MASSIVE STAR MULTIPLICITY: THE CEPHEID W Sgr

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ABSTRACT

We have obtained spectra of the W Sgr system with the Space Telescope Imaging Spectrograph on the Hubble Space Telescope (HST). The spectra resolve the system into a distant companion B which is the hottest star in the system and the spectroscopic binary (A = Aa + Ab). A and B are separated by 0′′.16. We have extracted the spectra of both of these. We see no flux in the Aa + Ab spectrum which cannot be accounted for by the Cepheid, and put an upper limit on the spectral type and mass of the companion Ab of F5 V and \( \leq 1.4 \, M_\odot \). Using the orbit from HST fine guidance sensor measurements from Benedict et al., this results in an upper limit to the mass of the Cepheid of \( \leq 5.4 \, M_\odot \). We also discuss two possible distant companions. Based on the photometry from the Two Micron All Sky Survey Point Source Catalog, they are not physical companions of the W Sgr system.

Key words: binaries: general – Cepheids

1. INTRODUCTION

Because W Sgr = HD 164975 = ADS 1102 is a very bright Cepheid, its radial velocities have been measured for more than a century. With hindsight, we can even say that the system has been teasing us for that long.

Although there were suggestions that there might be orbital motion as well as pulsation in the velocities, it was not until 1989 (Babel et al. 1989) that a spectroscopic orbit was determined from all the previous velocity observations. This was achieved largely because of the precision of the CORAVEL velocities, since the orbital velocity amplitude \( K \) is only 2.4 km s\(^{-1}\). Further radial velocity work (Albrow & Cottrell 1996; Petterson et al. 2004) has continued to improve the orbit.

In the meantime, the system had apparently been resolved with speckle interferometry (Morgan et al. 1978) with a separation between the components of 0′′.116. It was, however, not resolved by Bonneau et al. (1980). Babel et al. realized that their 4.9 year orbit was not compatible with the interferometric companion.

Ultraviolet low-resolution International Ultraviolet Explorer (IUE) spectra showed that a hot companion was clearly present (Böhm-Vitense 1985; Böhm-Vitense & Proffitt 1985; Evans 1991).

A breakthrough came with the Hubble Space Telescope (HST) fine guidance sensor (FGS) observations of Benedict et al. (2007), whose main aim was to measure the stellar parallax. They were able to measure the orbital motion of the primary (Cepheid) on the sky with the FGS. Combining these measures with the spectroscopic orbit of Petterson, Cottrell, and Albrow, they were able to solve for the orbital parameters including the inclination. By assuming a mass of the companion inferred from a spectral type, a mass for the Cepheid can be derived from the orbit.

Determining information about the companion in the 4.3 year orbit is the topic of this study. It can be noted from the summary above that there have been some contradictions and challenges in obtaining information about the orbit. The low orbital velocity amplitude necessitates high-accuracy velocities, and additional data would be valuable. Information on resolution of the system has not been consistent. In addition, using a mass of the secondary inferred from the IUE spectral type and the mass function of the orbit leads to a very small inclination for a reasonable Cepheid mass.

W Sgr = ADS 1102 also has two possible faint companions at 33″ and 47″ separations, which will also be discussed here to investigate the membership of the system. Wide companions are particularly useful in that they contain information about interactions the system has had with other stars in the vicinity. Possible companions such as these are worth investigating because they are relatively low-mass stars. Patience et al. (2002) find that high-mass systems are more likely to have small mass ratios than low-mass stars. Furthermore, higher-mass systems have larger maximum separations of companions (Kraus & Hillenbrand 2007a). It is valuable to investigate further both these characteristics for stars as massive as Cepheids (typically about 5 \( M_\odot \)). Differences between high-mass systems and low-mass systems point to differences in formation scenarios.

Assembling information about the properties of binary and multiple systems is a key ingredient in studying star formation processes. Currently, it is not clear how capture and fragmentation processes are balanced, nor the relation between multiple systems and disks. Furthermore, once the system configuration has been set, dynamical evolution can produce additional changes. It is becoming clear, however, that high-mass systems have a higher binary frequency and larger maximum separation than lower-mass systems.

2. OBSERVATIONS AND DATA REDUCTION

A number of images of the W Sgr system were taken under HST programs (PI: D. Massa). The system was on the target list of a program to resolve Cepheids with composite spectra and ultimately determine the distances (see Massa & Evans 2008). W Sgr was a good candidate for resolution because the low orbital velocity amplitude made a low inclination likely.
The strongest feature in the Cepheid spectrum is 2800 Å. The spectrum has been compressed by a factor of 8 in the horizontal direction and is on a log scale. The spectrum from 1200 to 1800 Å, however, is clearly resolved which it extends much further toward short wavelengths. The spectrum has been varied with position on the detector. It is evident in Figure 1 that the two spectra are close enough that a well-understood PSF is used for the extraction. The native 1024 × 1024 format of the STIS NUV MAMA detector anode array when used with the G230L grating has a plate scale of about 0.0248 pixel⁻¹ in the cross-dispersion direction. In the near-UV this provides only about 1 pixel per resolution element, and so is rather undersampled. There is however, a way to measure the subsampled PSF which is needed to extract the two W Sgr spectra. The G230L spectrum is rotated at a slight angle with respect to the anode array which measures the locations of photons incident on the MAMA detector. From one end to the other, the spectrum crosses about 16 rows of pixels, effectively subsampling the PSF in the cross-dispersion direction. The relative location of the spectrum in the cross-dispersion direction as a function of wavelength will be referred to as the spectral trace.

To measure the PSF we use an observation of a single star taken with the same mode as the science observations. The W Sgr G230L observations used the F25NDQ1 neutral density filter to keep the target below allowed bright object limits. However, for this filter/aperture combination, only a single calibration observation was ever done. This was data set o3zx08k0, with the WD standard GD153 as the target. For the W Sgr observations we used this observation to provide our reference cross-dispersion PSF.

The subsampled PSFs were prepared by using the STSDAS STIS package task “wx2d” to subsample each row of the original flat-fielded images of the PSF stars by 8 × in the cross-dispersion direction. The resulting cross-dispersion profile in each column was then smoothed over 32 pixels in the dispersion direction to average over the different pixel centerings and produce our adopted PSF profile as a function of wavelength. The fitting of these PSFs also allowed us to measure the tilt of the spectral trace as a function of wavelength over the detector.

As an example of fitting the components and projected separations, we will use observation o6f109020 of W Sgr. The flat-fielded image is shown in Figure 1. For each flat-fielded science image of the target star, we also used the wx2d task to produce images that were subsampled by 8 × in the cross-dispersion direction. Then at each pixel in the dispersion direction we fit the observed profile as a sum of multiple PSFs using a Marquardt–Levenson algorithm, and allowing the location and size of each component to be free parameters. This fit yields a position and a relative count rate for each component as a function of wavelength.

The location of the spectral trace is not completely stable from observation to observation. We adjusted the trace as initially determined from the PSF star to subtract any systematic shift of the position of the primary star as a function of wavelength. For image o6f109020, this gives the results shown in Figure 2. As can be seen in Figure 1, the hotter component dominates at short wavelengths and the cooler star at long wavelengths. This makes the relative separations measured at the ends of the spectra less reliable than those measured at wavelengths where the two components have more comparable fluxes. We therefore derived the adopted stellar separation for each image by only using the median difference between the stellar positions as measured between columns 200 and 600, where components A (= Aa + Ab) and B were clearly resolved. We estimate that the uncertainty in measuring the projected separation at a given PA is about 0.03 pixels.

Results for the separation as a function of position angle as measured in each image are shown in Table 1 for the series of images taken on 2002 June 6. A second series of images were taken on 2003 June 19. However, in this series, the Cepheid was not resolvable from the companion B and so the separation results are less reliable.
at a much brighter phase, and measurements were significantly less accurate. Combining the measured separations in Table 1, and assuming that the cross-dispersion plate scale for the filtered F25NDQ1 G230L image is 0.0248 pixel\(^{-1}\) we find that the hotter companion for W Sgr is located at a distance of 0.1645 ± 0.0006′′ at a position angle of 210.0° (further detail is provided by Figure 10 in Massa & Evans 2008).

### 2.3. Spectral Extraction

In order to obtain further information about the companion in the spectroscopic orbit, the two resolved spectra in the image were extracted. For this purpose, an STIS observation where the Cepheid is close to minimum light was selected to enhance the contribution from the close companion. The image used (o6f109010) also has one of the best projected separations. The exposure was taken at (mid-exposure): 2002 June 06 10:56:00 = 2,452,431.955. Using the period from Szabados (1989) \(P = 7.594904 \times 10^{-5}\) during the observation. Using the light curves of Moffett & Barnes (1984), corrected to this period, the Cepheid parameters at this phase are \(V = 4.92\) mag and \(B - V = 0.96\). The reddening for W Sgr is \(E(B - V) = 0.11\) corrected for the effect of the hottest companion (Evans 1991).

We prepared a flat-fielded image in which we subtracted out the contributions of the hottest star, W Sgr B, using the best-fit parameters derived above. We then used the standard STIS STSDAS x1d task to extract the spectrum for the W Sgr A = Aa + Ab. To minimize the residual contamination from errors in the subtraction of adjacent stars we used a 3 pixel high-extraction box to measure the flux. The x1d task automatically corrects the flux for the encircled energy extraction as a function of extraction box size. This gives us an extracted spectrum for each star while minimizing the contribution for adjacent stars.

### 2.4. Comparisons

As discussed above STIS provides two spatially resolved spectra, one of the hottest star in the system, the other the composite of the Cepheid and the companion in the spectroscopic orbit. The next step is to investigate whether we can identify the spectroscopic companion in the composite spectrum at any wavelength. In order to do this, we have compared the composite spectrum with two nonvariable supergiants which bracket the Cepheid in \((B - V)_0\) using IUE spectra. Table 2 lists the relevant parameters for the supergiants \(\beta\) Aqr and \(\alpha\) Aqr. The supergiants have been scaled to match the flux of the W Sgr spectrum between 2600 and 3000 Å.

Figures 3–6 show the comparisons. The normalized energy distributions of both \(\beta\) Aqr and \(\alpha\) Aqr match that of W Sgr reasonably well from 3200 to 2500 Å. Since they bracket W Sgr at this phase in \((B - V)_0\) (Table 2) the expectation is that the normalized spectrum of \(\beta\) Aqr (G0 Ib) should have a little more flux from 1800 to 2400 Å. Even in this comparison there is no indication that the W Sgr flux at 1800–1900 Å is any larger than would be predicted by the supergiant spectrum. That is, there is no indication of a higher proportion of flux contributed at the shortest wavelength due to a companion hotter than the Cepheid.
We attribute the extra flux in the supergiants in the 1800–2400 Å region to a subtle difference found in the spectral energy distributions (SEDs) of supergiants covering a range of spectral types from F2 Ib to G8 Ib (Evans & Teays 1996). They were compared with energy distributions of δ Cep at five phases. δ Cep has a period very similar to that of W Sgr (5.37 days) and should have very similar pulsation. The supergiants were found to have more flux than δ Cep when compared at phases with the same \((B − V)_0\). Morossi et al. (1993) found a similar result of extra flux at short wavelengths when comparing a sample of G and K giants with radiative Kurucz models. They attribute this to a nonradiative heating in the giants.

Unfortunately, we were unable to find an IUE exposure in the 1800–2000 Å region of a nonbinary Cepheid with as cool a value of \((B − V)_0\) as this phase of W Sgr. Such a spectrum would presumably match the W Sgr spectrum over the full 1800–3200 Å spectral range.

The difference in energy distributions between W Sgr and the supergiants β Aqr and α Aqr limits the detection of a companion which is fainter and only somewhat hotter than the Cepheid. Clearly Figures 3–7 show no sign of extra flux in the 1800–2000 Å region from a companion hotter than the Cepheid. There is one further consideration which limits the information we can obtain about the companion in the spectroscopic orbit. As mentioned above, the configuration used for the W Sgr exposures is little used, and not extensively calibrated.

Does the W Sgr observation allow us to put any limits on the spectroscopic companion Ab? To investigate this, we have made comparisons with IUE spectra of main-sequence stars. The stars and their optical properties are listed in Table 3, together with the IUE spectra used for the comparisons. Absolute magnitudes are also listed, taken from Schmidt-Kaler (1982). The absolute magnitude for W Sgr was taken from the Galactic Cepheid Database (Fernie, Beattie, Evans, & Seager: http://www.astro.utoronto.ca/DDO/research/cepheids/). The mean \(M_V = −3.76\) mag is corrected to \(−3.51\) mag for the phase of observation. Combining this with the information in Table 3, the main-sequence comparison spectra were scaled as appropriate for companions of W Sgr. The scaled main-sequence stars and the W Sgr spectra are shown in Figures 8 and 9 (rescaling the companions to the distance found directly by Benedict et al. (2007) makes an imperceptible difference to the figures).

An F0 V companion could be part of the composite STIS spectrum of W Sgr Aa + Ab only if there were no flux contributed by the Cepheid at 1800–1900 Å. The supergiants bracketing W Sgr at the phase of observation indicate that the Cepheid should contribute to the spectrum, at least at the level of \(0.2 \times 10^{-13}\) erg cm\(^{-2}\) s\(^{-1}\) Å\(^{-1}\). Even if the supergiant flux overestimates the contribution of the Cepheid, as found by Evans & Teays (1996), the flux from Ab would still be less than the F0 V star. An F5 V companion, on the other hand would have only a minute effect on the energy distribution, and could easily be a part of the system.
Table 3
Main-Sequence Comparisons

| Star   | A0 V | F0 V | F5 V |
|--------|------|------|------|
| HD 103287 | 2.44 | 2.86 | 6.80 |
| HD 12311  | 1.3  | 2.8  | 3.6  |
| HD 27524  | 0.01 | 0.00 | 0.00 |

Table 4
Distant Companions

| Star         | Sep (arcsec) | K (mag) | J − K (mag) | H − K (mag) |
|--------------|--------------|---------|-------------|-------------|
| W Sgr = ADS 11029 A | ... | 2.83 | 0.46 | 0.08 |
| ADS 11029 B | 33 | 9.57 | 0.61 | 0.24 |
| ADS 11029 C | 46 | 11.39 | ... | 0.20 |

3. DISCUSSION

3.1. The Mass of the Cepheid

From the discussion in the section above, an F0 V companion is ruled out. A companion as cool as F5 V or cooler is possible. Using the mass-spectral relation from Harmanec (1988), F0 V and F5 V stars have masses of 1.5 \( M_\odot \) and 1.3 \( M_\odot \), respectively. We adopt a mass \( \lesssim 1.4 M_\odot \) for the companion. From the orbital solution of Benedict et al. (2007), the mass of the Cepheid becomes \( M \lesssim 5.4 M_\odot \).

3.2. Distant Companions

The ADS lists two distant possible companions to W Sgr = ADS 11029 = CD −29 14447 = WDS 18050–2935 (Table 4). We examine the information about these two stars to see whether they are likely physical companions. A recent addition to this information is the photometry from the Two Micron All Sky Survey (2MASS) Point Source Catalog (Cutri et al. 2003), which is listed in Table 4 for B and C. The 2MASS photometry for both stars is quality A, except for J for star C which is an upper limit. For the brighter Cepheid itself, photometry at mean light has been taken from the recent compilation of van Leeuwen et al. (2007). This has been transformed back from the SAAO photometry to the 2MASS system using the relations provided by Carpenter (2001). These colors can be corrected for extinction using the \( E(B-V) \approx 0.11 \) mag (Evans 1991) and an extinction law of Mathis (1990).

The check we want to make is whether the colors and magnitudes are appropriate for main-sequence stars (slightly pre-main-sequence stars) if they are at the distance of W Sgr. We use a distance of 439 pc for W Sgr from the HST FGS parallax from Benedict et al. (2007). At this distance, components B and C have absolute magnitudes \( M_V \) of 1.32 and 3.14 mag, respectively. For comparison, we use the colors and magnitudes for Kraus & Hillenbrand (2007b, Table 5). The unreddened \((J-K)_0\) and \((H-K)_0\) for B corresponds to spectral type from late K to early M in this table. This range has \( M_K \lesssim 5.0 \) mag. For component C, \((H-K)_0\) and hence \( M_K \) is similar. Clearly, the observed magnitudes are too bright to be at the distance of W Sgr, and hence not physical companions.

3.3. Components

The ADS 11029 system, then, is made up of three components: the Cepheid (Aa) and the cool companion (Ab) and the hot component (B). If we use the maximum masses (above), the mass ratio of this pair is 0.26. These masses and the orbital period (Benedict et al. 2007) correspond to a semimajor axis of 5.0 AU for the Aa–Ab pair, corresponding to 0′′11.

We note that the absolute magnitude \( M_V = -3.97 \) mag found by Benedict et al. (2007) from the HST FGS measurements is in very good agreement with the absolute magnitude found from the IUE spectrum of the companion \( M_V = -4.00 \) mag (Evans 1991).

The third component B, the hottest star, is \( \geq 0′′1645 \) from A, which corresponds to a distance of \( \geq 72 \) AU at the distance of the system. This companion might have been the one found by Morgan et al., although the magnitude difference between it and the Cepheid (5.3 mag at V; Evans 1991) is very challenging. This star has a spectral type of A0 V, corresponding to a mass of \( 2.2 \) \( M_\odot \).

The ratio of the separations between the outer and inner systems is comfortably within Tokovinin’s (2004) empirical findings for triple systems.

The two more distant stars do not seem to be physically associated with the Cepheid system, making a total of three stars in the system.

4. SUMMARY

The STIS spectrum of W Sgr elucidates some of the puzzles about this well-studied Cepheid multiple system. The hottest star in the system, studied in IUE spectra is not the companion.
in the low-amplitude spectroscopic binary. It is a more distant third member of the system.

We have compared the ultraviolet spectrum of the unresolved spectroscopic binary with supergiant and main-sequence spectra to put limits on the temperature and mass of the companion. A companion as hot as F0 V is not compatible with the spectrum. Using this as an upper limit, we infer an upper limit to the mass of the companion of $1.4 M_\odot$. Combining this with the orbit of the system from Benedict et al. (2007), we find a mass for the Cepheid of $\lesssim 5.4 M_\odot$.

We have also investigated two more distant possible companions to see whether they are likely to be additional members of the system. The absolute magnitudes and colors were calculated from 2MASS $J$, $H$, and $K$ magnitudes assuming the two stars are the distance of the W Sgr system. The resulting magnitude–color combination is not consistent with main-sequence stars. That is, the two stars at $33''$ and $46''$ are not likely to be companions, and the system is limited to three components.

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