THE SMC SUPERSOFT X-RAY BINARY 1E 0035.4−7230 (SMC 13)

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ABSTRACT

Details of simultaneous photometric and spectroscopic observations of the optical counterpart of the “supersoft” X-ray source in the Small Magellanic Cloud 1E 0035.4−7230 (‘SMC 13’) are presented. Although the spectrum is dominated by emission lines of He II, the Balmer series of hydrogen is also present in emission with a strong decrement, and Balmer lines are seen as broad absorptions. Several high ionization emission features are also present including O VI (3811, 3834, and 5290\AA).

Radial velocities and photometry confirm that the binary period is \( \sim 0.1719 \) days, and an improved value of the period is derived from four years of photometry and analysis of ROSAT-HRI X-ray data. The orbital light variation is primarily due to an eclipse of the extensive accretion disk. X-ray and optical minima occur together. The UB\textsuperscript{V} light curves are similar to each other, and no clear phase-related color variations are found. He II emission-line velocities show a semi-amplitude of \( K \sim 100 \) km s\(^{-1}\), and maximum velocity occurs when the light curve indicates the compact star would be moving away from the observer, suggesting this emitting region may trace the orbital motion of the compact star. The range of possible masses implied for the X-ray source lies between 0.5 and 1.5\( M_\odot \) if the mass donor is a main sequence star filling its Roche lobe. The light curve suggests values at the high end of this range. The broad H absorption lines appear to have a much larger velocity amplitude and lower systemic velocity, making it difficult to understand their origin. We discuss possible models for the system.

Subject headings: accretion disks – stars: binaries – stars: individual (1E 0035.4−7230; SMC 13) – X-rays: stars

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1. INTRODUCTION

“Supersoft sources” (SSS) are very luminous X-ray objects (bolometric luminosities of $\sim 10^{38}$ ergs s$^{-1}$) with characteristic blackbody temperatures of $kT \sim 30 – 60$ eV (see review by Hasinger 1996). It now appears that the group contains several different types of systems including the nuclei of planetary nebulae, symbiotic stars, compact binaries, and hot white dwarfs. Even within the group of compact binaries several different models are possible, but all require accretion near, or even above, the Eddington limit. The high X-ray luminosities and optically bright accretion disks suggest very high mass transfer/accretion rates, well above that in classical low-mass X-ray binary systems (LMXB) like Sco X-1 or LMC X-2. Broad emission and P Cygni absorption profiles observed in the spectra of several SSS are additional evidence of mass transfer or loss. Whether the compact objects in these binaries are white dwarfs, neutron stars or black holes is still being debated. The most widely accepted SSS model involves steady nuclear burning on the surface of an accreting white dwarf (e.g., van den Heuvel et al. 1992, Pakull et al. 1993). However, the few dynamical studies which have been undertaken for these binary systems suggest a range of masses for the compact objects, indicating they may not all be white dwarfs (e.g., Beuermann et al. 1995, Cowley et al. 1990, Crampton et al. 1996). If some of the compact objects are neutron stars or black holes, the soft X-ray spectra indicate the stars must be surrounded by some type of cocoon which down-scatters the X-rays (Greiner, Hasinger, & Kahabka 1991, Kylafis & Xilouris 1993, Kylafis 1996).

Evidence of collimated outflows or “jets” has been found in two SSS, CAL 83 and RX J0513.9–6951 (Crampton et al. 1996). Livio (1996) argues that since jet velocities are typically equal to the escape velocity from the central object, the observed SSS jet velocities ($\sim 4000$ km s$^{-1}$ in RX J0513.9–6951) indicate that the central objects have masses appropriate to white dwarfs. However, analysis of the behavior of the X-rays and visible light during a brief “off-state” of CAL 83 in 1996 suggests that the white dwarf must be massive, very near to the Chandrasekhar limit (Alcock et al. 1997), if the steady nuclear burning model is correct. Thus, there is need for more and improved measurements of the stellar masses in supersoft X-ray binaries. We are in the process of obtaining data for several SSS, and this paper reports a new study of SMC 13.

1.1. 1E 0035.4–7230, SMC 13

The “supersoft” X-ray source 1E 0035.4–7230 was discovered during the Einstein Observatory X-ray survey of the Small Magellanic Cloud (Seward & Mitchell 1981). The source is alternatively known as ‘SMC 13’ (Wang & Wu 1992, Schmidtke et al. 1996), and for simplicity we will use that designation in this paper. Its optical counterpart was identified relatively recently with a faint ($V \sim 20.4$) blue star (Orio et al. 1994, Schmidtke et al. 1994). Schmidtke et al. (1996) and van Teesling et al. (1996) discussed early photometric and spectroscopic observations of this optical counterpart, but neither investigation resulted in a clear understanding of the nature and masses...
of the stellar components of the binary system. The short period of the system (P ∼ 0.1719 d) has also hampered the analyses since the relative phasing of data taken during different observing seasons could not be established, and hence there was considerable uncertainty in the precise period. In particular, since the pointed ROSAT-PSPC X-ray observations (Kahabka 1996) were made between 1 and 2.5 years earlier than the optical observations reported by Schmidtke et al. (1996), the relative phasing and even the shape of the X-ray light curve could not be determined reliably. Finally, the very short period made it difficult to obtain phase-resolved optical spectra.

In 1996 November, we were able to obtain additional photometry and greatly improved spectroscopic data for SMC 13 which are reported here and are combined with our earlier observations.

2. OBSERVATIONS AND MEASUREMENTS

2.1. Photometry

New photometric observations of SMC 13 were taken with the Tek2048#2 CCD on the CTIO 0.9-m telescope during five nights in 1995 November and six nights in 1996 November. This photometry is presented in Table 1. In addition, B and U photometry from 1993 and 1994, also obtained with the CTIO 0.9-m, which have not been previously published are presented in the same table. Our analysis uses our new photometry as well as the 1993 and 1994 data published by Schmidtke et al. (1996).

The observations were calibrated using Landolt (1992) standard stars and reduced using DAOPHOT (Stetson 1987). Differential magnitudes were calculated for the B and V filters relative to local photometric standards within the CCD frames using a procedure which minimizes errors by PSF fitting (Schmidtke 1988). Since the comparison stars used for the B and V frames are very red, they proved unsuitable for reducing U filter images. Hence, a separate set of local standards, considerably brighter in the ultraviolet, was defined for these data. The mean errors are approximately ±0.03 mag, as shown in Table 1. Overall, the system is very blue, with mean magnitude and colors of V = 20.4, B − V = −0.13 and U − B = −1.13.

2.1.1. Photometric Period and Ephemeris

The period of SMC 13 had previously been found to be near 0.1719 days (Schmidtke et al. 1996), but this short period combined with a separation of a year between each observing run made it impossible to determine the exact value, since cycle count was lost. This meant, for example, that one could not be certain of how the optical photometry phased with the 1992–93 ROSAT X-ray observations.
In the present study we have used all of the 1993–1996 V photometry to search for periods using the routine described by Horne & Baliunas (1986). The data are dominated by the large amount of 1994 V photometry. The resulting periodogram is displayed in Figure 1. There are three strong peaks corresponding to periods of 0.172007, 0.171925, and 0.171844 days. Light curves plotted on these periods are very similar. Thus, to aid in distinguishing between these possible periods we carefully examined the data from each run as a whole and those taken on individual nights (i.e., during a single orbital cycle) to check for changes in mean level or other peculiarities in the light curves.

There are clearly variations in both the shape and mean level of the light curve at different epochs. As in the supersoft binary CAL 87, the ingress portion of the ‘eclipse’ shows the most variation. In CAL 87, and by analogy perhaps in SMC 13, the changes in this part of the light curve are attributed to variations in the structure of the outer disk which partially occults the central bright source. Because much of the photometry was obtained in 1994, the light curves for each observing run and individual nights within a run were compared with the 1994 V light curve. The 1993 data should be given lowest weight because a different, smaller format CCD was on the telescope, and fewer comparison stars were used in the reduction. The 1993 and 1995 data show the same mean magnitude as in 1994, but there is some evidence that the amplitude may be somewhat smaller in 1995. However, in the 1995 data there are only a few points near the expected maximum in the curve so the range is not very well defined. On the second night of our 1996 observing run, SMC 13 was clearly about 0.10 mag brighter than the 1994 average curve, especially between phases 0.7 and 0.0. When those points are removed, the remaining 1996 photometry suggests that the system may have been ~0.05 mag brighter than in 1994. We have removed all of the 1996 second-night data from the subsequent period analysis, although they are plotted in the light curves shown in Figure 2.

A second method of period determination was then used to examine the dispersion in phase-binned data and select periods which minimize this dispersion. This analysis shows the best periods to be near 0.1719 and 0.1720 days. Both of these values correspond to the strongest peaks in the periodogram described above.

We have also examined all of the ROSAT-HRI data which are available in the public archives. There is an 800-sec observation taken in 1994 June and a series of observations taken within two consecutive days in 1995 May. It is very fortunate that these dates fall within the time covered by our optical data, so that there is no need to extrapolate back to the X-ray epoch with an uncertain period. The 1994 X-ray data were divided into two 400-sec blocks, and the 1995 data were broken into twelve ~600-sec pieces. These data were then phased on both the 0.1719 and 0.1720 day periods. There is a clear modulation of the X-ray count rate with a range of about a factor of two when plotted on either of these periods. However, using the longer period, the X-ray minimum falls at optical phase 0.5, while the X-ray minimum occurs at phase 0.0 when the 0.1719 d period is used. Since virtually all models predict that the X-ray and optical minima should coincide, at least approximately, and since the X-ray observations fall about a half-year between our optical
data sets, they allow us to break the uncertainty about the number of cycles between our optical observations taken one year apart. Hence we conclude that the true orbital period of SMC 13 is the shorter of the two “best” periods, $P = 0.171925 \pm 0.000001$ days. Although the period finding routines allow us formally to derive a period with slightly higher precision, trials with removing data from different nights or portions of a night show the accuracy in determining the period is limited to the errors given here. The ROSAT-HRI data are also plotted in Figure 2.

The determination of the time of minimum light, $T_0$, is not straightforward, partly because the shape of the optical ingress and egress change from observing season to observing season. In addition, there is considerable scatter in the light curve both from intrinsic flickering and from CCD photon noise due to the faintness of the system. We have adopted a value of $T_0$ which is the mean of the lowest points in the 1994 $V$ light curve, giving an ephemeris of:

$$T_0 = \text{HJD } 2,449,664.591 \pm 0.003 + 0.171925E \pm 0.000001 \text{ days}$$

The error in $T_0$ is our best estimate of the uncertainty in determining the time of minimum light. Since the optical photometry and spectroscopy were obtained on the same nights, any uncertainty in the precise period does not affect the comparison of the phase-related variations discussed below.

The older ROSAT-PSPC data which are given by Kahabka (1996) were obtained over a timescale of $\sim 1.5$ years with only one or two points being taken on any single day. This means that it is nearly impossible to determine the orbital period from these data, since changes in the X-ray flux level on timescales of days or weeks (as seen in the optical data) confuse any orbital modulations. Furthermore, because the data were taken in scan mode for the ROSAT All Sky Survey (RASS), it was necessary to make aspect corrections, so that the published count rates contain that further uncertainty. As was shown by Schmidtke et al. (1996) and Kahabka (1996), the long-term PSPC X-ray data show some modulation on the orbital period, but the time of minimum is largely dominated by three low points. Their occurrence before phase zero suggests they may be caused by the system being in a low state rather than by the orbital variation seen in the HRI data.

2.1.2. Light Curve, Colors, and X-ray Variability of SMC 13

The $V$, $B$, and $U$ light curves, based on the ephemeris given above, are plotted in Figure 2. $B - V$ colors have been computed using only those values of $B$ that were bracketed in time by two $V$ observations, or vice versa. The mean magnitude of the appropriate bracketing pair was used in calculating a $B - V$ color. Not all of the data could be used with this technique, but this method gives the most reliable colors for this continuously varying binary system. The $B - V$ color is plotted versus phase in Figure 2 also. There is no evidence for a systematic variation with phase. Since the system is so faint, very little $U$ photometry was obtained, and unfortunately phase zero is not well covered. It appears that the magnitude range is similar in all three colors
(Δm ∼ 0.3 mag). However, we note that most of U points during phases 0.6 to 0.9 are lower than would be expected from the V and B light curves. For comparison, in CAL 87 the largest variations in the light curves are also seen in this phase range, suggesting there may be changes in the disk structure which causes the occultation. In SMC 13 such changes may sometimes cause the hottest part of the disk to suffer greater obscuration, hence depressing the U light more than the other colors in this part of the orbit. However, we have insufficient data to establish a clear phase-related color variation.

We note that the optical amplitude in SMC 13 is relatively small (∼0.3 mag) while the X-ray count rate apparently varies by about a factor of two. By contrast, in the high inclination, optically eclipsing SSS CAL 87 (ΔmV ∼ 1.2 mag) the X-ray variation is less than a factor of two (Schmidtke et al. 1995). This points out that a range of conditions probably exists among the various supersoft binary systems. Below we discuss the interpretation of the light curve and possible models for the system.

2.2. Spectroscopy

2.2.1. Data

The new spectroscopic data were obtained with the CTIO 4-m telescope during five nights in November 1996, with the KPGL1 grating and Loral 3K detector. The spectra cover the wavelength range ∼3700–6700Å and have a resolution of ∼1.0Å per pixel. With a 1′′.5 slit, corresponding to three pixels, the spectral resolution is ∼3Å. Due to the faintness of the star and its short period, the length of the exposures (2400 s, corresponding to 0.16P in phase) was a compromise between achieving reasonable signal-to-noise and minimizing the duration of orbital phase covered by each integration. A total of 17 spectra of SMC 13 were obtained. One-dimensional spectra were extracted and processed following standard IRAF techniques to yield wavelength-calibrated spectra which have a peak S/N ∼12. Calibration spectra (He-Ar) were taken before and after each stellar exposure, and the wavelengths are established to ∼0.1 pixel or better. Details of the measurements made from these spectra are given in Tables 2 and 3.

2.2.2. The Spectrum of SMC 13

The spectrum of SMC 13 is characterized by moderately strong emission lines of He II and hydrogen, particularly He II-4686Å and Hα, on a very blue continuum (see Figure 3). The strengths of those He II Pickering lines which lie between the Balmer lines (e.g., 5411, 4541, 4200Å, etc.) show that only at Hα does hydrogen contribute significantly to the blended H+He II emission lines near the Balmer wavelengths. Higher He II Pickering lines, not normally seen in spectra of X-ray binaries, are found when the spectra are co-added. O VI emission is also present
at 3811, 3835, and 5290 Å. Several weak unidentified emission features which are seen in other SSS appear to be present in SMC 13, including lines near 4495 Å and 6380 Å. These may be possibly be N IV lines, but we note that there is no evidence of N IV at 4057 Å. Also, neither C III nor N III emissions in the 4630–4650 Å range are present. The unidentified line near 6380 Å might be [Fe X] 6374 Å which is seen in some symbiotic stars and recurrent novae. There is no evidence of the C IV lines (5801 and 5812 Å) which are present in some other supersoft systems (e.g. CAL 83 and RX J0513.9−6951). The emission at 4200 Å is partly an instrumental artifact and not an anomalously strong He II line.

SMC 13 spectra, co-added in phase bins, also reveal broad absorption features at the Balmer lines which appear on both sides of the emission cores (see Figure 4). Both emission and absorption are visible together at Hβ; at the higher Balmer lines the steep emission decrement leaves only the broad absorption line, while at Hα the emission feature dominates. When the spectra are co-added in the restframe of Hγ absorption, the equivalent widths of Hδ, Hγ and Hβ absorption can be measured; they are 0.5, 1.0, and 1.4 Å, respectively. Their FWHM are ~13 Å, and their full widths at zero intensity are ~45 Å. These line widths are comparable to those of main sequence A stars but their strengths are much weaker. The FWHM are also similar to those of some types of hot white dwarfs (e.g., Feige 110), but the full width at zero intensity (i.e., the wings) of white dwarf lines are typically wider, ~75 Å. No other stellar absorption features are apparent either in the individual spectra or in the co-added spectra. The possible origin of the H absorption lines is discussed below.

In Figure 3 we compare the summed spectrum of SMC 13 to that of the prototype SSS, CAL 83. The spectra of CAL 83 were obtained during the same observing run with the identical instrumental configuration, so they can be compared directly with those of SMC 13, although they have higher S/N. We note that the continuum of SMC 13 is much bluer than CAL 83. (It is also bluer than the hottest, eclipsed region in CAL 87.) While the emission lines are very similar in the two systems, there are some distinct differences. The most prominent emissions, He II 4686 Å and Hα (we give it in quotation marks since its velocity and strength compared to other He II lines shows it must be a blend of H and He II), are weaker in SMC 13 than in CAL 83. Cowley et al. (1997) show that SMC 13 has the weakest emission lines among six SSS they intercompare. In SMC 13 the average equivalent width of He II-4686 is 2.9 Å (with FWHM = 10 Å), compared with 10 Å (with FWHM = 5 Å) for CAL 83. However, the width of 4686 Å is comparable to that in the eclipsing system CAL 87, suggesting the inclination of the SMC 13 system may be high. Hα has a strongly negative velocity (~88 km s⁻¹ if it were only H). Even if the line were entirely due to He II-6560, its mean velocity (+36 km s⁻¹) is more negative than the mean velocity of He II-4686 (+225 km s⁻¹). This either implies some outflow from the system or a distorted line profile perhaps due to overlying absorption. We discuss this further below. O VI is weaker in SMC 13 than in CAL 83.

The 1996 spectra are much better than, but consistent with, the ones we obtained in 1994 (Schmidtke et al. 1996). However, van Teesling et al. (1996) found Hα in absorption and the other
Balmer absorptions stronger in 1995 October than in any of our data.

Highly shifted emission features which appear to be formed in outflows or jets have been observed in the supersoft sources CAL 83 and RX J0513.9−6951 (Crampton et al. 1996, Southwell et al. 1996). No such features were found in the SMC 13 spectra, but the signal-to-noise of the spectra are much lower because of its faintness, so perhaps they would not be detectable.

2.2.3. Phase-related Spectral Variations

Measurements of line strengths and velocities have been made on individual spectra and on spectra which have been co-added in six phase bins. These measurements are presented in Tables 2 and 3. Figure 4 plots the phase-binned spectra of SMC 13 in order of orbital phase. Equivalent widths and radial velocities of some lines are plotted versus phase in Figure 5. Note that although He II-4686 shows some variation of equivalent width with phase, it is not simply a reflection of the light curve since its maximum occurs near phase 0.8. The ‘Hα’ blend of H+He II shows a large scatter in equivalent width, with changes between nights being as large as any that may be phase-related.

Figure 4 and Table 2 show that the broad hydrogen absorptions vary in strength and velocity through the orbital cycle. Hγ absorption appears to be weakest near phase 0.5 when the system is brightest. The velocities of the absorption components have a much larger amplitude than either He II-4686 or ‘Hβ’ emission, but they are closely co-phased with the emission. We discuss this further below.

2.2.4. Spatially Extended Line Emission?

Pakull & Angebault (1986) and Pakull & Motch (1989) first reported detection of spatially resolved ionized nebulae surrounding X-ray sources, including one around the SSS CAL 83. More recently, Rappaport et al. (1994) developed detailed models for ionization nebulae expected around SSS. Remillard, Rappaport, & Macri (1995) then obtained [O III] and Hα images to search for additional such nebulae in the Magellanic Clouds. Although they reported successfully detecting the known nebula around CAL 83, no nebulosity was found around SMC 13 or any of the other eight SSS they observed.

Examination of the average of all our long slit spectra of SMC 13 similarly shows no evidence of spatially extended line emission at [O III], Hβ, or He II, although comparable observations of CAL 83 show the extended emission at all of these lines. Since SMC 13 is so much fainter, we estimate that any such emission is less than 5% of the stellar emission lines.
2.2.5. Radial Velocity Measurements

The radial velocities of the strong-line peaks were measured individually by fitting parabolae through them and also by cross-correlating the emission lines from individual spectra against the mean of all spectra. In practice, this was possible only for He II-4686 and the ‘Hα’ blend. All other emission lines were too weak and noisy to derive phase-dependent measures, even using the co-added spectra.

He II-4686 shows a clear radial velocity variation with phase. A circular orbit fit to our radial velocities, using the ephemeris given in §2.1.1, yields a semi-amplitude $K = 100 \pm 19$ km s$^{-1}$ with maximum positive velocity at phase 0.75 ± 0.03. Given the uncertainly of both the fit to a velocity curve and the time of minimum light, $T_0$, this phasing agrees with what is expected if the He II velocity traces the orbital motion of the eclipsed component (i.e. arises primarily in an accretion disk about the compact star). However, it is likely that the He II is not distributed entirely symmetrically, as indicated by its equivalent width variation which shows its maximum intensity occurs near phase 0.8.

‘Hα’ may show a similarly-phased velocity variation, but with considerably more scatter and a much lower amplitude ($K \sim 25$ km s$^{-1}$). Since this line is clearly a blend, its He II component probably shows the same velocity variation as 4686Å. But this component is blended with a stronger Hα component whose velocity must be quite different from He II. The overall negative velocity of the line center from any possible blend of Hα + He II, as described in §2.2.2, is puzzling. We have verified in other spectra taken during the same observing run that the wavelength scale is reliable, in spite of being near the end of the detector. Its negative velocity implies outflow seen at all phases, but no receding emission is present. Possibly the emission line is shifted by absorption from an inflowing medium (“reverse P-Cygni” effect) seen at all phases. However, we know of no other such system, and there is no obvious source of this inflowing gas.

Attempts to measure the absorption line velocities (by cross-correlation) of Hβ, Hγ and Hδ on the individual spectra were unsuccessful, but measurements of phase-binned spectra show that the absorption lines move in phase with the emission lines although with a larger amplitude. (See the spectra in Figure 3 and the velocity plot in Figure 4.) Because Hβ is strongly contaminated with central emission, only Hγ was used to measure the absorption velocities, although the variation can be seen in Hβ and Hδ as well.

We have only five absorption-line velocity measures, and although their variation does not appear very sinusoidal, there are too few points to be certain. A formal fit of a circular orbit to them yields a semi-amplitude $K = 464 \pm 120$ km s$^{-1}$ with maximum positive velocity occurring at photometric phase 0.82 ± 0.06, remarkably close to the He II velocity phasing considering the small number of points used in the fit. The mean velocity is $\sim 200$ km s$^{-1}$ lower than the systemic velocity for He II-4686 emission (mean absorption velocity is $+21 \pm 113$ km s$^{-1}$ while He II emission velocity is $+217 \pm 14$ km s$^{-1}$). We note that this curiously low velocity is similar to the mean velocity found for ‘Hα’ emission, as described in §2.2.2. From the symmetry of the
Hγ absorption line, the velocities do not appear to be contaminated by the narrow emission component, but there could be some effect. Weak emission contamination would cause us to overestimate this amplitude, if the absorption has a larger velocity amplitude than the emission. However, it is difficult to achieve the large amplification which is observed.

Much better spectra would be required to discuss the shape of the absorption velocity curve in more detail. The origin of this high velocity amplitude is difficult to interpret. It suggests the lines arise from some part of the binary system centered several times further from the center of mass than the He II emission. It is possible that the broad absorption arises in the optically thick accretion disk, an idea which was first suggested for the UX UMa stars by Warner (1976) and further developed in some detail by Mayo, Wickramasinghe, & Whelan (1980). (Also see an illustration of such a profile in RZ Gru in Figure 4.6 by Warner, 1995.) However, any disk absorption should have the same velocity amplitude as the disk. Eclipses by the disk edge or the companion star can distort the descending velocity curve and even increase its amplitude, but they cannot produce the observed large amplitude and negative shift of the mean velocity. On the other hand, it also appears improbable that the absorption arises on the mass-losing star because of its spectral signature and the phasing of the velocities.

3. THE SMC 13 BINARY SYSTEM

3.1. Orbital Velocities

It is clear that the period found in the photometry also fits the observed velocities very well. Thus, the velocities confirm that the orbital period is \( \sim 0.1719 \) d. The He II velocities are properly phased for orbital motion of the compact star. However, in standard models for disk hot spots, the place where the mass transfer stream impacts the disk is the site of extra line emission, so we may not have a ‘clean’ measure from which to determine the stellar masses. In SMC 13 the maximum He II line flux occurs at phase 0.8, which is when the hot-spot region is closest to our line of sight. It is not possible to measure strengths of other lines in individual spectra, but if we co-add six spectra around the He II line maximum and six at minimum, the O VI 5290Å line is stronger by a factor two in the He II maximum bin. Thus, some of the line emission must also have non-orbital velocity. However, the non-orbital velocity of material passing though the hot-spot is likely to be small, since there are no strong forces here and also because it occurs where the stream is stopped by the disk. This spot also lies near the center of mass, and thus its velocity should not lead to an overestimate of the orbital motion. Finally, the close agreement between spectroscopic and photometric phases suggest that non-orbital motions are small. We note the velocity amplitude could be underestimated by the phase smearing of the spectroscopic observations and by contributions from the hot-spot.

To get some idea of the range of possible masses of the component stars, we assume that the measured He II emission-line velocity is approximately the same as that of the compact star’s
orbital motion. The He II velocity amplitude (K ∼ 100 km s$^{-1}$) yields a mass function, f(M) = 0.0178M$\odot$. The resulting masses for various values of the orbital inclination are shown in Figure 6, where the dashed line shows where a main-sequence star of that mass would fill its Roche lobe. The secondary star masses lie in the range of 0.4 - 0.5M$\odot$ for cases where this component fills its Roche lobe, regardless of the value of the inclination. This means that the companion star must be much fainter than the whole system, since the apparent magnitude of a 0.5M$\odot$ star at the distance of the SMC is m$_V$ ∼27. Hence, it contributes almost nothing to the overall luminosity of the system. The compact-star masses cover a wide range, depending on the orbital inclination. For high values of the inclination the compact star mass is near the upper limit for white dwarfs. We discuss below the most likely values for orbital inclination and the implied compact-star masses.

We caution that we cannot be certain that the measured velocities are entirely representative of the compact star’s motion. Nevertheless, most of the effects discussed here would result in underestimating the velocity amplitude and hence the masses.

3.2. Light Curve

3.2.1. Models

Schandl et al. (1996) and Meyer-Hofmeister et al. (1997) have used detailed models to reproduce the observed light curve for the SSS CAL 87. They assume a relatively thick accretion disk with a high rim (which they call a “spray”) extending halfway around the disk on the “following” side. The high disk rim is caused by the impact of an accretion stream onto the disk. This rim is irradiated by the central white dwarf and becomes a significant source of optical continuum light. In their model, the thick disk rim is opaque and decreases azimuthally away from the hot-spot. The thick region at the hot-spot begins to hide the central hot source before the true eclipse by the secondary star begins. Their analysis leads to an orbital inclination of i ∼ 78° for CAL 87 when masses of 0.75 and 1.5M$\odot$ are adopted for the white dwarf and the secondary star, respectively.

Meyer-Hofmeister et al. demonstrate that for other SSS they have studied, this type of model also fits the observed light curves very well. In the models, light from both the disk and the X-ray heated companion star are considered. The disk edge may occult parts of its interior, and the companion star’s brightness depends on its aspect because of X-ray heating. Hence, both the disk and the star may be eclipsed by each other or be self-occulted. Predicted light curves for non-eclipsing inclinations are also modelled by Meyer-Hofmeister et al. They show that the light curve shape is diagnostic of the inclination. In non-eclipsing systems (e.g., CAL 83, RX J0513.9−6951) the light variation is principally due to the azimuthal variation of the reprocessed radiation from the high disk rim with a lesser contribution from the heated inner hemisphere of the secondary star. In the systems they considered, the disk is smaller than the companion star in the z-direction, so that high inclinations are required in order for deep disk eclipses to occur.
The light curve ‘maximum’ is flat in an eclipsing system and curved in non-eclipsing systems. The light curve ‘minimum’ is a combination of the eclipse of the disk and viewing the unheated side of the companion star. The tell-tale signature of such an eclipse is the asymmetry due to the azimuthal variation of the high disk rim. Such a picture is consistent with the eclipse asymmetry seen in SMC 13 (Figure 3).

3.2.2. SMC 13 Light Curve and Component Masses

The orbital light curve of SMC 13 displays one maximum and one minimum per cycle, similar to the behavior observed in other SSS (e.g., Meyer-Hofmeister et al. 1997), rather than showing a double-humped, ellipsoidal variation of the companion star found in some X-ray binaries. If the light curve of SMC 13 were due entirely to X-ray heating of the companion star, then the light from the companion star would provide a large fraction of the total light, and hence we might expect to see spectral signatures from this star. Since the only absorption lines move in phase with He II emission, this is not possible. (We also note that CAL 83 and RX J0513.9–6951, which are considered to be low inclination systems, have narrower emission lines, as expected from a disk viewed nearly face-on.) Thus we conclude that a partial eclipse of a luminous accretion disk around the compact star is the major cause of the observed light variation in SMC 13. The agreement in phase of the X-ray light curve is consistent with this picture, since the X-rays must come from the hot, compact star.

The mean magnitude of SMC 13 is $V \sim 20.4$ which corresponds to $M_V \sim +1.4$, assuming a SMC distance modulus of 18.7 (van den Bergh 1992) and an average reddening $E_{B-V} = 0.1$ mag. For comparison, CAL 87 has a longer period ($P=0.44$ d) and is more luminous (uneclipsed magnitude $M_V \sim +0.3$). In SMC 13, the shorter period indicates a smaller system and hence a less luminous accretion disk. The lack of color variation through the orbital cycle of SMC 13 suggests that the hotter inner portions of the disk are never occulted, unlike the case in CAL 87 where the system becomes redder during central eclipse as the hottest regions are covered (Cowley et al. 1991). Thus, we infer a somewhat smaller inclination for SMC 13 than for CAL 87. The SMC 13 light curve has a flat maximum and an asymmetrical minimum, both signatures of an eclipsing system. The mass ratios indicated by our discussion of the mass function set the range of possible inclinations for which partial eclipses occur as 70° or larger. Thus, the inclination is likely to lie in the range $\sim 70^\circ$ to $\sim 78^\circ$. This implies the most probable mass for the compact star in SMC 13 is between 1.3 and 1.5$M_\odot$ (see Figure 3).

If our measured emission-line velocities are due to orbital motion, then the system differs from the previously studied supersoft binaries which have more massive secondary stars. In SMC 13 the inclination derived from both the light curve and the emission-line widths implies a low mass companion star and a compact-star mass very near the upper mass limit for white dwarfs. The system also differs from other SSS in having a lower disk luminosity and weaker emission-line flux. This probably arises primarily from the small size of the accretion disk in this very short period.
system, but other factors which affect the disk luminosity could include a lower mass transfer rate or a fainter disk due to different surface temperature or X-ray flux from the compact star.

If the absorption-line velocities instead of the emission lines were to indicate the orbital motion of the compact star, the resulting mass function would be $f(M)=1.4M_\odot$, which gives impossibly large masses (for the observed luminosity of the system) for all values of the inclination or mass ratio. The weakening of the absorption lines at phase 0.5 argues against their being formed on the far side of the disk, where the orbital lever arm is larger. If the absorption velocities are distorted by lower-amplitude emission, the puzzle remains although its magnitude may be smaller than we measure. We do not understand the origin of these lines.

4. Summary

SMC 13 has the shortest period and lowest luminosity of the spectroscopically studied SSS binaries. (RX J0439.8−6809 has a slightly shorter period (Schmidtke & Cowley 1996) but no spectroscopic work has been undertaken on this extremely faint system.) SMC 13 also has the weakest emission lines in terms of equivalent widths, and the Balmer lines are seen in absorption unlike other SSS. It is very blue and shows no color change with orbital phase. The light minimum is asymmetrical and broad, and there are small changes in the light curve over timescales of days to years.

The light curve appears to be primarily due to a partial eclipse of the disk by the mass-losing star viewed at an inclination $i \sim 75^\circ$. The phasing of the He II emission velocities suggests these lines may trace the orbital motion of the compact star. However, the line-strength variations indicate there is a hot spot on the disk with enhanced line emission which could lead to an underestimate of the velocity amplitude of the compact star. The measured emission-line velocities and orbital inclination imply masses near to $0.5M_\odot$ for the mass donor and $1.4M_\odot$ for the compact star, if non-orbital velocities are small. The latter value lies near the white dwarf upper mass limit and thus appears to be inconsistent with the ‘standard’ SSS model in which the compact star is low-mass white dwarf and the mass donor is a 1–2$M_\odot$ star. Furthermore, the steady nuclear burning model requires a high rate of mass flow onto the white dwarf from the companion, and it may be harder to sustain this with a lower mass companion.

Detailed modelling of the SMC 13 light curve should be carried out to elaborate on the simple analysis presented here. Higher resolution spectroscopic observations of the hydrogen absorption lines and of ‘Hα’ may help us understand their origin and peculiar velocities.

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Table 1: $UBV$ Photometry of SMC 13

| HJD     | $U$   | error | HJD     | $U$   | error |
|---------|-------|-------|---------|-------|-------|
| 2440000+ |       |       | 2440000+ |       |       |
| 9333.58743 | 19.190 | 0.061 | 9335.60002 | 18.987 | 0.061 |
| 9665.55582 | 19.113 | 0.047 | 9666.60808 | 19.203 | 0.057 |
| 10045.55228 | 19.147 | 0.028 | 10045.60055 | 19.221 | 0.032 |
| 10045.65033 | 18.967 | 0.025 | 10046.56874 | 19.121 | 0.039 |
| 10049.59877 | 18.989 | 0.055 | 10389.63870 | 19.004 | 0.046 |
| 10390.56703 | 18.900 | 0.035 | 10393.53105 | 19.191 | 0.027 |
| 10393.57317 | 19.128 | 0.027 | 10393.61346 | 18.960 | 0.022 |

| HJD     | $B$   | error | HJD     | $B$   | error |
|---------|-------|-------|---------|-------|-------|
| 2440000+ |       |       | 2440000+ |       |       |
| 9330.62604 | 20.176 | 0.048 | 9333.57590 | 20.180 | 0.039 |
| 9335.58782 | 20.120 | 0.067 | 9665.54322 | 20.112 | 0.037 |
| 9666.59662 | 20.197 | 0.046 | 10044.57470 | 20.204 | 0.026 |
| 10044.59165 | 20.163 | 0.035 | 10044.66803 | 20.069 | 0.026 |
| 10044.64514 | 20.174 | 0.033 | 10044.66217 | 20.174 | 0.026 |
| 10044.67831 | 20.258 | 0.035 | 10044.74061 | 20.354 | 0.037 |
| 10044.75631 | 20.166 | 0.038 | 10045.54068 | 20.284 | 0.048 |
| 10045.57259 | 20.318 | 0.037 | 10045.58873 | 20.383 | 0.037 |
| 10045.62019 | 20.202 | 0.039 | 10045.63657 | 20.089 | 0.029 |
| 10046.58133 | 20.217 | 0.026 | 10046.59797 | 20.393 | 0.035 |
| 10046.60645 | 20.374 | 0.033 | 10046.61448 | 20.368 | 0.032 |
| 10046.62229 | 20.382 | 0.040 | 10046.63020 | 20.291 | 0.034 |
| 10046.63839 | 20.280 | 0.024 | 10046.65451 | 20.130 | 0.026 |
| 10048.57762 | 20.030 | 0.047 | 10048.58613 | 20.078 | 0.062 |
| 10048.59391 | 20.106 | 0.044 | 10048.60177 | 20.165 | 0.045 |
| 10048.60964 | 20.035 | 0.053 | 10049.58680 | 20.079 | 0.050 |
| 10389.62732 | 20.181 | 0.033 | 10389.65323 | 20.086 | 0.024 |
| 10390.55565 | 20.040 | 0.029 | 10390.59916 | 20.085 | 0.028 |
| 10390.61612 | 20.210 | 0.038 | 10390.63383 | 20.228 | 0.039 |
| 10390.65206 | 20.219 | 0.032 | 10390.66888 | 20.105 | 0.037 |
| 10393.51962 | 20.196 | 0.035 | 10393.54295 | 20.395 | 0.039 |
| 10393.55883 | 20.359 | 0.042 | 10393.58530 | 20.221 | 0.041 |
| 10393.60173 | 20.071 | 0.027 | 10394.59813 | 20.346 | 0.034 |
| 10394.61495 | 20.084 | 0.026 |   |   |   |
| HJD      | V     | error | HJD      | V     | error |
|----------|-------|-------|----------|-------|-------|
| 2440000+ |       |       | 2440000+ |       |       |
| 9330.61758 | 20.231 | 0.037 | 9332.54302 | 20.430 | 0.048 |
| 9333.56800 | 20.343 | 0.045 | 9334.55199 | 20.329 | 0.041 |
| 9334.60883 | 20.347 | 0.039 | 9334.66236 | 20.531 | 0.051 |
| 9335.54130 | 20.464 | 0.054 | 9335.54936 | 20.481 | 0.050 |
| 9335.55707 | 20.492 | 0.070 | 9335.56453 | 20.363 | 0.052 |
| 9335.57229 | 20.404 | 0.067 | 9335.57972 | 20.349 | 0.065 |
| 9659.52743 | 20.203 | 0.026 | 9659.53779 | 20.263 | 0.025 |
| 9659.54579 | 20.294 | 0.034 | 9659.55367 | 20.340 | 0.039 |
| 9659.56155 | 20.333 | 0.025 | 9659.57129 | 20.440 | 0.025 |
| 9659.57917 | 20.496 | 0.034 | 9659.58705 | 20.435 | 0.027 |
| 9659.59492 | 20.477 | 0.033 | 9659.60278 | 20.499 | 0.036 |
| 9659.61065 | 20.489 | 0.036 | 9659.61851 | 20.480 | 0.039 |
| 9659.62678 | 20.392 | 0.032 | 9659.63516 | 20.347 | 0.027 |
| 9659.64301 | 20.313 | 0.026 | 9659.65087 | 20.371 | 0.045 |
| 9659.65888 | 20.308 | 0.027 | 9659.66677 | 20.323 | 0.027 |
| 9659.74022 | 20.395 | 0.032 | 9659.74920 | 20.466 | 0.035 |
| 9659.75708 | 20.472 | 0.034 | 9660.51450 | 20.256 | 0.033 |
| 9660.52322 | 20.258 | 0.029 | 9660.53108 | 20.202 | 0.033 |
| 9660.53899 | 20.245 | 0.024 | 9660.54686 | 20.207 | 0.026 |
| 9660.55482 | 20.240 | 0.027 | 9660.56272 | 20.251 | 0.027 |
| 9660.57062 | 20.273 | 0.031 | 9660.57864 | 20.185 | 0.030 |
| 9660.58654 | 20.286 | 0.027 | 9660.59439 | 20.362 | 0.031 |
| 9660.60226 | 20.392 | 0.024 | 9660.61016 | 20.456 | 0.025 |
| 9660.61802 | 20.403 | 0.029 | 9660.62649 | 20.464 | 0.033 |
| 9660.63517 | 20.573 | 0.039 | 9660.64363 | 20.492 | 0.027 |
| 9660.65149 | 20.414 | 0.033 | 9660.65941 | 20.424 | 0.034 |
| 9660.66745 | 20.341 | 0.032 | 9660.67529 | 20.269 | 0.023 |
| 9660.68312 | 20.257 | 0.027 | 9660.74863 | 20.360 | 0.036 |
| 9660.75729 | 20.362 | 0.054 | 9660.76518 | 20.458 | 0.086 |
| 9662.56354 | 20.266 | 0.025 | 9662.60377 | 20.206 | 0.025 |
| 9662.64551 | 20.249 | 0.030 | 9664.56456 | 20.438 | 0.046 |
| 9664.58180 | 20.540 | 0.047 | 9664.59015 | 20.614 | 0.054 |
| 9664.59804 | 20.482 | 0.034 | 9664.60596 | 20.486 | 0.043 |
| 9664.61386 | 20.413 | 0.037 | 9664.62195 | 20.365 | 0.047 |
| HJD   | V    | error | HJD   | V    | error |
|-------|------|-------|-------|------|-------|
| 2440000+ |      |       | 2440000+ |      |       |
| 9665.51520 | 20.294 | 0.075 | 9665.53453 | 20.284 | 0.054 |
| 9665.56831 | 20.398 | 0.045 | 9665.57624 | 20.384 | 0.045 |
| 9665.58429 | 20.360 | 0.053 | 9665.59205 | 20.401 | 0.039 |
| 9665.59986 | 20.450 | 0.047 | 9665.60768 | 20.560 | 0.052 |
| 9665.61559 | 20.532 | 0.038 | 9665.62344 | 20.551 | 0.041 |
| 9665.63111 | 20.480 | 0.033 | 9665.63873 | 20.436 | 0.047 |
| 9665.58841 | 20.297 | 0.046 | 10044.56651 | 20.460 | 0.034 |
| 10044.58320 | 20.313 | 0.029 | 10044.59998 | 20.313 | 0.046 |
| 10044.63706 | 20.256 | 0.026 | 10044.65368 | 20.260 | 0.022 |
| 10044.67029 | 20.355 | 0.029 | 10044.73204 | 20.449 | 0.029 |
| 10044.74846 | 20.417 | 0.042 | 10045.53240 | 20.388 | 0.030 |
| 10045.56471 | 20.455 | 0.035 | 10045.58060 | 20.492 | 0.032 |
| 10045.61227 | 20.339 | 0.024 | 10045.62860 | 20.296 | 0.027 |
| 10046.58981 | 20.431 | 0.026 | 10046.64669 | 20.322 | 0.032 |
| 10049.57870 | 20.217 | 0.035 | 10389.61874 | 20.390 | 0.044 |
| 10389.66136 | 20.199 | 0.029 | 10390.54777 | 20.164 | 0.032 |
| 10390.59079 | 20.218 | 0.027 | 10390.60755 | 20.256 | 0.027 |
| 10390.62530 | 20.370 | 0.032 | 10390.64218 | 20.436 | 0.028 |
| 10390.66051 | 20.278 | 0.029 | 10390.67679 | 20.207 | 0.033 |
| 10391.52999 | 20.321 | 0.041 | 10391.58165 | 20.211 | 0.025 |
| 10391.62174 | 20.221 | 0.028 | 10392.57174 | 20.235 | 0.032 |
| 10392.63801 | 20.210 | 0.028 | 10393.51140 | 20.267 | 0.036 |
| 10393.55092 | 20.478 | 0.035 | 10393.59355 | 20.264 | 0.028 |
| 10394.60680 | 20.367 | 0.033 | 10394.62378 | 20.240 | 0.025 |
CAPTIONS TO FIGURES

Fig. 1.— Periodogram for SMC 13 based on $V$ photometry obtained in 1993, 1994, 1995, and 1996.

Fig. 2.— $UBV$-filter light curves and $B - V$ photometry of SMC 13 from data obtained during observing runs in 1993 (open triangles), 1994 (filled triangles), 1995 (open squares), 1996 (excluding night 2, filled squares), and 1996 night 2 (open stars). The ephemeris given in the text is used. Also shown plotted on the same period are the $ROSAT$-HRI X-ray data obtained from the archives.

Fig. 3.— Mean spectrum of SMC 13 compared with mean of CAL 83 from the same observing run. Principal lines are marked.

Fig. 4.— Co-added spectra in six phase bins, showing Balmer-line velocity changes.

Fig. 5.— Phase variation of radial velocities and equivalent widths of He II-4686 emission (filled circles) and H absorption (crosses). The dashed curve is the fit of a circular orbit to the emission-line velocities.

Fig. 6.— SMC 13 mass diagram for He II emission velocities. The dashed line shows where a main-sequence star of mass $M_2$ fills its Roche lobe. Most probable masses lie on or just below this line for inclination values near $i \sim 75^\circ$. 

