The Mass of the Classical Cepheid S Muscae

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**Abstract.** Cepheid masses are a key element used to test evolutionary tracks of intermediate-mass stars. Using the GHRs in the Echelle-B mode, we have measured the orbital radial-velocity changes for the companion of the Cepheid S Muscae (S Muscae B). Spectra taken at minimum and maximum orbital velocities were cross-correlated and produced a velocity difference of $30.6 \pm 1.0$ km s$^{-1}$. The Cepheid orbital-velocity difference for the same phases is $26.9 \pm 0.4$ km s$^{-1}$, leading to a mass ratio of $1.14 \pm 0.03$.

Determinations of the spectral type of the companion S Mus B range from B3 V to B5 V, with an average spectral type of B3.8 V. This spectral type combined with the main-sequence mass–spectral type relation from Andersen (1991) and Harmanec (1988) results in a mass of $5.2 \pm 0.2 M_\odot$. This mass and the mass ratio yield a mass of $5.9^{+0.7}_{-0.6} M_\odot$ for the Cepheid S Muscae A.

This mass plus the absolute magnitude of $M_V = -4.29$ (log $L/L_\odot = 3.62$) of the Cepheid indicate that core convective overshoot in its main-sequence progenitor was slightly in excess of the value used to produce the Geneva evolutionary tracks.

1. **Introduction**

The “Cepheid mass problem” arose nearly three decades ago when masses derived from the first hydrodynamic pulsation calculations were typically half as large as those from evolutionary calculations. A recent reevaluation of interior opacities (e.g., Iglesias & Rogers 1991) has resulted in larger pulsation masses.
Figure 1. The GHRS spectra. In descending order from the top are the first S Mus observation, the second S Mus observation, and the comparison star. All spectra have been smoothed with a five-point boxcar. The comparison star has been scaled to the flux of the S Mus spectra. The top two spectra have been offset by $10 \times 10^{-12}$ and $5 \times 10^{-12}$ respectively for clarity but the vertical lines at the left of each spectrum show the zero-to-continuum range. Wavelength is in Å and flux is in ergs cm$^{-2}$ s$^{-1}$ Å$^{-1}$.

In the meantime, it has been realized that uncertainties resulting from the treatment of overshoot at the boundary of the convective core can produce an uncertainty in the predicted luminosity for a given mass comparable in size to the pulsation-evolution discrepancy.

The observational determination of a Cepheid mass has only become possible through satellite-ultraviolet spectroscopy. Since a number of Cepheids have companions hot enough to dominate the composite spectrum in the ultraviolet, an orbital-velocity amplitude can be measured for the companion, which can be combined with the ground-based velocity amplitude of the Cepheid to produce the mass ratio.

2. Observations

Only the Cepheid S Mus has a companion hot enough and bright enough to be observed with the highest resolution (echelle) of the GHRS. We observed it at orbital-velocity maximum and minimum from 1718 to 1726 Å. The first observation was made through the Large Science Aperture (LSA) before the installation of COSTAR. Both exposures used a PEAKUP for accurate centering.
Figure 2. Cepheid masses. The observed Cepheid masses for S Mus (circle, this study) and SU Cyg (square, Evans & Bolton 1990) are shown compared with the mass-luminosity relations for the tips of the blue loops calculated by three different groups. Masses and luminosities are in solar units.

In addition, wavelength-calibration exposures were taken at the beginning and end of each orbit.

The two spectra are shown in Figure 1. As a comparison star, we observed the B3 V star HD 66591 in the same way as S Mus B, also shown in Figure 1. It is clear that S Mus B has a higher rotational velocity than HD66591 (which has no appreciable rotational broadening).

The two S Mus spectra were cross-correlated and the velocity difference was found to be 30.6 km s$^{-1}$. The uncertainty in the velocities is dominated by the centering in the aperture. For the first spectrum taken through the LSA, this is estimated to be 0.5 diodes, which corresponds to 1.5 km s$^{-1}$ (Heap et al. 1995). From a new ground-based orbit for the Cepheid including some new data from Stappers & Cottrell (1996), the Cepheid orbital-velocity difference at the phases of the GHRS observations is 26.9 km s$^{-1}$.

3. Discussion

The remaining parameter needed to determine the Cepheid mass is the mass of the companion. The spectral type or temperature of the companion has been determined in a number of ways, including the ultraviolet energy distribution, line strengths in IUE high-resolution spectra, and Voyager observations. From these determinations, a spectral type of B3.8 V is derived. Full details are given
in Böhm-Vitense et al. (1997). Using the masses from eclipsing binaries from Andersen (1991), Harmanec (1988), and Popper (1980) this corresponds to a mass of 5.2 $M_\odot$.

The mass we derive for the Cepheid S Mus is thus $5.9^{+0.7}_{-0.6} M_\odot$. The errors include both the errors from the GHRS velocity measurement and the uncertainty in the spectral type or mass of the companion which are the dominant sources of error.

Figure 2 shows this mass and also the mass of the Cepheid SU Cyg from IUE spectra (Evans & Bolton 1990). For comparison, the predictions of the luminosity of the tips of the blue loops ($Z = 0.02$) from three groups with different values of core convective overshoot are shown. Becker (1981) has no overshoot, Maeder & Meynet (1988) have a modest amount, and Bertelli et al. (1986) have the largest amount. The location of S Mus indicates a value of overshoot slightly larger than that used by Maeder & Meynet. Combining the S Mus result and that of SU Cyg indicates an overshoot value between that of Maeder & Meynet and Becker.

New pulsation calculations such as those of the bump masses from Moskalik (1995) predict a similar mass for S Mus: 5.7 or 6.6 $M_\odot$, depending on which period-radius relation is used.

Finally, we stress that these mass measurements are unique tests of evolutionary calculations since they couple a directly observed mass with a luminosity from the instability fiducial.

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