Cepheid Masses: FUSE Observations of S Mus

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ABSTRACT

S Mus is the Cepheid with the hottest known companion. The large ultraviolet flux means that it is 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 obtained a FUSE spectrum in order to improve the determination of the temperature of the companion. Two regions which are temperature sensitive near 16,000 K but relatively unaffected by H\textsubscript{2} absorption (940 Å, and the Ly β wings) have been identified. By comparing FUSE spectra of S Mus B with spectra of standard stars, we have determined a temperature of 17,000 ± 500 K. The resultant Cepheid mass is 6.0 ± 0.4 M\textsubscript{☉}. This mass is consistent with main sequence evolutionary tracks with a moderate amount of convective overshoot.

\textit{Subject headings:} stars, clusters, X-rays, star formation

\footnote{Based on observations made with the NASA-CNES-CSA Far Ultraviolet Spectroscopic Explorer Satellite. FUSE is operated for NASA by the Johns Hopkins University under NASA contract NAS5-32985}
1. Introduction

Observational determinations of Cepheid masses are a long-standing goal both in order to have a thorough understanding of these primary distance indicators and also because they provide an excellent benchmark for stellar evolutionary calculations. The most important uncertainty in evolutionary tracks of massive stars near the main sequence is the importance of core convective overshoot, which determines the lifetime on the main sequence and the luminosity in subsequent phases. When the mass of a Cepheid can be measured, it can be combined with an accurate luminosity, and compared with theoretical predictions.

Ultraviolet high resolution spectroscopy has provided a group of double-lined spectroscopic binaries containing a Cepheid. Specifically, the orbital velocity amplitudes of the hot companions of Cepheids could be measured originally with IUE, and until recently with the Hubble Space Telescope (HST) Space Telescope Imaging Spectrograph (STIS) or Goddard High Resolution Spectrograph (GHRS). This orbital velocity amplitude can be combined with the orbital velocity amplitude of the Cepheid from a ground-based orbit and the mass of the companion to produce the mass of the Cepheid. Typically, a very accurate temperature or spectral type for the hot companion can be obtained from IUE low resolution spectra from 1200 to 3200 Å, from which a mass can be accurately inferred.

For the S Mus system, the orbit of the Cepheid S Mus A has been determined several times with increasing accuracy as more data have been obtained (Evans, 1990; Böhm-Vitense et al. 1997; and Petterson et al. 2004).

The hot companion of the Cepheid, S Mus B, is sufficiently bright at 1720 Å that it could be observed with the echelle mode of HST/GHRS which provided a resolution of 80,000 (Böhm-Vitense et al. 1997). The orbital velocity amplitude of S Mus B they found from two GHRS observations is 30.6 km s$^{-1}$ with an uncertainty of 5%. The uncertainty is dominated by the centering of the star in the large science aperture for the first observation. This is the most accurate velocity amplitude measured for a Cepheid companion.

The high temperature of S Mus B, however, means that its temperature (and hence its inferred mass) is less accurately determined than that for cooler companions in other systems. For late B stars, the energy distribution turns over between 1200 and 1400 Å, making that region of the spectrum extremely temperature sensitive. For an early B star, the spectrum rises monotonically toward shorter wavelengths to the end of the IUE spectral range (∼1200 Å). This means the effects of reddening and temperature are much more difficult to disentangle, and hence the temperature is less accurately determined. The reddening of the system is E(B-V) = 0.21 mag (Evans, Massa and Teays 1994), which is large enough that it must be taken into account.
A number of approaches to determining the temperature in the wavelength range 1200 to 3200 Å have been used, as summarized by Böhm-Vitense et al (1997), including energy distributions from IUE low resolution spectra, and Si lines near 1300 Å from IUE high resolution spectra (Evans, Massa and Teays, 1994). In addition, two Voyager spectra were obtained to extend the energy distribution to 950 Å (Evans, Holberg and Polidan, 1996). The difficulty in interpreting these spectra comes from the heavy absorption by H$_2$ molecular absorption bands. In the low resolution Voyager spectra, approximate corrections had to be incorporated to compensate for this absorption.

As a substantial refinement to this basic approach, we obtained a high-resolution FUSE spectrum of S Mus B in order to determine its temperature more precisely, with the ultimate goal of improving the estimated mass of its Cepheid companion.

2. **FUSE Observations**

*FUSE* consists of four coaligned, prime-focus telescopes and Rowland-circle spectrographs that provide high-resolution (∼15,000) spectra of the wavelength region between 905 and 1187 Å. To maximize throughput across this waveband, two of the telescope/spectrograph channels have SiC coatings to cover the range ∼905 – 1105 Å, while the other two have LiF coatings to cover ∼980 – 1187 Å. The spectra from all four channels are recorded simultaneously by two photon-counting detectors. Details of the design and performance of these instruments are provided by Moos et al. (2000) and Sahnow et al. (2000), respectively.

The S Mus system was observed by *FUSE* on 2002 March 2 as the only target in Guest Investigator program C011. The observations were obtained through the $30'' \times 30''$ (LWRS) aperture in time-tag (TTAG) mode. The total integration time was 16.26 ks, which was divided into four exposures taken during four consecutive orbital viewing windows. Thus, the observation spans the interval from 6:42 to 12:35 UT; or MJD 52335.2798 to 52335.5242.

The photon lists from the four exposures were concatenated for each detector segment before the spectra were extracted and calibrated by means of CalFUSE version 2.2.3. These processing steps included application of corrections for small, thermally-induced motions of the diffraction gratings; removal of extraneous counts due to “event bursts”; removal of detector and scattered-light backgrounds; removal of thermal and electronic distortions in the detectors; correction of residual astigmatism in the spectrograph optics; extraction of a one-dimensional spectrum by summing over the astigmatic height of the two-dimensional image; correction for the minor effects of detector dead time; and application of flux and wavelength calibrations. These manipulations produced four spectra from the two SiC channels, and
four spectra from the two LiF channels, which are characterized by signal-to-noise ratios of 20–25 in the stellar continuum.

In addition, archival FUSE spectra of the comparison stars listed in Table 1 were retrieved from MAST\textsuperscript{1}. Since the comparison stars are bright, they were observed in histogram (HIST) mode through the LWRS aperture, with substantially shorter integration times than was used for S Mus. All these data were processed uniformly with CalFUSE version 2.4.1 on an exposure-by-exposure basis, before being aligned and coadded for comparison with the far-UV spectrum of S Mus.

3. Comparisons

The approach outlined in §1 is to use FUSE spectra of B-type stars with well-determined temperatures to constrain the temperature of S Mus B. We therefore sought spectral regions that are sensitive to temperature in the spectral range of B3 V to B5 V, which are also lightly contaminated by H\textsubscript{2} absorption lines. For comparison purposes we used FUSE spectra of stars with temperatures and gravities determined by one of us (DM) from Strömgren photometry, using the calibration of Napiwotzki et al (1993), listed in Table 1. The observed spectra were reddened to match the E(B-V) of S Mus [E(B-V) = 0.23 mag]. We used the Fitzpatrick (1999) $R(V) = 3.1$ curve, extrapolated into the Far-UV. Such an extrapolation has been demonstrated by Sofia et al. (2005) to be a reasonable approximation for the Far-UV extinction. They were then overplotted on the S Mus spectrum using the flux in the wavelength range 1140 to 1170 Å to normalize them. Figs. 1 and 2 show two examples of the comparisons for HD 51013 (B3 V) and HD 37332 (B5 V) respectively. The E(B-V) of S Mus corresponds to a column density of $N_{HI} = 1.4 \times 10^{21}$ cm\textsuperscript{−2}. H\textsubscript{2} absorption for this column density has been overplotted to assess how severely the stellar spectrum is affected in different wavelength regions. Standard values for the ISM provided a column density of H\textsubscript{2} a little less than $10^{20}$ cm\textsuperscript{−2}, for example Evans et al. (1996).

In this temperature range two regions were identified from these comparisons as being both temperature sensitive and relatively unaffected by H\textsubscript{2}: (1) the wings of Ly\textbeta (\(\simeq\) 1010 to 1040 Å) and (2) the two shortest wavelength regions with measurable flux, 945 and 960 Å. The core of Ly\textbeta is strongly absorbed by H\textsubscript{2}, but the wings are only lightly absorbed. The wings of Ly\textbeta are gravity sensitive, but we have restricted our comparisons to main sequence

\textsuperscript{1}The archiving of non-HST data at MAST is supported by the NASA Office of Space Science via grant NAG5-7584 and by other grants and contracts. STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555.
stars, so this should not be a problem.

Enlarged versions of these regions of the same two standard stars (HD 51013 and HD 37332) are presented in Figs. 3 and 4 with the spectrum of S Mus and an $\text{H}_2$ absorption template overplotted.

All 4 figures show that S Mus B is a very good match to HD 51013 (B3 V) and distinctly different from HD 37332 (B5 V) in the temperature sensitive wavelength regions in Figs. 3 and 4. Figures such as 1 and 2 were examined for all the stars in Table 1. S Mus B is also clearly different (hotter) than HD 35899 (B5 V) in these regions. Based on the temperatures for the two stars in Table 1 which most closely match S Mus B (HD51013, $T = 17,100\text{K}$, and HD 35899, $T = 16,700\text{K}$), we adopt $T = 17,000\text{K}$ for S Mus B with an uncertainty of ± 500K.

Subsequent to the FUSE S Mus observation we have been obtaining FUSE spectra of the massive stars in eclipsing binaries (Andersen, 1991) in order to determine their temperatures by the same approach (Evans et al., 2005). We have come to realize that evolution beyond the zero age main sequence results in enhanced contrast in lines. We suspect there may be a modest amount of evolution in S Mus B based on the line strength in Figs 1-4. We will revisit the S Mus spectrum when we have completed the analysis of the eclipsing binaries.

4. Discussion

In order to determine the mass of S Mus B corresponding to this temperature, we used masses from the compilation by Andersen (1991) derived from very accurate eclipsing binary solutions. We have combined these with recent temperatures from Ribas et al. (2000). These temperatures are based on Strömgren photometry, and should be comparable to the temperatures of the standard stars. In Fig. 5 we show the relation between temperature and mass for the stars in the Anderson list more massive than 2.5 $M_{\odot}$ (O and B stars). In order to obtain a mass corresponding to the temperature of S Mus B, we did a linear fit to the data for $\log T_{\text{eff}}$ 4.27 to 4.17 ($T$ 18,500 to 14,800 K). The resulting mass for 17,000 K is 5.3 $M_{\odot}$. A change of 500 K results in a change of 0.26 $M_{\odot}$.

The orbital velocity amplitude ratio of the Cepheid to the hot companion was found to be 1.14 ± 0.06 from the GHRS echelle observations of the companion and the ground-based Cepheid orbit (Böhm-Vitense et al. 1997). Combining this with the companion mass found here results in a Cepheid mass of 6.0 ± 0.4 $M_{\odot}$. This value only differs slightly from the previous determination (5.9 ± 0.7 $M_{\odot}$ Böhm-Vitense et al., 1997) but the error bars are significantly reduced.
This temperature and mass determination supersedes previous estimates, because it lifts
the degeneracy in the energy distribution longward of 1200 Å and avoids the need for the
approximate corrections for H₂ absorption required to interpret Voyager spectra.

Fig. 6 summarizes the information currently available for Cepheid masses. (Luminosities
are taken from Evans et al, 1998). For comparison, the luminosity predicted for the tips of
the blue loops the evolutionary tracks from several several groups is shown. The two lines
in the center are from the Padua and Geneva groups for moderate overshoot. To the left is
prediction from the Padua tracks for their maximum overshoot. The line on the right is from
Becker (1981) with no overshoot. The mass we have determined for S Mus clearly favors
moderate overshoot.

5. Summary

We have used a FUSE spectrum of the hot companion of the Cepheid S Mus to determine
the temperature of S Mus B. By combining the mass corresponding to the temperature with
the previously determined orbital velocity ratio of the two stars results in a mass of the
Cepheid of 6.0 ± 0.4 M☉.

Acknowledgments It is a pleasure to thank FUSE staff for assistance in obtaining this
data. Comments from an anonymous referee improved the discussion. This research was
supported by NASA FUSE grant NAG5-11946 (to NRE) and Chandra X-ray Center NASA
Contract NAS8-03060
REFERENCES


Evans, N. R. 1990, PASP, 102, 551


This preprint was prepared with the AAS LATEX macros v5.2.
Table 1. Comparison Stars

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<th>Star</th>
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<th>Exptime (sec)</th>
<th>Spectral Type</th>
<th>E(B-V) (mag)</th>
<th>T (K)</th>
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Fig. 1.— S Mus compared with HD 51013 (B3 V). The lighter, noisier line is the S Mus spectrum. The dotted line is the H$_2$ absorption spectrum. The wavelength is in Å; the flux has been normalized.

Fig. 2.— S Mus compared with HD 37332 (B5 V). Line types are the same as in Fig. 1. The wavelength is in Å; the flux has been normalized.

Fig. 3.— The region near Ly$\beta$. S Mus is the solid line; the B3 V star is the dotted line; the B5 V star is the dashed line; the H$_2$ absorption is the dot-dash line. A narrow airglow line in the center of Ly$\beta$ has been excised. The wavelength is in Å.

Fig. 4.— Spectral comparisons in the 950 Å region. The symbols are the same as in Fig. 3. The wavelength is in Å.

Fig. 5.— The mass-temperature relation for O and B stars from the list of eclipsing binaries of Andersen and temperatures from Ribas, et al. Mass is in M$_\odot$; temperature is in K.

Fig. 6.— Measured Cepheid masses. For comparison, theoretical predictions from evolutionary tracks are shown with decreasing convective overshoot from left to right. Dashed line: Bertelli, et al. 1986; dot-dash line: Bertelli, et al. 1994; solid line: Schaller, et al. 1992; dashed line: Becker, 1981) Mass and luminosity are in solar units.