SIX SUPERSOFT X-RAY BINARIES: SYSTEM PARAMETERS AND TWIN-JET OUTFLOWS
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ABSTRACT
A comparison is made between the properties of CAL 83, CAL 87, RX J0513.9—6951, 1E 0035.4—7230 (SMC 13), RX J0019.8+2156, and RX J0925.7—4758, all supersoft X-ray binaries. Spectra with the same resolution and wavelength coverage of these systems are compared and contrasted. Some new photometry is also presented. The equivalent widths of the principal emission lines of H and He II differ by more than an order of magnitude among these sources, although those of the highest ionization lines (e.g., O VI) are very similar. In individual systems, the velocity curves derived from various ions often differ in phasing and amplitude, but those whose phasing is consistent with the light curves (implying the lines are formed near the compact star) give masses of ~1.2 $M_{\odot}$ and ~0.5 $M_{\odot}$ for the degenerate and mass-losing stars, respectively. This finding is in conflict with currently prevailing theoretical models for supersoft binaries. The three highest luminosity sources show evidence of “jet” outflows, with velocities of $\sim 1-4 \times 10^3$ km s$^{-1}$. In CAL 83 the shape of the He II $\lambda$4686 profile continues to show evidence that these jets may precess with a period of ~69 days.

Subject headings: accretion, accretion disks — binaries: close — ISM: jets and outflows — X-rays: stars

1. INTRODUCTION

The close-binary “supersoft sources” (SSSs) are now recognized as a distinct class of very luminous ($L_{bol} \geq 10^{38}$ ergs s$^{-1}$) X-ray sources characterized by extremely soft X-ray spectra with little or no radiation above ~0.5 keV (e.g., Trümper et al. 1991). Several reviews of the observational properties of these sources have recently been published (e.g., Hasinger 1996; Greiner 1996; Kahabka & van den Heuvel 1997). All SSSs appear to have high mass-accretion rates and exhibit long-term X-ray and optical variability that is thought to reflect variations in the rate of mass transfer. In addition, some SSSs show evidence of collimated outflows or “jets” (Crampton et al. 1996, hereafter CHC96; Southwell, Livio, & Pringle 1997). Van den Heuvel et al. (1992) suggested that the X-ray properties of SSSs are best explained by a model involving steady nuclear burning on the surface of a white dwarf accreting material at the Eddington rate. Many observations appear to support this model (Greiner 1996), although alternative interpretations (e.g., Kylafis & Xilouris 1993) have not yet been ruled out.

During a 1996 November Cerro Tololo Inter-American Observatory (CTIO) observing run we obtained spectra and some photometry of six close-binary supersoft sources. One of these lies in the Small Magellanic Cloud, 1E 0035.4—7230 (hereafter SMC 13). CAL 83, CAL 87, and RX J0513.9—6951 (hereafter RX J0513) are all members of the Large Magellanic Cloud, whereas RX J0019.8+2156 (hereafter RX J0019) and RX J0925.7—4758 (hereafter RX J0925) are galactic systems. Since these objects were observed with the same spectrographic configuration, inter-comparison of their spectra is very straightforward. In addition, we present previously unpublished photometry for CAL 83 and a few observations of RX J0513 and RX J0925.

New data for CAL 87 are being published in a separate paper (Hutchings et al. 1998). Long-term spectroscopic and photometric monitoring of these sources is important since the SSSs exhibit significant variations over timescales of months and years.

A summary of the properties of these six supersoft binaries is given in Table 1, where they are listed in order of decreasing orbital period. The bolometric luminosity ($L_{bol}$) listed is the average value given in Greiner’s (1996) catalog; it depends strongly on the assumed model, adopted distance, and amount of absorption assumed.

2. OBSERVATIONS AND MEASUREMENTS

2.1. Spectroscopic Data

Spectra of the SSSs were obtained with the CTIO 4 m telescope during five nights in 1996 November with the KPG1 grating and Loral 3K detector. The spectra cover the wavelength range 3700–6700 Å and have a resolution of ~1.0 Å per pixel. With a 1” slit, corresponding to three pixels, the spectral resolution is ~3 Å. Because of the range in magnitudes of these systems, quite different total exposure times and phase coverage were achieved, but the spectrographic setup, and hence resolution, etc., was the same. The Solar-Heliocentric Julian Dates (HJD) of midexposure, exposure times, and phases (where known) for four of the sources are listed in Table 2. Complete phase coverage was obtained for the other two, SMC 13 and CAL 87, but details of these spectra are given elsewhere (Crampton et al. 1997; Hutchings et al. 1998).

One-dimensional spectra were extracted and processed following standard IRAF techniques. He-Ne lamp spectra were taken before and after each stellar exposure to calibrate the wavelengths that are established to ~0.1 pixel ($\pm 6$ km s$^{-1}$) or better. The wavelength-calibrated spectra have a peak signal-to-noise ratio (S/N) of ~12 per pixel.

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TABLE 1

| Name            | Period (days) | $m_V$ [max (min)] | $K_{\text{bol}}$ (km s$^{-1}$) | $i$ (deg) | $M_V$ (ergs s$^{-1}$) | $L_{\text{bol}}/10^{37}$ a | References |
|-----------------|--------------|-------------------|-------------------------------|----------|----------------------|-----------------------------|------------|
| RX J0925 ...... | 3.79         | 17.1 (17.3)       | 84                            | 30–40    | ~0$^b$               | 0.03–0.07$^b$              | 1, 2       |
| CAL 83 ......... | 1.04         | 16.3 (17.5)       | 35                            | 25       | ~1.3                 | 10–100                      | 3, 4, 5, 6 |
| RX J0513 ...... | 0.76         | 16.6 (17.8)       | 11                            | 15       | ~2.0                 | 1–60                        | 7, 8, 5, 9, 10, 11 |
| RX J0019 ...... | 0.66         | 12.2 (13.0)       | 67                            | 56       | +0.6$^c$             | 0.3–0.9$^c$                | 12, 13, 14, 15, 16 |
| CAL 87 ......... | 0.44         | 19.0 (20.8)       | 73                            | 78       | +0.3                 | 6–20                        | 17, 18, 19 |
| SMC 13 ......... | 0.17         | 20.2 (20.6)       | 100                           | 75       | +1.4                 | 0.8–2                       | 20, 21     |

$^a$ From Greiner 1996.
$^b$ For an assumed distance of 1 kpc and $E(B-V) = 2.1$.
$^c$ For an assumed distance of 2 kpc and $E(B-V) = 0.12$.

REFERENCES

(1) Motch et al. 1994; (2) Motch 1996; (3) Cowley et al. 1991; (4) Crampton et al. 1987; (5) Gansicke et al. 1998; (6) Smale et al. 1988; (7) Alcock et al. 1996; (8) Crampton et al. 1996; (9) Motch & Pakull 1996; (10) Reinsch et al. 1996; (11) Southwell et al. 1996; (12) Beuermann et al. 1995; (13) Greiner & Wenzel 1995; (14) Matsumoto 1996; (15) Meyer-Hofmeister et al. 1997; (16) Will & Barwig 1996; (17) Cowley et al. 1990; (18) Schandl et al. 1996; (19) van Teeling, Heise, & Kahabka 1996; (20) Crampton et al. 1997; (21) Schmidtke et al. 1996.

2.2. Photometric Data

Multicolor CCD photometry of the southern sources was obtained with the 0.9 m telescope at CTIO. The images were reduced using DAOPHOT (Stetson 1987) and calibrated using observations of Landolt (1992) standard stars. To improve photometric accuracy, differential measurements were made relative to comparison stars with a field of view (see Schmidtke 1988). Table 3 presents all of our previously unpublished photometry for the southern SSSs, taken during four observing runs between 1993 December and 1996 November.

$BV$ measurements of the galactic source RX J0019 were obtained from 1995 June 23 through 1996 January 14 using a 0.75 m automated photometric telescope (APT) at Fairborn Observatory, then located on Mt. Hopkins, Arizona. Details regarding a similar telescope and single-channel photometer are given by et al. The source was monitored up to 3 times per night, following a prescribed sequence that included observations of the variable star (RX J0019), comparison star (SAO 73882, $V = 8.809, B - V = 0.482$), check star (SAO 73903, $V = 9.164, B - V = 0.497$), and a nearby sky patch. Differential photometry of RX J0019 was calculated using only those sequences in which the standard error of the mean for both variable and comparison star was less than 0.02 mag in each filter. Two observations that met these internal consistency checks displayed large random errors and were removed.

TABLE 2

| Name       | HJD 2,400,000+ | Exposure (s) | Phase (s) |
|------------|---------------|--------------|-----------|
| RX J0513 ...... | 390.733       | 900          | 0.17      |
| RX J0744 ...... | 390.744       | 900          | 0.18      |
| RX J0803 ...... | 390.803       | 900          | 0.88      |
| RX J0788 ...... | 399.788       | 900          | 0.17      |
| CAL 83 ...... | 390.819       | 1000         | 0.66      |
| CAL 83 ...... | 392.679       | 1200         | 0.44      |
| RX J0019 ...... | 393.502       | 60           | 0.39      |
| RX J0925 ...... | 391.859       | 1000         | ...$^b$   |

$^a$ From maximum positive He II velocity, using ephemerides in text.
$^b$ Period for RX J0925 too poorly known to calculate phase.

TABLE 3

| HJD 2,400,000+ | $V$ | $\sigma_V$ | $B$ | $\sigma_B$ |
|---------------|-----|------------|-----|------------|
| CAL 83        |     |            |     |            |
| 1993 Dec ...... | 49.33,558 | 17.472 | 0.010 | ... ... ... |
| 1995 Nov ...... | 50.04,759 | 16.881 | 0.006 | ... ... ... |
| 1996 Nov ...... | 50.38,912 | 17.220 | 0.010 | ... ... ... |
| 1996 Nov ...... | 50.39,724 | 17.342 | 0.008 | ... ... ... |
| 1996 Nov ...... | 50.39,759 | 17.308 | 0.019 | 50.39,763 | 17.318 | 0.020 |
| 1996 Nov ...... | 50.39,829 | 17.282 | 0.014 | 50.39,833 | 17.280 | 0.016 |
| 1996 Nov ...... | 50.39,824 | 17.264 | 0.005 | 50.39,846 | 17.241 | 0.014 |
| 1996 Nov ...... | 50.39,837 | 17.248 | 0.014 | 50.39,842 | 17.215 | 0.007 |
| RX J0925      |     |            |     |            |
| 1993 Dec ...... | 49.49,308 | 17.19 | 0.02 | 49.49,310 | 19.15 | 0.02 |
| 1993 Dec ...... | 49.49,328 | 17.28 | 0.02 | 49.49,328 | 19.25 | 0.02 |
| 1993 Dec ...... | 49.49,333 | 17.31 | 0.04 | ... ... ... |
| RX J0513      |     |            |     |            |
| 1995 Nov ...... | 50.04,735 | 16.810 | 0.007 | ... ... ... |
from the data set, yielding 115 $BV$ measurements on 66 nights. As a result of the 0.02 mag constraint, differentials taken during times of rapid flickering are ignored. APT data are most useful in assessing the general behavior of the RX J0019 light curve.

3. DESCRIPTION OF INDIVIDUAL OBJECTS

In this section we describe our spectra of individual objects and compare them with previous observations. To facilitate intercomparison, all spectra were normalized using identical methods. The resulting spectra of the six SSSs are shown in Figures 1a and 1b, in order of decreasing emission-line intensity. For display purposes, the spectra were smoothed with a 1.5 Å width Gaussian, and the wavelength-length scales of the galactic sources were shifted to match the Magellanic Cloud sources. Several of the prominent features are marked, as well as some of the strongest diffuse interstellar absorption bands (DIB). The SSSs all vary both with phase and over longer time intervals, so these spectra are just snapshots of their spectral appearance. Furthermore, the galactic source RX J0925 is heavily reddened so the S/N in the short-wavelength region of its spectrum is low.

A discussion of each source is given in the following sections. For simplicity, they are arranged below in order of right ascension: RX J0019.8 + 2156 (galactic), SMC 19 = 1E 0035.4 – 7230 = RX J0037.3 – 7214 (SMC), RX J0513.9 – 6951 (LMC), CAL 83 = RX J0543.7 – 6822 (LMC), CAL 87 = RX J0546.9 – 7108 (LMC), and RX J0925.7 – 4758 (galactic). 

3.1. RX J0019.8 + 2156

RX J0019 is one of the two galactic supersoft sources that we observed. Because its distance is not well known, the values of its absolute magnitude and some other quantities given in Table 1 are not well established. The system lies between 1 and 2 kpc. Following Greiner (1996), we have used a distance of 2 kpc to compute values in the table.

Two spectra of RX J0019 were obtained, and neither shows any evidence for spatially extended emission lines in our two-dimensional images, even though the system is close enough so that it might be possible to detect a modest surrounding nebula if one were present. The spectra were taken at spectroscopic phases 0.39 and 0.47, where phase zero is defined as maximum positive velocity (i.e., standard spectroscopic notation). To compute these phases we adopted the photometric ephemeris of Will & Barwig (1996) \[ P = 0.6604721 \text{ days}, \ T_0(phot) = \text{HJD 2448,887.5091} \] and added 0.25$P$ to that value. Beuermann et al. (1995) have shown that this is approximately correct for this system. We have added our two exposures to give the mean spectrum shown in Figure 1. Note that the spectrum closely resembles that of CAL 83, except that the 4640–4650 Å blend is much weaker. Beuermann et al. (1995) have shown that the systemic velocity is $-59 \text{ km s}^{-1}$ and the semiamplitude is $K = 67 \text{ km s}^{-1}$. Measurement of our strong emission lines gives a velocity of $-94 \text{ km s}^{-1}$, indicating the source was observed near quadrature, as the computed spectroscopic phases also indicate.

Satellite lines are visible on both sides of the strongest emission lines (see Fig. 1). He II $\lambda 4686$ shows both positive and negative emission components of about equal strength. The H Balmer lines and He II Pickering lines show the shortward displaced component in absorption. In H there is a sharp absorption, but in the He II lines there is a much weaker absorption that appears as a steep edge to the emission, but it is not seen as a separate line. The longward component is in emission at the Balmer lines but not seen at the Pickering lines. The O vi lines do not show either displaced component. All of these high-velocity lines, whether emission or absorption, show similar offsets from the central emission component. From the six strongest lines, the average shortward velocity relative to the main line is $-690 \text{ km s}^{-1}$ and the longward velocity is about $+712 \text{ km s}^{-1}$, which are the same to within the $\pm 35 \text{ km s}^{-1}$ measurement error. These observations suggest the presence of a double-sided (bipolar) jet, as has previously been found in RX J0513 (CHC96; Southwell et al. 1996). The difference in the strengths of the absorption component between various ions could indicate that the temperature of the jet falls with distance from the star, so that in the outer regions of the jet the lowest ionization lines are seen in absorption. Modeling of the light curve for RX J0019 gives an orbital inclination of $i = 56\degree$ (Schandl, Meyer-Hofmeister, & Meyer 1996). By comparison with RX J0513 with its low orbital inclination and high-velocity jets, one might expect a system with a higher inclination to show lower velocity jets since they are not pointed toward the observer.

Two high-dispersion spectra of RX J0019 were obtained at the Multiple Mirror Telescope (MMT) by Mark Wagner on 1995 October 12 and 1996 August 4. The 1995 spectrum shows no evidence of displaced lines at He II 4686 Å, but at H$\alpha$ there is a weak, positively displaced emission component at about $+800 \text{ km s}^{-1}$. On the short-wavelength side of the line there is a moderately broad absorption centered at about $-800 \text{ km s}^{-1}$. The 1996 August spectrum shows stronger jet lines, with both positively and negatively displaced emissions at He II 4686 Å and He II 5411 Å. H$\beta$, H$\gamma$, and H$\delta$ all show an emission at about $+830 \text{ km s}^{-1}$ and evidence that there is a similar negatively displaced emission, but it is strongly divided by a fairly narrow absorption at about $-450 \text{ km s}^{-1}$. Thus, the appearance of the jet lines changed considerably in about 10 months, with the displaced features more prominent in 1996 August than in 1995 October. By 1996 November these displaced lines had become even stronger and could easily be seen on the moderate-resolution spectra taken at CTIO.

A series of spectra taken during two consecutive nights in 1995 September at Lowell Observatory show no evidence of jet lines, but the spectra did not include the H$\alpha$ region. This is in agreement with the high-dispersion 1995 October MMT spectrum that showed no displaced lines at He II 4686 Å. Thus, over a period of about a year either the strength of the jets changed or at times the velocity of these jetlike features may have changed, perhaps due to precession, causing them to merge with the central emission.

Greiner & Wenzel (1995) demonstrated that the long-term ($\sim 100$ yr) light curve of RX J0019 displays irregular variability with an amplitude of $\sim 1$ mag on timescales of several years and smaller variations in a few weeks. We do not know whether the spectral changes are correlated with the long-term photometric changes.

We have obtained some photometric data covering the period 1995 June to 1996 January with the APT telescope on Mt. Hopkins. This $V$-band photometry confirms that RX J0019 is still variable on timescales of months. We have identified three levels of mean intensity in the APT data, with the source being in a "low" state on November 10–30,
F.1

**FIG. 1a**

Spectra in two wavelength regions: (a) 3800–5500 Å and (b) 5100–6600 Å. The supersoft X-ray binaries, RX J0513.9−6951, RX J0019.8+2156, CAL 83, CAL 87, RX J0925.7−4758, and SMC 13, are arranged in order of decreasing emission-line strength from top to bottom. Some prominent features are identified. DIB marks diffuse interstellar bands.
a "medium" state during October 12–28, and a "high" state for all remaining observations. Because the difference between high and medium states is small, further monitoring is needed to confirm whether there is a true distinction. Figure 2 shows the RX J0019 light and color curves, folded on the ephemeris of Will & Barwig (1996). Data for the three states are represented by different symbols, with V observations from the low and medium states adjusted by 0.220 and 0.103 mag, respectively, to bring them up to the high-state scale. The shape of the V light curve does not vary from state to state. It is dominated by a very broad, asymmetrical primary eclipse, having more scatter during ingress (near phases 0.7–0.8) than egress. This behavior strongly resembles that of CAL 87 (see Schmidtke et al. 1993) although the depth of primary minimum is significantly less (~0.5 mag for RX J0019 vs. ~2.0 mag for CAL 87). Our high-state magnitude range (V = 12.4–12.9) closely matches the photometry of Matsumoto (1996), but differs from that given by Beuermann et al. (1995) whose 1992 September 15–22 data are ~0.25 mag brighter than our high-state values at all phases.

The bottom panel of Figure 2 shows the (B − V) color curve for RX J0019. Unlike the V data, no shift has been applied since the mean color (B − V = +0.008) does not vary significantly between states. However, the curve has an unusual orbital modulation, with the source being bluest during both primary and secondary minima. Because the pattern is present in data from all three states, it is not an artifact of combining low, medium, and high-state observations. Fitting a sinusoid to the B − V measurements yields

![Graph showing photometry of RX J0019.8 + 2156 from 1995 June to 1996 January, folded on the ephemeris of Will & Barwig (1996). The system was found at three brightness states; each is shown by a different symbol. The high-state magnitudes (crosses) are plotted as observed. Data from the medium (open circles) and low (filled circles) states have been adjusted brighter by 0.103 and 0.220 mag, respectively. The shape of the V light curve does not appear to change from state to state. The bottom panel shows the overall (B − V) color curve with no shifts applied since the mean color does not vary significantly between states.](image-url)
a peak-to-peak amplitude of 0.024 mag, which is much larger than the internal consistency of the data set. Differential photometry between the check and comparison stars is constant for both $V$ and $B - V$ with a $1 \sigma$ dispersion of only 0.005 mag in each parameter. Hence, the observed color variations for RX J0019 appear to be real and not caused by variations in the comparison star.

Our APT data and extensive photometry obtained in 1995 September at Lowell Observatory (Schmidtke et al. 1998) also show short-term changes in the light curve from cycle to cycle and night to night. Similar behavior has been reported by Meyer-Hofmeister et al. (1998) in observations taken between 1996 October and December.

The mean color of RX J0019 ($B - V < 0.01$) indicates that the system is slightly reddened. Using the same $B - V$ color as for RX J0513 ($B - V = -0.11$) implies absorption of $A_V \sim 0.36$ for RX J0019. From our out-of-eclipse magnitude of $V \sim 12.4$ and adopted a distance of 2 kpc (Greiner 1996), one obtains $M_V \sim +0.6$, with considerable uncertainty.

3.2. 1E 0035.4—7230 = SMC 13

Of the observed SSSs, SMC 13 is the faintest, has the shortest period, and shows the weakest H and He II emission lines, although the lines O VI ($\lambda\lambda$3811, 5290) are comparable in strength to other SSSs. Presumably the weakness of H and He II is due to its necessarily small accretion disk in this short-period (0.1719 days; Schmidtke et al. 1996) system. The O VI lines that are formed in the innermost disk do not appear to be affected. Crampton et al. (1997) carried out a spectroscopic analysis based on 17 spectra obtained in 1996. These spectra have been averaged and are shown in Figure 1. As in CAL 87, the emission lines are noticeably broader than for the other SSSs. SMC 13 and CAL 87 are the two systems with the highest orbital inclinations (see Table 1), so the breadth of the lines must result from viewing the rotating disk nearly edge-on.

Although the emission-line spectrum of SMC 13 is similar to other supersofts, there is also a weak, broad Balmer absorption when the spectra are binned by phase. He II emission yields a well-defined velocity curve whose phasing suggests the lines are formed near the compact star and reveal its orbital motion. Modeling of the light curve by Meyer-Hofmeister, Schandl, & Meyer (1997) indicates that the system is marginally eclipsing, with $i = 75^\circ$. Using the He II emission velocity amplitude to derive the mass function, we determine masses of $0.4 M_\odot$ for the donor and $1.3 M_\odot$ for the compact star, quite different from those expected in the scenario of van den Heuvel et al. (1992).

The puzzle in this system is the Balmer absorption. It is present in all phase bins. The lines show a high-velocity amplitude, with $K \sim 400$ km s$^{-1}$. Its phasing is not well defined, although it is compatible with being a result of orbital motion of the compact star. However, the large amplitude implies improbably high masses for both components. The different amplitudes of the absorption and emission lines suggest they originate at different distances from the center of mass. Since the absorption be must seen against a continuum source, it is hard to imagine a geometry that produces this, unless the observed absorption-line velocity curve is not related to any orbital motion. The high absorption-line velocities cannot be due to gas outflow since the mean velocity would be expected to be more negative than that from the emission lines, which is not it. Thus, the “best” radial velocity curve in SMC 13 is based on the emission lines. We do not understand the origin or interpretation of the absorption lines.

3.3. RX J0513.9—6951

The spectrum of RX J0513 has been described by Pakull et al. (1993), Cowley et al. (1993), CHC96, and Southwell et al. (1996). RX J0513 exhibits the strongest emission lines of all the SSSs and also shows weak, highly shifted emission features that arise from collimated outflows or “jets” (CHC96; Southwell et al. 1996). The 1996 spectra are similar to those taken in 1994 (CHC96), although the detailed shapes of the lines, including those of the jet lines, show changes.

An intercomparison of our 1993, 1994, and 1996 spectra in the spectral region 4600—5000 Å is shown in Figure 3. The long-wavelength wings of Hβ and He II 4686 are stronger in 1994 and 1996 than in 1993 (also see Fig. 7 of CHC96) as is the complex of C III, N III, and N v lines shortward of 4686 Å. In 1996 the highly displaced “jet” lines are much weaker and may have lower velocities than in 1994. The violet-shifted He II (4686 Å) emission line is the best defined of the jet features. In order to compute the outflow velocities for these lines, we have adopted a systemic velocity for RX J0513 of +280 km s$^{-1}$ and determined the displacement from a central line with that velocity. In the 1996 spectra the negatively displaced He II emission has a wavelength of 4634.9 Å (−3529 km s$^{-1}$) compared with 4628.0 Å (−3971 km s$^{-1}$) in 1994. In the 1996 spectra there is a relatively strong P Cygni absorption feature at 4809.8 Å, compared to its being mostly in emission in 1994. Since only hydrogen lines show absorption components, we identify this displaced feature with Hβ, giving it an outflow velocity of −3458 km s$^{-1}$, similar to the He II high-velocity emission line. In the 1996 spectra there is a sharp emission feature at 4935.5 Å. If it is the redshifted component of Hβ, it has an outflow velocity of +4296 km s$^{-1}$, but the width of the feature in 1993 and 1994 suggests they could be blends. Hence the 1996 feature could be entirely due to an unidentified emission line that contributes to the blend. The corresponding positive component of λ4686, which should be near 4760 Å, is not present in our 1996 spectra.

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Fig. 3.—The 4600—5000 Å region of the spectrum of RX J0513.9—6951 in 1996 compared to those observed in 1994 and 1993. The dashed lines are located at the positions of the 1994 “jet” lines. These features were much weaker in 1996.
In Figure 4 the 1996 Hα and Hβ line profiles are compared with the 1994 Hβ line. These spectra are displayed on a velocity scale to show that features with similar velocities are present at both Hα and Hβ. In the 1996 spectra there is a highly displaced absorption line at 6496 Å (−3332 km s$^{-1}$ with respect to the systemic wavelength of Hα), which has a shape and velocity similar to the one near Hβ. Thus, the negatively displaced He II λ4686 emission line and the absorption features shortward of the H lines have comparable velocities. There appears to be an emission line at ~6656 Å (outflow velocity of +3976 km s$^{-1}$ if it is the redshifted emission component of Hα). However, this feature is so close to the end of the spectrum, its wavelength is not reliably determined. The lack of a corresponding He II component makes it uncertain if the feature is the positively displaced jet line.

In an effort to look more closely at the asymmetry of the 1996 emissions at Hα and Hβ, we have reflected the long-wavelength side of the emission profile onto the short-wavelength side and then subtracted the blueward profile. The difference between the two sides shows evidence of absorption at velocities of about −500 to −1700 km s$^{-1}$ and about −2200 to −4000 km s$^{-1}$. This, of course, assumes a symmetrical emission profile that is defined by the redward side. In 1994 the hydrogen emission was more symmetrical. Doing a similar reflection and subtraction to the 1994 spectra shows the high-velocity absorption was weakly present. Thus apparently there are both low- and high-velocity absorption components at the hydrogen lines. This behavior may be analogous to stellar winds where the densities and velocities change as the material is accelerated outward.

Thus, comparison of our 1996 and 1994 spectra show that the principal emission lines (He II and H) have similar strengths although their profiles have changed. The O VI lines have comparable strengths in both years, within our measurement errors, whereas the complex of lines near 4650 Å (C III, N III, C IV) is considerably stronger in the 1996 spectra. The negatively displaced P Cygni H absorption lines are stronger in 1996, although they were weakly present in 1994, whereas the positively displaced “jet” emission lines are weaker in 1996 than in 1994. The change in the strength of the displaced absorption component suggests that our line of sight in 1996 may have been more along the approaching jet causing the features to be seen in absorption.

In this source the line of sight is near the polar axis (i ~ 15°), and thus we may be looking along the jets. The fact that the shortward-shifted component is seen in absorption suggests that either the disk or the jet emission itself lies behind the absorber; both require our line of sight to be almost parallel to the jet. We would not expect to see high-velocity absorption in any other situation, so that this is a further indication that the inclination of the system is very low. The absorption profile, as in a stellar wind, shows a terminal velocity close to that seen in the receding jet emission. This means we may be looking through an accelerating region of the jet, going from ~90% to its final value. The variation of the profile and depth of the absorption over timescales of a year indicates that the absorbing column or the velocity profile in the outflow change or that our line of sight is not always directly along the jet (perhaps due to precession).

Alcock et al. (1996) and Reinsch et al. (1996) have published extensive photometry of RX J0513 that shows that the system exhibits recurring low states, fading irregularly by ~1 mag every few months. Our 1992, 1994, and 1996 spectra all appear to have been taken when it was in its normal “high” state. Our photometry (Crampton et al. 1996) confirms that the source was in a high state when our 1994 spectra were obtained. One 1995 November image also shows the source to have been in its bright state, with $V = 16.8$. This is in good agreement with overlapping data of Alcock et al. (1996). We do not have any 1996 photometry for RX J0513, but the spectral appearance suggests the source was bright.

By contrast, during our 1993 observations RX J0513 was in a low state (Reinsch et al. 1996), and the principal emission lines of H and He II were weaker. Reinsch et al. (1996) report similar observations and explain both the emission-line and photometric behaviors with a simple model in which decreasing mass transfer causes the photosphere of the accreting white dwarf to shrink, thus reducing the illumination of the disk, which is responsible for most of the optical emission.

Using the extensive MACHO photometric data, Alcock et al. (1996) detected a small orbital variation with a semi-amplitude of ~0.02 mag and a period $P = 0.76278$ days. (As an aside, Alcock et al. 1996 give $T_0$ as time of maximum light rather than the usual notation as time of minimum light.) The value of the period is consistent, within the errors of both determinations, with the spectroscopic period found by Crampton et al. (CHC96) of 0.75952 days and later confirmed by Southwell et al. (1996). Because of the very small range of the light variation, $T_0$ is poorly determined. Therefore, to compute phases listed in Table 2 we have used the Alcock et al. (1996) value for the period but the epoch of maximum radial velocity from the CHC96 spectroscopic study [$T_0$(max vel) = HJD 2,449,332.63]. Using these phases, our 1996 November spectra are expected to have velocities slightly above the systemic value, and our measurements show that they do.

The very small amplitudes of both the orbital velocity and light variations indicate that RX J0513 is viewed nearly pole-on. If the emission lines (and most of the light) orig-
minate in the accretion disk, then for the simplest case minimum light should occur at spectroscopic phase 0.25. However, minimum light (as defined by $T_0 + 0.5P$, using the Alcock et al. 1996 $T_0$) occurs at spectroscopic phase $0.05 \pm 0.03$. In such a low-inclination system, minimum light is probably not a good indicator of when the stars are at conjunction, but rather when some disk structure or stream occults some of the light from the inner disk. However, if the light curve really did reveal the relative orientation of the stars, then the observed velocities would all be due to nonorbital motions.

To summarize, RX J0513 is brightest of the supersoft binaries we observed. This may imply that it is undergoing the highest rate of mass transfer. It shows the most pronounced high-velocity jets of all the SSSs we have observed, but of course its low orbital inclination makes detection of these more favorable than in high-inclination systems.

3.4. CAL 83 = RX J0543.7 − 6822

The spectrum of CAL 83 has been described by Pakull, Ilovaisky, & Chevalier (1985), Crampton et al. (1987), and Smale et al. (1988). The latter authors determined the orbital period to be 1.044 days from their extensive photometric observations. Based on spectroscopic observations obtained between 1982 and 1987, the period was later refined to be 1.0475 days et al. (with the epoch(Cowley 1991) obtained between 1982 and 1987, the period was later.

To summarize the average magnitudes in different epochs going back to 1980. However, there are insufficient CAL 83 data to determine whether the high and low states vary regularly (perhaps related to the 69 day spectroscopic variations) or irregularly as in RX J0513.

Pakull & Motch (1989), Bland-Hawthorn (1995), and Remillard, Rappaport, & Macri (1995) have published [O III] images of the nebula around CAL 83, which appears to be ionized by the soft X-ray flux from the central source. Rappaport et al. (1994) presented detailed calculations of the ionization and temperature structure expected in such nebulae. Remillard et al. (1995) gave an analysis of spectra similar to our own as well as their [O III] and H$\alpha$ images, making detailed comparison with their theoretical models. Our spectra, taken with a 1.5 × 90° slit centered on CAL 83, show emission extending over ~ 75° with enhancements at ± 13° from the central star in all lines except H$\alpha$ λ4686. A portion of one of our two-dimensional spectra is displayed in Figure 5. The intensity of H$\alpha$ λ4686 declines radially outward from the star. Extended emission is also visible at [O III] 3727 Å, H$\gamma$, H$\beta$, [O III] 4959 Å + 5007 Å, and H$\alpha$ (only H$\alpha$ λ4686, H$\beta$, and [O III] are displayed in Fig. 5). H$\alpha$ is weaker than expected, probably because it was partially removed by our background subtraction procedure (based on flux near the ends of the slit) since it has a

**TABLE 4**

| Observation UT | Mean mag | Reference | Notes |
|----------------|----------|-----------|-------|
| 1980 and 1982 | $B = 16.9\pm17.5$ | 1 | $(B-V) = +0.02$ to $-0.06$ |
| 1984 Aug 23–26 | $V = 16.32$ | 2 | |
| 1984 Dec 11–24 | $V = 16.87$ | 2 | 0.22 mag orbital amplitude |
| 1985 Nov 11–14 | $V = 17.28$ | 3 | $(B-V)_{max} = -0.025$ |
| 1993 Dec 10 | $V = 17.47$ | 4 | Only one observation |
| 1995 Nov 25 | $V = 16.88$ | 4 | Only one observation |
| 1996 Nov 2–8 | $V = 17.28$ | 4 | $(B-V)_{max} = -0.010$ |

REFERENCES.—(1) Pakull et al. 1985; (2) Smale et al. 1988; (3) Crampton et al. 1987; (4) this paper.
larger spatial extension. Nevertheless, the spatial variation over our 90° slit is extremely small, much less than for the other lines. In the figure note the very different distributions of intensity along the slit for He II λ4686 compared to Hβ and the [O III] λ4959 and λ5007 lines.

3.5. CAL 87 = RX J0456.9 − 7108

CAL 87 is unique in showing deep eclipses that, in principle, provide important constraints on the system parameters. Ironically, there are many uncertainties in the interpretation of the velocities of various observed lines. This is caused partially by the high inclination, since at this orientation one detects the complex motions in the accretion disk.

The light-curve analysis carried out by Schandl et al. (1996), using a model with an azimuthally irregular disk, yields an orbital inclination of 78°. Regardless of the light-curve model used, the inclination must be larger than ~65° to cause eclipses of any kind. When orbital inclinations are this high, the masses derived through the mass function change little with inclination.

In our original study of CAL 87, He II λ4686 was measured from a series of spectra observed in 1988 December (Cowley et al. 1990). The resulting radial velocity curve showed the He II emission line to have a semiamplitude of $K = 40$ km s$^{-1}$ that was properly phased with respect to the light curve to suggest it might be formed near the compact star. Using this low amplitude to compute the mass function resulted in large masses for the compact star ($> 4 M_\odot$) for any donor mass greater than 0.4 $M_\odot$. A few spectra obtained in 1993 showed quite different phasing and amplitudes, suggesting that the system undergoes significant changes, but there were not enough data to quantify the changes or to redetermine the masses.

In 1996 we obtained a major new data set (Hutchings et al. 1998) from which we have derived more extensive spectroscopic information, but these data still do not finally resolve the question of the masses. The spectrum shown in

![Two-dimensional spectrum of CAL 83](image)

Figure 5.—Two-dimensional spectrum of CAL 83 in the wavelength region 4600–5050 Å. The 1:5 slit was oriented east-west centered on CAL 83, and the resolution along the slit was 0:5 per pixel. The spatial extent shown is 93°, and east is up. The background light, including that from the continuum of CAL 83 and from nearby stars, has been subtracted. Remnants of some defective CCD columns are visible near the center. Note the very different distributions of intensity along the slit for He II λ4686 compared to Hβ and the [O III] λ4959 and λ5007 lines.

Figure 1 is a simple average of the 25 spectra taken in 1996, scaled by their average fluxes. The individual spectra show strong Balmer absorption lines that vary with phase, as well as He II and O VI emission and Ca II absorption. All lines have different amplitudes and phasing. The phasing of the velocity curves may result from a combination of superposed absorption on the emission lines distorting their profiles, azimuthally varying obscuration in the disk, and nonorbital motions in the system. The Balmer absorptions are the only velocities that are phased a quarter cycle away from the eclipse, so that they might reflect the orbital motion of the compact star. Their semiamplitude is $K = 73$ km s$^{-1}$, which, if orbital, implies masses similar to those found for SMC 13, as discussed above. A massive white dwarf ($1.3 M_\odot$) would have a donor star with a mass of only ~0.4 $M_\odot$ in this system. Again, this differs from the “standard” model in which the nondegenerate star is expected to be in the range 1–2 $M_\odot$. The O VI and He II emission lines have lower $K$ values (near ~30 km s$^{-1}$), but the maximum of the velocity curve occurs about 0.14P too early, suggesting contamination with nonorbital motions. Since the phasing is rather poorly constrained, we can consider what masses these rather high-excitation lines that must be formed near the compact star would give. They imply donor star masses of about 0.4 $M_\odot$ and a massive compact star with $M > 4 M_\odot$ (Hutchings et al. 1998), similar to the older result for CAL 87 (Cowley et al. 1990).

Over the last several years we have obtained photometry of CAL 87, primarily to confirm the time of minimum light. The ephemeris has been very steady over many years, with that given by Schmidtke et al. (1993) being highly accurate. The time of minimum light is given by

$$T_0 = \text{HJD } 2,447,506.8021(\pm 0.0002) + N \times 0.4426777(\pm 0.0000016) \text{ days}.$$  

Our observations obtained in 1994 November and 1996 November show that the depth of the minimum has decreased by over half a magnitude since 1987/1988. The
long-term changes in the light curve are discussed in detail by Hutchings et al. (1998).

3.6. RX J0925.7−4758

RX J0925 is one of the two galactic supersoft sources we observed. Although the mean magnitude of the system is relatively bright \((V \sim 17.2)\), our single spectrum is weak and very noisy below \(\sim 4500 \text{ Å}\) due to the high interstellar absorption that is estimated to be more than six magnitudes (Mocht 1996). The emission lines are relatively weak and narrow compared to other SSSs (see Fig. 1 and Table 5). The narrow width of the emission lines and the small observed range of the optical light curve \((\Delta m_r \sim 0.2\) mag) suggest RX J0925 is viewed at a moderately low-inclination angle. However, the fairly large amplitude of the emission-line velocities, \(K_{\text{eff}} = 84 \text{ km s}^{-1}\) (Mocht, Hasinger, & Pietsch 1994) means the system must be at a higher inclination than the nearly face-on systems CAL 83 and RX J0513. We estimate the inclination may be in the range \(i = 30^\circ−40^\circ\), based on these factors.

The distance and hence the luminosity of RX J0925 are poorly known. Mocht et al. estimate \(E(B−V) = 2.1\) from comparison of the color with RX J0513. The strength of the diffuse interstellar bands (marked as DIB in Fig. 1) also suggests \(E(B−V) \sim 2\). Mocht (1996) concludes that the source lies between 1 and 2 kpc, considering the strength of the interstellar features, the color, and the implied bolometric luminosity. This gives RX J0925 an absolute visual magnitude in the range \(M_V \sim −1\) to \(+1\).

Mocht et al. (1994) and Mocht (1996) argue from X-ray, photometric, and spectroscopic data that the orbital period of this system is near \(\sim 3.8\) days. However, alias periods near one day are not yet completely ruled out, and any one of these would make more sense physically. Until a reliable period has been determined from data spanning several orbital cycles, the parameters for this system must be considered quite uncertain.

If the 3.8 day period is used, the data of Mocht et al. (1994) provide only partial phase coverage. The fairly long period and large velocity range together imply the component stars must be widely separated. For example, at \(i = 30^\circ\) a 1 \(M_\odot\) compact star would have a 3 \(M_\odot\) companion whose radius must be \(\sim 8 R_\odot\) in order to fill its Roche lobe. Such a star would be substantially evolved since a main-sequence star of this mass is much too small. For an inclination of \(i = 40^\circ\), the secondary mass and required radius are somewhat smaller, but still an evolved star is required. In either case, the mass donor would have an absolute magnitude of \(M_V \sim 0\) and hence should be visible in the spectrum. We have looked carefully, particularly in the long-wavelength region, for absorption lines indicating the presence of an A–F giant and find none. This search should be repeated with higher S/N spectra. However, if the orbital period is shorter or the velocities not orbital, the secondary star could be considerably smaller and hence not visible in the composite spectrum.

Although the He II and H Balmer emission lines are much weaker than in most of the other SSSs, the strength of the O VI line at 5290 Å and the N II/C III complex at 4630–4660 Å are comparable. The strengths of these lines are likely to be due to the level of ionization in the disk rather than an abundance effect. The C/N blend is present in many low-mass X-ray binaries, even in systems whose location and motion indicate they are Population II objects.

Our spectra show no evidence of displaced lines that would indicate the presence of outflows or jets. However, the low signal-to-noise ratio of the spectrum does not provide a good opportunity to search for these weak features. Better spectra need to be obtained for this purpose.

4. COMPARISON OF THE SSS SPECTRA

A summary of equivalent widths of selected lines is given in Table 5, as well as the FWHM of He II \(\lambda 4686\). It is obvious from the intensities of the H and He II emission lines, particularly those for RX J0513, CAL 83, and RX J0019, that the Balmer decrement is much stronger than that of the He II Pickering series, so that a substantial fraction of H\beta and the higher Balmer series emission must be attributed to He II. Although the height or peak flux of the emission lines varies monotonically from top to bottom in Table 5 (as shown in Fig. 1), the equivalent widths of most lines are very similar for CAL 83, RX J0019, and CAL 87. There are substantial variations in the emission-line widths and in the strength of the Balmer absorption components. In particular, the Balmer lines of RX J0019 and CAL 83 show evidence of strong P Cygni–type profiles.

The strength of the C IV doublet at 5801, 5812 Å appears to decline systematically from top to bottom of the sequence shown in Figure 1, but there is a large variation in the strength of the complex of C III/N III blend near 4640–4650 Å. The strength of this feature in RX J0925 is probably not associated with higher CNO abundances in galactic objects compared to Magellanic Cloud sources since it is very weak in the other galactic source, RX J0019. Probably the level of ionization in the inner disk plays a major role in the strength of this blend. CHC96 (Fig. 7) show the contribution of various lines in this region to the 4640–4650 Å complex in RX J0513. In the latter object and CAL 87, the

### Table 5

| Name      | He II \(\lambda 4686\) | He II \(\lambda 4541\) | He II \(\lambda 5411\) | Hα \(\lambda 6563\)* | Hβ \(\lambda 4861\)* | Hγ \(\lambda 4340\)* | O VI \(\lambda 5290\) | O VI \(\lambda 3811\)* | FWHM (Å) |
|-----------|------------------------|-----------------------|-----------------------|---------------------|---------------------|---------------------|-----------------------|-----------------------|----------|
| RX J0513  | −22.5                  | −1.5                  | −3.1                  | −41.3               | −11.8               | −4.1                | −0.5                  | −1.7                  | 5.8      |
| CAL 83    | −12.1                  | −0.8                  | −1.8                  | −21.9               | −4.8                | −1.9                | −1.3                  | −1.6                  | 5.4      |
| RX J0019  | −14.1                  | −1.1                  | −2.2                  | −23.6               | −4.0                | −1.1                | −0.7                  | −0.9                  | 7.4      |
| CAL 87    | −14.2                  | −1.2                  | −2.4                  | −19.1               | −4.3                | −1.6                | −1.8                  | −1.9                  | 12.4     |
| RX J0925  | −5.3                   | −0.5                  | −0.5                  | −4.1                | ...                 | ...                 | −0.8                  | ...                   | 5.1      |
| SMC 13    | −2.6                   | −0.3                  | −0.4                  | −6.8                | +1.3                | +1.1                | −0.7                  | −1.1                  | 11.0     |

* H lines may include a contribution from He II Pickering lines.

* Weaker O VI line at 3835 Å not included in measurement.
emission extends to at least 4665 Å, indicating that C III
and/or C IV lines are major contributors. The strength of the
C IV doublet at 5801, 5812 Å in RX J0513 supports this
same interpretation. In contrast, the equivalent widths of
the very high-excitation lines of O VI appear to be almost
constant for all systems.

The emission lines in CAL 87 and SMC 13 are much
wider than those of the other sources, consistent with the
known inclinations of CAL 87 (i = 78°, eclipsing) and the
estimated high inclination of SMC 13 (i ∼ 75°; Crampton et
al. 1997). This implies they are broadened primarily by
Keplerian motions in their accretion disks.

Gänsicke et al. (1998) have discussed the ultraviolet
spectra of CAL 83 and RX J0513, the two most luminous
SSSs in the LMC. They find the systems display very similar
spectra, with N V (1239, 1243) and O V (1371) being the most
noticeable emission lines in the range 1150–1450 Å. In both
stars, each component of the N V doublet appears split as if
formed in a rotating ring or disk. Their small separation
supports the other indications that the inclination in each of
these systems is very low.

5. HIGHLY SHIFTED LINES AND JETS

RX J0513 shows widely displaced emission lines on both
sides of the strongest emission features that are thought to
arise from bipolar outflows or jets with velocities of ∼4000
km s⁻¹ (CHC96; Southwell et al. 1997). The lower velocity
displaced lines in RX J0019 and the broad λ4686 emission
wings in CAL 83 may also indicate high-velocity outflows
(Crampton et al. 1987; this paper). In CAL 83 the red wing
of He II λ4686, shown in Figure 1, extends to ∼2450 km
s⁻¹. The violet components of each line in the CAL 83
appear to have been absorbed, giving these lines a charac-
teristic P Cygni profile with an outflow velocity of about
−690 km s⁻¹. Similar emission and absorption features are
visible in RX J0019 in both the H Balmer and He II Pick-
ering series, indicating outflows with velocities of ∼800 km
s⁻¹.

Livio (1997) has argued by analogy with jets in other
astrophysical objects (from young stellar objects to active
galactic nuclei) that highly collimated outflows or jets occur
whenever a central energy/wind source is surrounded by an
accretion disk threaded by a vertical magnetic field. Fur-
thermore, he points out that the jet velocities are always
the order of the escape velocity from the central object. In
the case of SSSs, the observed ∼700–4000 km s⁻¹ velocities
are consistent with the escape velocity from a white dwarf.

Pringle has suggested that accretion disks that are
strongly irradiated by a central object are unstable to
warping, and Southwell et al. (1997) discuss the SSS in
this context. As a result of warping, the associated jets are likely
to precess, so that periodic motions of the shifted lines are
expected. CHC96 showed that their observations of CAL 83
are consistent with such behavior, with a possible period of
∼69 days. Recent data continue to support this. Similarly,
in this paper we have presented evidence that there are
long-term changes in the jet features in RX J0019, although
no timescale has yet been established.

6. DISCUSSION

The emission-line intensities in the six observed SSSs
appear to be strongly correlated with their absolute magni-
tudes, apparently more so than with L X or with the size of
the orbit (and hence size of the accretion disk). Undoubtedly,
the accretion rate plays a major role in the brightness of the sources, but orientation of the systems
must be significant too. The high orbital inclinations of
CAL 87 and SMC 13 may account in part for their fainter luminosities.

The high accretion rate may produce a thick rim extend-
ing halfway around the accretion disk and contributing a
substantial fraction of the optical luminosity (Schandl et al.
1996; Meyer-Hofmeister et al. 1997). Detailed models of
SSS light curves by Meyer-Hofmeister et al. (1997) indicate
that the accretion rate in the RX J0513 system is four times
that in RX J0019 or CAL 87, supporting the idea that the
strong emission-line intensities observed in RX J0513 are a
result of high mass transfer. At larger accretion rates, the
rim of the accretion disk is higher, and therefore it presents
a larger cross section to the compact star. This “screen”
is illuminated by the compact star, so the contribution from
its integrated brightness is enhanced relative to other con-
tributors to the total light. There is increasing evidence that
the principal emission lines arise in a hotspot or “screen”
and hence are directly affected by the accretion rate.
However, the high-excitation O VI lines appear to show
little variation from system to system, or with epoch, and so
may arise from a more stable inner region of the accretion
disk. We note that the O VI lines weaken or disappear near
minimum light in CAL 87 and SMC 13, appearing to be
eclipsed. Unfortunately, the weakness of the O VI lines and
the faintness of the systems preclude accurate velocity mea-
surements that might reveal the orbital motion of the
compact star in these two systems.

Long-term spectral variations that seem to be common in
all the SSSs may be due to a combination of irregular variations in the mass-accretion rate (e.g., RX J0019, CAL
83) and precessing accretion disks (e.g., CAL 83). According
to Meyer-Hofmeister et al. (1997) the erratic variability in
the long-term light curves can be explained in terms of
changing extent and height of the “screen.” However, these
changes could also result from variation in the rate of mass
transfer. Such changes could equally well be responsible for
the intensity and profile variations observed in the emission
features. Simultaneous spectroscopic and photometric
monitoring over several months on systems like CAL 83
and RX J0019 should be helpful in the study of disk preces-
sion.

A model that successfully reproduces the X-ray and
optical luminosities is that proposed by van den Heuvel et
al. (1992) in which a 0.7–1.2 M ☉ white dwarf accretes matter
from a companion star of about twice its mass at a suffi-
ciently high rate that steady nuclear burning occurs on its
surface. But, as we have shown, spectroscopic data for many
of these systems indicate that the mass donor has only about
half the mass of the compact star. This conflict between the
spectroscopic observations and the currently most popular
model needs to be resolved with improved spectroscopic
studies and a fresh look at the models.

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