from which the mass of the companion can be inferred very accurately.

The first step in the process is to determine the orbits of the Cepheids from the ground. As a sidelight, from a recent compilation of Cepheid orbits (Evans et al. 2004) approximately half the Cepheid binaries have been found to be triple systems. There is some bias in this fraction, since a massive secondary will increase the probability that the binary motion of the Cepheid is detected and studied. However, Cepheids have proved a valuable source of information about the multiplicity of massive stars.

The Cepheid S Mus, however, has required a different approach than other Cepheid binaries. For a summary, see Evans et al. (1998, 2004). Its companion is the hottest known in a Cepheid system. This allowed an observation with the HST GHRS echelle mode (Böhm-Vitense et al. 1997), providing the most accurate velocity available for a binary Cepheid. However, this high temperature made it difficult to determine the temperature of the companion. Specifically, the energy distribution of the spectrum rises monotonically in the IUE region (1200 to 3200 Å). This means the changes in the spectrum with temperature are small, and also that the temperature is coupled with reddening. The first step in remedying this was to obtain a Voyager spectrum of S Mus B (Evans, Holberg, & Polidan 1996). The Voyager spectral region (to wavelengths as short as 900 Å) is complicated by the H_2 absorption. Because Voyager spectra have low resolution, only approximate corrections can be applied to correct for the H_2 absorption.

We recently obtained a FUSE spectrum in the 900 to 1200 Å region. The aim of the project was to identify features which are temperature sensitive in the relevant spectral range (B3V to B5V) which are only slightly affected by H_2 lines. We have used spectra from the FUSE archive (Table 1) to look for appropriate features. The spectra were *reddened* to the $E(B-V)$ of S Mus ($E(B-V) = 0.23$ which corresponds to a column density of $N_H = 1.4 \times 10^{21}$ cm^{-2}) and then normalized using the flux in the wavelength range 1140 to 1170 Å. The comparison stars are listed in Table 1, together with the temperatures and gravities determined by one of us (DM) from Strömgren photometry, using the calibration of Napiwotzki et al. (1993).

Table 1. Comparison Stars

Star	Spectral Type	$E(B-V)$ (mag)	T (K)	$\log g$ cm s^{-2}
HD 97991	B1 V	0.02	25 500	4.00
HD 121800	B1.5 V	0.07	20 300	1.30
HDE 233622	B2 V	0.03	21 000	3.60
HD 51013	B3 V	0.00	17 100	4.30
HD 261878	B3 V	0.04	15 500	4.50
HD 72350	B4 IV	0.16	15 650	3.00
HD 35899	B5 V	0.03	16 700	4.30
HD 37332	B5 V	0.02	15 600	4.50
HD 37641	B6 V	0.05	12 800	4.40

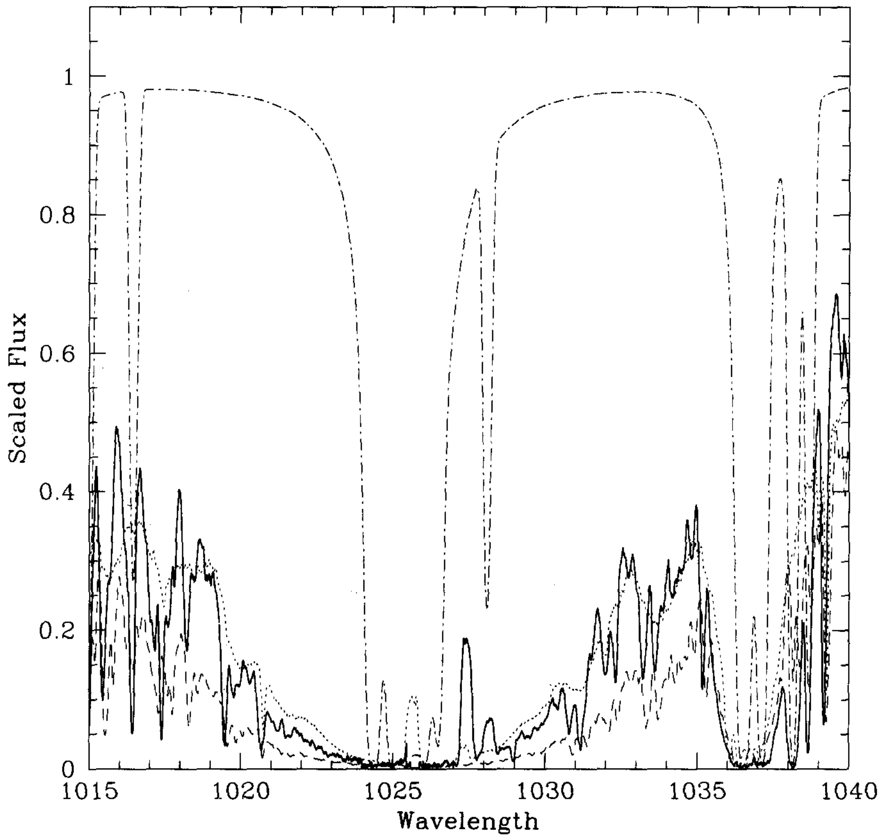

Figure 1. Ly β for the Cepheid companion S Mus B (solid line) compared with HD 51013 (T = 17 100 K; dotted line) and HD 37332 (T = 15 600 K; dashed line). The dot-dash line is the H_2 absorption, showing that outside the line core; the wings are relatively unaffected by H_2 absorption.

https://doi.org/10.1017/S0252921100010976 Published online by Cambridge University Press

Two regions were identified for temperature determination: Ly β and the region near 940 Å, the shortest wavelength where flux is apparent in the S Mus B spectrum. Fig. 1 shows the comparison between the Ly β for S Mus B and the comparison stars, HD 51013 (B3V) and HD 37332 (B5V). Ly β is gravity sensitive, but we have restricted our comparisons to main sequence stars to remove that dependency. S Mus B is clearly a very good match to HD 51013 (B3V), and markedly different from HD 37332 (B5V). The same is true in the 940 Å region. Based on this, we adopt 17 000 K as the temperature, with an uncertainty of $\pm$500 K.

In order to derive a mass corresponding to this temperature we have used the masses from Andersen (1991). We have combined these with the more recent temperatures from Ribas et al. (2000), based on Strömgren photometry, which should be comparable to the temperatures for our standard stars. The mass for S Mus B from the FUSE temperature and a linear fit to early B stars from the Andersen–Ribas set is $5.3 \pm 0.26\,M_{\odot}$.

The resulting mass from the previously measured velocity amplitude ratio (1.14 ± 0.06, Böhm-Vitense et al. 1997) is $6.0 \pm 0.4\,M_{\odot}$. This is very similar to the previous mass for the Cepheid (Böhm-Vitense et al. 1997), but with a significantly smaller uncertainty.

References

Andersen, J. 1991, ARA&A, 3, 91

Böhm-Vitense, E., Evans, N.R., Carpenter, K., Beck-Winchatz, B., Robinson, R. 1997, ApJ, 477, 916

Evans, N.R., Böhm-Vitense, E., Carpenter, K., Beck-Winchatz, B., Robinson, R. 1998, ApJ, 494, 768

Evans, N.R., Holberg, J.B., Polidan, R.S. 1996, AJ, 112, 264

Evans, N.R., Carpenter, K., Robinson, R., Dekas, A., Kienzle, F. 2004, in preparation

Napiwotzki, R., Schönberner, D., Wenske, V. 1993, A&A, 268, 653

Ribas, I. 2000, MNRAS, 313, 99

https://doi.org/10.1017/S0252921100010976 Published online by Cambridge University Press

Discussion

Aerts: How large is your convective overshooting parameter that fits best for S Mus?

Evans: The mass of S Mus is close to that predicted by the moderate overshoot (0.2 pressure scale heights) of both the Geneva group (Schaller et al. 1992, A&AS, 96, 269) and the Padua group (Bertelli et al. 1994, A&AS, 106, 275).

Kawaler: Could you clarify what core overshoot is being constrained? Cepheids have He burning cores which are convective.

Evans: It is the boundary during the main sequence phase between the convective core and the radiative envelope. This determines the amount of fuel available during H burning, the main sequence lifetime, and also the luminosity during the He burning blue loops.

Cassisi: What is the typical uncertainty on the luminosity for the observational points in the M-L plot you have shown before?

Evans: If you look at the scatter around the Period-Luminosity-Color relation, the uncertainty in the distance is about 10%.

Nancy Evans

https://doi.org/10.1017/S0252921100010976 Published online by Cambridge University Press