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ROSAT Observations of the Symbiotic Stars PU Vulpeculae and FG Serpentis, and the Cataclysmic Variable V Sagittae

D. W. HOARD AND GEORGE WALLERSTEIN

Department of Astronomy, University of Washington, Box 351580, Seattle, Washington 98195
Electronic mail: hoard@astro.washington.edu, wall@astro.washington.edu

L. A. WILLSON

Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011
Electronic mail: s1.law@isumvs.iastate.edu

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ABSTRACT. *ROSAT* PSPC pointed observations of PU Vulpeculae on 1992 November 10–12 UT give a count rate of $4.00 \pm 0.75 \times 10^{-3}$ cts s^{-1} in the energy range from 0.1 to 1.8 keV. The count rate outside this energy range is approximately zero. An analysis of the energy spectrum, with the requirement that the result be consistent with the observed reddening of about 0.50 mag, yields $T = 0.25$ (+0.19, −0.13) keV and $\log(N_{\rm H}) = 21.40$ (+0.28, −0.35) for a bremsstrahlung emission model. FG Serpentis was not detected during an 8467 s *ROSAT* PSPC pointed exposure on 1992 March 8–23 UT. Serendipitous X-ray sources detected nearby give an upper limit of $\sim 9.3 \times 10^{-4}$ ct s^{-1} for the X-ray emission from FG Ser. The post-outburst X-ray fluxes of FG Ser and PU Vul are compared to those of three other symbiotic novae, HM Sagittae, V1016 Cygni, and RR Telescopii. The eclipsing nova-like variable V Sagittae was serendipitously observed during the *ROSAT* exposure of PU Vul and found to have a count rate of 0.013 ± 0.003 cts s^{-1}, which is about the same as it showed during *Einstein* IPC observations in 1979–80. A period of 6.0 hr is detected in the X-ray data; this period is roughly half the length of the observed orbital period of V Sge.

1. INTRODUCTION

1.1 The Symbiotic Novae

The symbiotic novae are binary stars consisting of a red giant, often a Mira-type variable, and a hot compact object, usually presumed to be a white dwarf. Further, each of these systems has shown only one outburst within roughly the past century (Allen 1980). The decay times after outburst are on the order of decades, which implies that hydrogen burning on the white-dwarf component is likely to be responsible for the outburst events. Some well-known examples of this class of star are RT Serpentis, RR Telescopii, V1016 Cygni, and HM Sagittae.

Optical observations of symbiotic novae show two general types of spectra at maximum light (i.e., during outburst). In the first type, a spectrum resembling that of an A–F supergiant is seen after outburst, followed later by the appearance of emission lines of increasing excitation. An example of this type is RR Tel, in which a continuum spectrum (like that of an F supergiant) was seen for about five years after outburst (1944–1949), followed by the rapid appearance of emission lines. These lines reached the level of [Fe VII] about 15 years after the outburst (Thackeray 1977). V1016 Cyg and HM Sge are examples of the second type; these systems showed spectra characterized by strong emission lines from a highly ionized plasma as soon as they were discovered (McCuskey 1965a,b; Dokuchaeva 1976; Bopp 1977).

A survey of symbiotic stars for X-ray emission by Allen (1981) using the *Einstein* satellite revealed that the symbiotic novae RR Tel, V1016 Cyg and HM Sge are bright in X-rays. Kwok and Leahy (1984) determined the X-ray fluxes for these three stars from Allen's data. When plotted against the time since outburst, the fluxes can be fitted by a power law with an exponent near unity (see Fig. 3). An additional observation showed that the X-ray flux of HM Sge was decaying at a rate consistent with an *e*-folding time scale of one to several decades. (Willson et al. 1984).

1.2 PU Vulpeculae

In 1978, Kuwano (1979) and Honda (1979) independently found the variable star PU Vulpeculae to be rapidly brightening. It had varied irregularly in the magnitude range $B = 14.5$ to $B = 16.6$ between 1900 and 1977 (Liller and Liller 1979); it reached $B = 9.25$ by mid-1979 (Whitney 1979). After a dip to $B = 13.0$ in mid-1980 that lasted altogether about 500 days, it returned to about $B = 9.6$ and showed only small brightness fluctuations thereafter (Belyakina et al. 1984, 1989). Recently, Garnavich and Trammel (1994) observed a second such dip; they interpreted these events as eclipses in the binary system. Their observations constrained the eclipse duration to be between 5 and 13 months, and gave a period for PU Vul of 13.6 ± 0.3 yr, assuming that there were no unobserved eclipses between 1980 and 1994. Kolotilov et al. (1995) and Nussbaumer and Vogel (1995) have compiled long-term light curves of PU Vul that demonstrate the absence of any additional eclipses (see also Mürset and Nussbaumer 1994), and allow more precise estimates for the eclipse period: 13.47±0.02 yr and 13.42±0.27 yr, respectively.

The spectrum of PU Vul was first described as like that of a late-A supergiant at the onset of the outburst, then as an M giant during the dip, and later as an F supergiant (Yamashita et al. 1983). Kenyon (1986) recognized that it should be classified as a symbiotic nova. By 1987, PU Vul began to show emission lines whose excitation increased steadily to include He II and Fe II lines (e.g., Gochermann 1991; Feibelman et al. 1991; Tomov et al. 1991; Klein et al. 1994) presumably excited by the O VI resonance lines near 1036 Å; however, the emission features at 6830 and 7088 Å expected from Raman scattering of the O VI doublet (Schmid 1989) are not seen in PU Vul. The presence of He II and O VI indicate high excitation and suggested the possibility that Pu Vul might be an X-ray source.

1.3 FG Serpentis

FG Serpentis (=AS 296; Schweitzer 1990) was first discovered as a very strong Hα source by Merrill and Burwell (1950). It has since been classified as an S-type symbiotic (i.e., infrared radiation produced by the star itself rather than by dust in the system) composed of a white dwarf and an M5 giant (e.g., Sanduleak and Stephenson 1973; Taranova and Yudin 1985; Munari and Whitelock 1989). Munari et al. (1992) derived an orbital period of 650 days from photometric observation of two eclipses in the interval 1988–92. Kurochkin (1993) determined a similar period of 630 days from archival plates taken between 1949 and 1987.

The star underwent a major outburst in 1988 characterized by an increase in brightness of $\Delta B \approx 4$ mag (Munari 1988) and a significant flux increase towards the blue end of its spectral energy distribution (Munari and Whitelock 1989). Optical spectra of FG Ser obtained between 1988 July 18 UT and 1992 March 23 UT (the last of these spectra was obtained during our *ROSAT* exposure) showed a shell-type spectrum (Wallerstein et al. 1993). Gutiérrez-Moreno et al. (1992) conclude from *IUE* observations that FG Ser is a symbiotic nova whose outbursts are caused by a thermonuclear runaway in the hydrogen-burning shell of an $M \approx 0.5 M_\odot$ white dwarf that is accreting from the late-type giant. It is possible that FG Ser is more properly identified as a Z Andromedae type star (i.e., a "normal" symbiotic) that undergoes rare and long-lived outbursts, rather than a symbiotic nova. Such a classification is suggested by the small amplitude of FG Ser's outburst; its relatively short orbital period is also typical of Z And symbiotic stars (Kenyon 1986).

2. OBSERVATIONS

The *ROSAT* pointed observation of PU Vul took place on 1992 November 10–12, using the Position Sensitive Proportional Counter (PSPC; a description of this instrument is in Trümper et al. 1983). The total exposure time on PU Vul was 26,730 s distributed in 14 intervals of approximately equal length during the dates of observation. This is the only *ROSAT* observation of PU Vul, and the first X-ray detection of the star. A 1981 *Einstein* IPC exposure of 5913 s duration shows no source above the background at the position of PU Vul.

The symbiotic star FG Ser was observed in a separate *ROSAT* PSPC pointed observation during the interval 1992 March 8–23 UT. The total exposure time was 8467 s. A search of the *Einstein* and *ROSAT* public archives turned up no previously detected X-ray sources within a 2 arcmin radius of the optical position of FG Ser.

The cataclysmic variable V Sagittae was located 31 arcmin off-axis in the field of our *ROSAT* observation of PU Vul. The analysis of this serendipitous observation is described in the Appendix to this paper.

3. RESULTS

The Post-Reduction Off-line Software package (PROS[1], v2.3.1) was used within the Image Reduction and Analysis Facility (IRAF[2], v2.10.2) environment for all aspects of the data reduction.

3.1 PU Vulpeculae

Since PU Vul is located only 0.32 arcmin off-axis in the *ROSAT* image, no vignetting correction was applied to the data.

3.1.1 Aperture photometry and timing analysis

The PROS task *imcnts* was used to measure the net counts over the entire time of observation in a circular aperture centered around PU Vul's position in the X-ray image. The background contribution was removed by subtracting the number of counts per pixel within a circular annulus surrounding the photometry aperture. The aperture has a radius of 1.25 arcmin; the background annulus has inner radius 1.67 arcmin and outer radius 2.08 arcmin.

The aperture photometry was first performed in successive 24-channel-wide subsets of the entire available energy range (256 channels covering ≈0.1–2.4 keV), in order to determine the subrange of energies in which there are (positive) net contributions to the total number of source photons. This initial analysis showed that all of the source photons were detected in the energy range from 0.1 to 1.8 keV. The gross number of counts in the photometric aperture over this energy range was 227 and the area-normalized counts from the background annulus totaled 120, giving 107±20 net counts for PU Vul, or a count rate of $4.00 \pm 0.75 \times 10^{-3}$ cts s^{-1}.

Hardness ratios for the X-ray emission from PU Vul were calculated by determining the net counts in several energy subranges: A=0.11–0.42 keV, B=0.52–2.02 keV, C=0.52–0.91 keV, and D=0.91–2.02 keV. These are the energy ranges used in the standard *ROSAT* data-reduction procedures. The hardness ratios are

$$\mathrm{HR1} = (B-A)/(B+A) = +0.78 \pm 0.25 \qquad (1)$$

and

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[1] Maintained by the Harvard-Smithsonian Center for Astrophysics.

[2] Operated by the National Optical Astronomy Observatories.

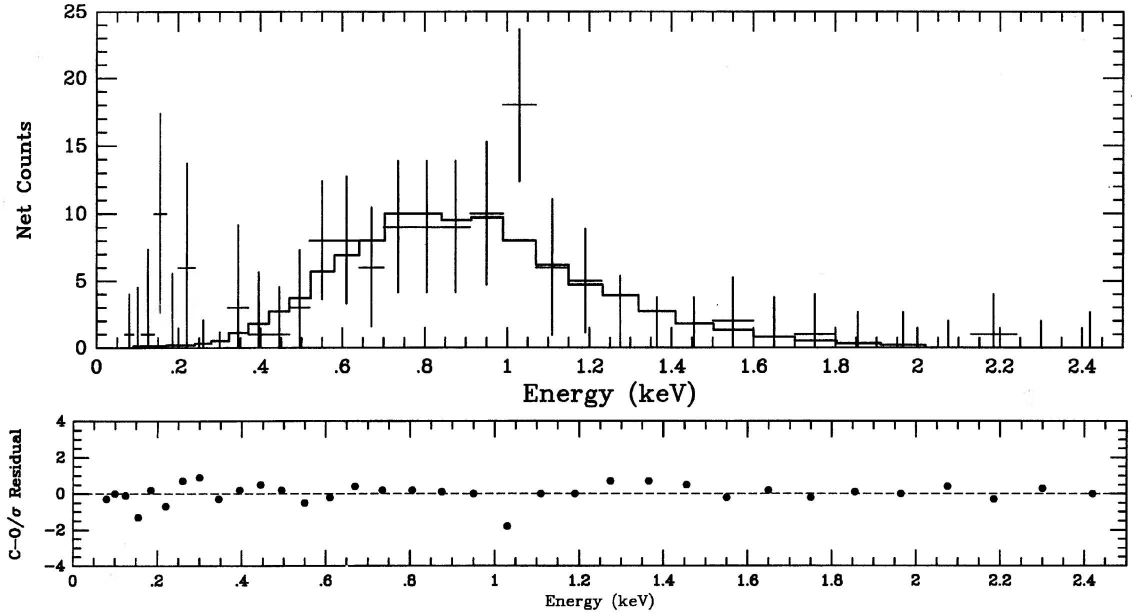

FIG. 1—The upper plot shows the spectral energy distribution of the net PU Vul photons (crosses) from the 1992 November 10–12 UT *ROSAT* observation. Bins with only vertical error bars contain upper limits. The model fit to the data is shown with a solid line. The lower plot contains the $(C-O)/\sigma$ residuals of the model fit.

$$\mathrm{HR2}=(D-C)/(D+C)=-0.08\pm0.16, \qquad (2)$$

indicating that PU Vul is a rather soft X-ray source.

Visual inspection of an X-ray light curve constructed for PU Vul with the PROS task *ltcurv* has convinced us that the photons arrived at an essentially uniform rate (about 6–8 photons per observing interval). That is, there is no indication of any "flare" or other time-resolved highly energetic event, but rather, just a constant rate of X-ray emission.

3.1.2 Spectral analysis

The energy distribution of the net source counts for PU Vul was determined with the PROS task *qpspec*. As predicted from the hardness ratios, the spectrum peaks at relatively low energy, around 0.8 keV. It declines steeply at higher energies to essentially zero counts beyond about 1.8 keV (see Fig. 1). The spectrum is mostly smooth, but there are two regions, near 0.2 and 1.0 keV, with anomalously high photon counts. The low-energy feature is consistent with approximately zero counts within the noise level of that region of the spectrum. We cannot rule out the possibility that the high-energy spike might be an actual feature in the spectrum; however, the statistically small number of total counts, as well as the poor energy resolution of the PSPC, argue against that conclusion.

3.1.3 Spectral model

A simple emission model was fitted to the entire observed X-ray spectral distribution of the PU Vul data with the PROS task *fit*. The model assumes that the emission mechanism is thermal bremsstrahlung specified by a single set of parameters:

(1) The temperature of the source, T, in keV.

(2) The logarithm of the gas column density between the observer and the source, $\log(N_{\mathrm{H}})$, which characterizes the Morrison–McCammon absorption (Morrison and McCammon 1983).

(3) A normalization parameter equal to the logarithm of the flux density at 1 keV (in units of keV $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{keV}^{-1}$) in the observer's frame, corrected for any absorption. These parameters may be either fixed at a given value or left free to vary within a specified range. The best-fit values of the free model parameters are determined by *fit* via the simplex minimization method (see Hawley et al. 1986 or Kallrath and Linnell 1987 for examples of astronomical applications of the simplex minimization procedure).

Gochermann (1991) estimated $E_{B-V}=0.5$ mag for PU Vul from the width of the 4428 Å interstellar absorption feature in its spectrum. This value, in conjunction with the color-index-to-gas-density relation of Burstein and Heiles (1978),

$$\langle N_{\mathrm{H}}/E_{B-V}\rangle=5.0\times10^{21}\ \mathrm{atoms\ cm^{-2}\,mag^{-1}}, \qquad (3)$$

was used to calculate the interstellar gas column density in the direction to PU Vul, $N_{\mathrm{H}}=2.5\times10^{21}$ atoms cm^{-2}. In order to minimize the number of free-parameter values to be determined from the small number of detected photons, and to force the model to be consistent with other methods of determining N_{H}, the absorption parameter in the model was initially fixed at this value. The parameter space around N_{H} was later explored to assess the validity of the calculated value (see below).

The X-ray spectrum was binned into 34 energy channels, each containing 0–10 photons. For the initial model, in which the column density was fixed and only the temperature and normalization allowed to vary, *fit* gave an unreduced χ^2 of 9.66. The uncertainties in the final values of the model parameters were determined with the PROS task *search_grid*, which calculates a χ^2-grid around the spectral model parameters by varying the best-fit parameter values in small increments and recalculating the χ^2 for each new, slightly different model. The χ^2-contour values on this grid that correspond to various confidence levels are estimated from Lampton et al. (1976), and the corresponding uncertainties are then measured directly off the plots. The final model parameters and 1σ (i.e., 68% confidence) uncertainties are: $T=0.25$ $(+0.19,\ -0.13)$ keV, $\log(N_{\rm H})=21.40$ $(+0.28,\ -0.35)$, and $\log(\text{normalization})=-4.43$ $(+0.36,\ -0.33)$. The model fit to the data and fit residuals are shown in Fig. 1; the χ^2-contour plots used to determine the parameter uncertainties are shown in Fig. 2.

The χ^2-grid analysis provides some additional support for our initial choice of $\log(N_{\rm H})$. If the original value calculated for $N_{\rm H}$ had been unreasonable, then we would not expect to obtain the nicely closed uncertainty contours seen in Fig. 2. Given the final uncertainties in $N_{\rm H}$, as determined from the *search_grid* process, the values of the original parameters used to calculate $N_{\rm H}$ can have uncertainties of (at most) ± 0.3 in E_{B-V} or $\pm 3-4\times 10^{21}$ atoms cm^{-2} mag^{-1} in $\langle N_{\rm H}/E_{B-V}\rangle$. These are generous error bars, and easily accommodate other values of these parameters that are quoted in the literature (e.g., $E_{B-V}=+0.4$ for PU Vul from Vogel and Nussbaumer 1992; $\langle N_{\rm H}/E_{B-V}\rangle=4.6-5.4\times 10^{21}$ atoms cm^{-2} mag^{-1} from Diplas and Savage 1994; $\langle N_{\rm H}/E_{B-V}\rangle=3.8\pm 0.9\times 10^{21}$ atoms cm^{-2} mag^{-1} from Groenewegen and Lamers 1989).

3.1.4 The X-ray luminosity

The PROS task *xflux* was used to calculate the flux and luminosity of PU Vul, integrated over the entire *ROSAT* sensitivity range (0.1–2.5 keV), for the bremsstrahlung emission model. The observed and unabsorbed flux values, as well as the final model parameters, are summarized in Table 1. In order to calculate the luminosity from the flux, the distance to the source must be determined. Unfortunately, this is not a simple task. We will address the question of the still uncertain distance to PU Vul in Sec. 4.1. Meanwhile, we have used *xflux* to calculate the X-ray luminosity at a number of distances ranging between 1 and 5 kpc; these values scale with distance according to the relation

$$L_X=(1.1\times 10^{32}\ \text{erg s}^{-1})(d/\text{kpc})^2. \qquad (4)$$

3.2 FG Serpentis

Although accreting sources typically emit X-radiation, FG Ser was undetected in the *ROSAT* exposure. The upper limit for the X-ray count rate is approximately 9.3×10^{-4} cts s^{-1}. This rate is the average background level at the position of the three serendipitous X-ray sources nearest to the (optical) position of FG Ser (see Table 2). If we assume that the scaling from count rate to unabsorbed X-ray flux of the PU Vul data $(1.1\pm 0.2\times 10^{-11}$ erg cm^{-2} cts^{-1} s$^{-2})$ also holds for FG Ser, then we can estimate an upper limit to the X-ray flux of FG Ser, $S_X<1\times 10^{-14}$ erg s^{-1} cm^{-2}.

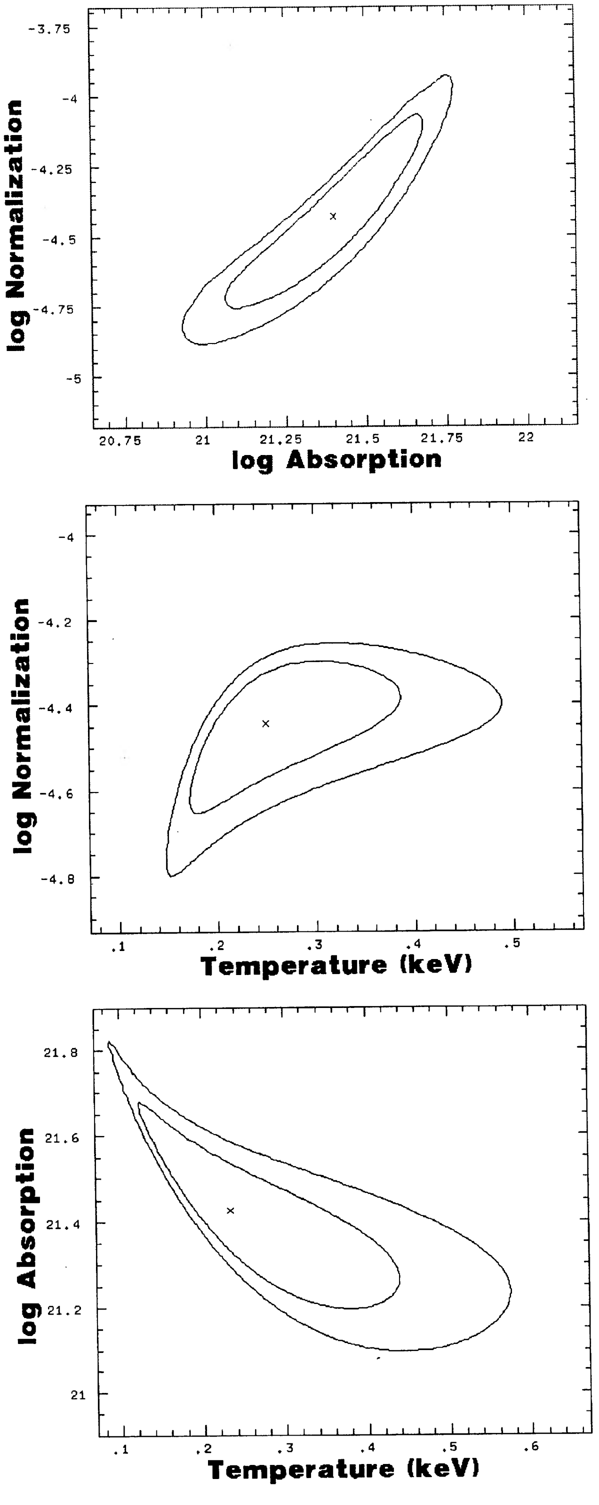

FIG. 2—The χ^2 contour plots used to determine the uncertainties in the model parameters. The contours shown are at the 68% (inner contour) and 90% (outer contour) confidence levels.

TABLE 1
Photometry and Model Parameters for PU Vul

Photometry:	
Total Energy Range:	0.1 – 2.4 keV
Energies with Nonzero Counts:	0.1 – 1.8 keV
Net Source Counts:	107 ± 20
Exposure Time:	26730 s
Count Rate:	$4.00 \pm 0.75 \times 10^{-3}$ cts/s
Spectral Model:	
Emission Mechanism:	Thermal Bremsstrahlung
Chi-squared of fit:	9.66
Temperature:	$0.25^{+0.19}_{-0.13}$ keV
$\log(N_H)$:	$21.40^{+0.28}_{-0.35}$
log(normalization):	$-4.43^{+0.36}_{-0.33}$
Observed Flux:	4.25×10^{-14} ergs/cm^2/s
Unabsorbed Flux:	9.20×10^{-13} ergs/cm^2/s
X-ray Luminosity:	$(1.1 \times 10^{32}$ erg/s$)(d/\mathrm{kpc})^2$

4. CONCLUSIONS

4.1 PU Vulpeculae

Wallerstein et al. (1984) proposed that the X-ray emission from symbiotic novae could be produced by the collision of a high-density, low-velocity ($v \sim 10$ km s^{-1}) wind from the cool star and a low-density high-velocity ($v \sim 1000$ km s^{-1}) wind from the hot star. In the region between the two stars, where the winds meet head on, standing shock fronts with large velocity discontinuities will be formed, providing a source for the observed X-rays. If the white dwarf masses are about the same for all these systems, and if the outbursts are all due to the onset of hydrogen shell burning in accreted hydrogen-rich material, then the X-ray fluxes from these systems should be about the same at similar intervals since outburst. Kwok and Leahy (1984) argued further that in such a model the X-ray fluxes should decrease inversely as the time since outburst.

Kwok and Leahy (1984) reanalyzed Allen's (1981) *Einstein* observations of three symbiotic novae (HM Sge, V1016 Cyg, and RR Tel) taken at 4, 15, and 35 years past outburst, respectively. Using single-component bremsstrahlung emission models, they derived relative X-ray fluxes for these three stars of 1.0:0.16:0.13. If all three were at the same distance, a $1/t$ dependence of the X-ray flux would give a ratio of 1.0:0.27:0.11, which is already close to the observed ratio. To improve the analysis, we must improve our estimates of the relative distances to these three systems.

TABLE 2
FG Ser Background Count Rates

Source No.	Background (cts/s)	RA(2000)	dec(2000)
9	9.418×10^{-4}	18:15:42	-00:11:43
10	9.288×10^{-4}	18:14:42	-00:15:33
12	9.147×10^{-4}	18:15:17	-00:19:46
FG Ser	$\approx 9.3 \times 10^{-4}$	18:15:07	-00:18:36

TABLE 3
Characteristics of Selected Symbiotic Systems

Name	Time Since Outburst (yr)	Distance (kpc)	X-ray Flux (10^{-13} erg/s/cm^2)	Ref
HM Sge	4	2.3^a	50	2,3
FG Ser	4	$0.93^d/2.2^b$	$<0.1^f$	1,4,5
PU Vul	14	2.5^c	9.20	1
V1016 Cyg	15	3.4^a	8.2	2,3
RR Tel	35	2.5^a	6.7	2,3
RR Tel	48	2.5^a	6.0^f	1
AG Peg	≈ 143	$0.65–0.80^e$	7.4^f	1,6

REFERENCES: (1) this paper; (2) Kwok and Leahy 1984; (3) Whitelock 1987; (4) Whitelock and Munari 1992, and Munari et al. 1992; (5) Wallerstein et al. 1993; (6) Kenyon et al. 1993, and Vogel and Nussbaumer 1994.

NOTES: (a) from the Mira period-luminosity relation (uncertainty ≈ 10%); (b) from reddening considerations (uncertainty ±0.2 kpc); (c) assuming outburst luminosity was the same as in RR Tel (uncertainty ~ 0.5 kpc); (d) assuming the cool component is a bulge- rather than disk giant; (e) from luminosity considerations; (f) assuming the same scaling from count rate to observed flux as in PU Vul.

Whitelock (1987) used the infrared period-luminosity (PL) relation initially derived by Glass et al. (1987) from observations in the Magellenic Clouds to estimate distances to the Miras in these three systems; her distances are given in Table 3. While the internal error cited by Whitelock for the Mira P-L relation is small (around 10%), there are several reasons to be cautious when applying it to the Miras in these symbiotic systems. First, there is a dispersion in the P-L relation for Miras resulting from stars of different metallicities and/or masses having somewhat different luminosities at a given period (e.g., Wood et al. 1991); this dispersion is small in a relatively homogeneous population, but larger errors could result if isolated systems are compared with each other. Second, the Miras in the symbiotic systems have pulsation periods that are longer, on the average, than typical field Miras. One explanation for this effect is that these stars would be dust-shrouded OH-IR stars were it not for the presence of the companion. In that case, the "naked" Mira P-L relation would not be directly applicable; however, the P-L relation for Magellenic Cloud Miras does give at least a first approximation to the relative distances to the Mira-containing symbiotic systems. If we use the relative distances derived by Whitelock to scale the X-ray fluxes of these three systems to a common distance of 2.5 kpc, then we derive an X-ray flux ratio of 1.0:0.36:0.16. Given the uncertainty of the P-L relation, this ratio also agrees well with a $1/t$ dependence.

At the time of our *ROSAT* observation of PU Vul, it had been ≈14 yr since its 1978 outburst. The *Einstein* and *ROSAT* energy sensitivity ranges differ somewhat (0.2–4 keV vs. 0.1–2.4 keV, respectively); however, PU Vul's count rate falls off dramatically at energies larger than about 1.8 keV, which implies that there is only a small flux contribution that goes uncounted in the 2.4–4 keV interval to which *ROSAT* is not sensitive. To determine whether the X-ray flux of PU Vul also follows the pattern found by Kwok and Leahy (1984), we must first determine its distance relative to the other symbiotic novae. Unfortunately, the cool component in PU Vul is not a Mira (Whitelock 1995), so the P-L relation cannot be used to estimate its distance.

As described in Secs. 1.1 and 1.2, RR Tel and PU Vul displayed similar development in their outbursts: (a) they both initially showed a continuous spectrum in contrast to the emission line spectra shown by V1016 Cyg and HM Sge; and (b) their light curves were similar in shape. If we assume, then, that the outbursts of RR Tel and PU Vul reached approximately the same maximum luminosity, we can estimate the distance to PU Vul relative to RR Tel by comparing their maximum observed brightnesses. PU Vul reached a maximum brightness of $V\approx8.8$ with $(B-V)=+0.44$ (Whitney 1979). Its $(B-V)$ color excess of 0.5 mag (Gochermann 1991) corresponds to an absorption of ≈1.5 mag in the V-band (Mihalas and Binney 1981), giving an unabsorbed maximum magnitude of $V_0\approx7.3$. Using this value with the unabsorbed color index, $(B-V)_0=-0.06$, gives $B_0\approx7.2$. RR Tel reached a maximum brightness of $m_{pg}\approx7$ (Thackeray 1950). This system is located at much higher galactic latitude ($b=-32°$) than PU Vul ($b=-8.5°$); consequently, the interstellar absorption is expected to be smaller for RR Tel. Published values of E_{B-V} range from $+0.08$ to $+0.10$ (Jordan et al. 1994, and references therein). This corresponds to roughly 0.4 mag of absorption in the B-band (Mihalas and Binney 1981). Photographic and B magnitudes are comparable values, so the maximum brightness of RR Tel was $B_0\sim6.6$. These two magnitudes are similar, which suggests that the two stars are at approximately the same distance, $d=2.5$ kpc. The flux of PU Vul is shown in Fig. 3—it also appears to be consistent, within the uncertainties, with a $1/t$ decay from a universal initial X-ray luminosity.

In 1993, *ROSAT* PSPC pointed observations were made of two symbiotic novae, RR Tel and AG Pegasi. The observation of RR Tel is especially interesting since it can be directly compared to the results of Allen's *Einstein* observation from a decade earlier. AG Peg (see, e.g., Kenyon et al. 1993) is remarkable for being both the oldest and slowest known symbiotic nova—it is still fading from an outburst that occurred around 1850. The scaling factor from Sec. 3.2 can be used to give a rough estimate of the X-ray fluxes for these stars from their count rates as listed in the 1st *Revised WGA Catalog of ROSAT Point Sources* (see, e.g., White et al. 1994): $5.7\pm0.5\times10^{-2}$ ct s^{-1} for RR Tel and $6.7\pm0.4\times10^{-2}$ ct s^{-1} for AG Peg. While the automatically extracted WGACAT count rate for AG Peg agrees with that determined by Mürset et al. (1995), the WGACAT count rate of RR Tel may still include a large additional uncertainty. The X-ray flux estimates are listed in Table 3 and shown in Fig. 3. Distances quoted in the literature for AG Peg range from 0.65 kpc (Vogel and Nussbaumer 1994) to 0.80 kpc (Kenyon et al. 1993). We have chosen the representative value of 0.73 kpc to determine the scaled X-ray flux in Fig. 3.

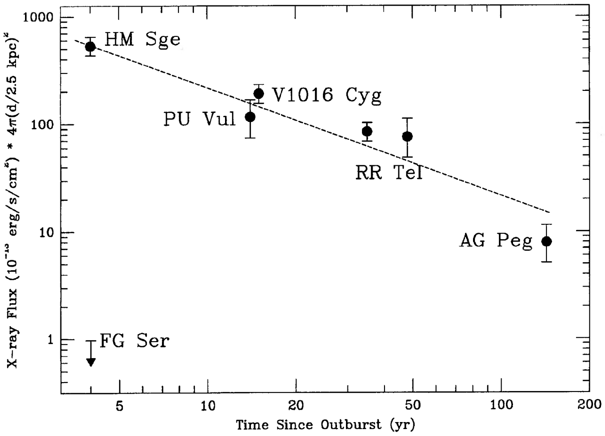

FIG. 3—The relationship between time since outburst and X-ray flux for five symbiotic novae (PU Vul, HM Sge, V1016 Cyg, RR Tel, and AG Peg) and one probable non-nova (FG Ser). The fluxes of PU Vul, RR Tel (later point), AG Peg, and FG Ser are taken from this paper, the others are from Kwok and Leahy (1984); the flux of FG Ser is an upper limit. All of the fluxes have been scaled to a common distance of 2.5 kpc and multiplied by a factor of 4π. The distances of HM Sge, V1016 Cyg and RR Tel were determined using the Mira period-luminosity relation with infrared photometric periods (Whitelock 1987); the error bars on these points show the effect on the relative flux scaling of the $\approx10\%$ uncertainty in the distances. The distance to PU Vul was estimated from a luminosity comparison with RR Tel (see Sec. 4.1)—this distance is considerably more uncertain. The error bars on the PU Vul data point show the effect of an uncertainty of ±0.5 kpc in the distance. The error bars on the later RR Tel point include the effects of the uncertainty in the count rate and the $\approx20\%$ uncertainty in the count-rate-to-flux scaling factor (see Sec. 3.2) as well as the 10% distance uncertainty. The AG Peg error bars include the count-rate and scaling-factor uncertainties, plus the effect of the 0.15 kpc range of its distance estimates. The distance to FG Ser is still uncertain (see Sec. 4.2), but the upper limit on its flux reflects the largest of the distance estimates. The dashed line is a power-law fit through all the points except FG Ser. The fit has exponent -1.0 ± 0.2 and $\chi^2=7.8$.

The X-ray observations of these five stars (PU Vul, HM Sge, V1016 Cyg, RR Tel, and AG Peg) are consistent with the hypothesis that there is a general decay law for the X-ray flux in symbiotic novae following outburst. Before this relation can be used to test theoretical models or to predict the X-ray fluxes of other sources, a reliable means of more accurately estimating the distances to these systems must be found.

4.2 FG Serpentis

As with PU Vul and the other symbiotic novae, an estimate of the distance to FG Ser is important when making a comparison to its X-ray flux. Taranova and Yudin (1985) and Wallerstein et al. (1993) used infrared photometric colors and equivalent widths of diffuse interstellar absorption bands, respectively, to derive a distance of $d\approx2.2$ kpc for FG Ser. On the other hand, Whitelock and Munari (1992) and Munari et al. (1992) discuss the possibility, based on its infrared and kinematic properties, that the cool component in FG Ser is more appropriately identified with a bulge/thick disk giant than a bright, disk giant, as is usually assumed. They derived a substantially smaller distance, $d\approx0.93$ kpc, from infrared colors.

At the time of our 1992 *ROSAT* observation, FG Ser was four years past outburst—the same "age" as HM Sge at the time of the 1979 *Einstein* observation. Yet, the measured flux of FG Ser was at least 500 times smaller than that of HM Sge. In order to have the same X-ray luminosity as HM Sge, FG Ser would have to be over 20 times more distant, at $d \approx 50$ kpc! This would imply an optical luminosity of $L > 10^{39}$ erg s^{-1} and an absolute magnitude at maximum of $M_V \approx -9$—very different from the other symbiotic novae and quite implausible. Thus, although the question of the distance to FG Ser is still unresolved, we can rule out the possibility that FG Ser had an X-ray luminosity comparable to that of HM Sge at about the same time after outburst. It is much more likely that FG Ser simply was emitting little or no X-ray flux at the time we observed it. PU Vul also showed low X-ray flux when observed by *Einstein* shortly after its outburst.

Since both FG Ser and PU Vul have been found to be eclipsing systems, we have compared the times of their X-ray observations to the times of eclipse in order to check whether the X-ray emitting region could have been obscured by one of the component stars during the observations. According to the FG Ser eclipse ephemeris of Munari et al. (1992),

$$T_0 = 2448492(\pm 4) + 650(\pm 10)E, \tag{5}$$

inferior conjunctions of the secondary star occurred on JD 2448492±14 and JD 2449142±14. Our *ROSAT* observations took place during the interval JD 2448690−8705, around phase 0.35, which should be safely away from both the primary and secondary eclipses.

The 1981 *Einstein* observation of PU Vul was made on JD 2444711. The eclipse ephemerides of both Nussbaumer and Vogel (1995),

$$T_0 = 2444550(\pm 50) + 4900(\pm 100)E, \tag{6}$$

and of Kolotilov et al. (1995),

$$T_0 = 2449458(\pm 10) + 4918(\pm 8)E, \tag{7}$$

predict that the orbital phase of PU Vul was $\phi \approx 0.03$ at that time. The eclipse duration has not been well determined, but appears to be on the order of 500 days, thereby spanning an orbital phase interval of $\Delta\phi \approx 0.1$. If the duration of the eclipse is in fact this long, then the *Einstein* observation of PU Vul did occur during eclipse, albeit only at a late stage shortly before egress. Thus, while the *ROSAT* observation of FG Ser was almost certainly unhampered by eclipses, we cannot exclude the possibility of some obscuration of the X-rays during the *Einstein* observation of PU Vul. However, we consider it more likely, based in part on its similarities to FG Ser, that PU Vul was simply not emitting X-rays shortly after outburst.

There are several properties of FG Ser and PU Vul that may be related to their lack of X-ray emission shortly after outburst. First, the cool secondary stars in both systems are not Mira variables (e.g., Whitelock and Munari 1992). A strong wind from the red giant is needed to produce X-rays by the colliding winds mechanism; non-Mira red giants typically have much weaker winds than Miras. Second, Wallerstein et al. (1993) derived outflow velocities on the order of only 50 km s^{-1} from emission lines in the optical spectrum of FG Ser at the time of our *ROSAT* observation. This low value is more consistent with the escape velocity near the edge of an extended accretion disk than with the much higher velocity expected from a wind originating near a white dwarf star. Third, both FG Ser and PU Vul showed continuous spectra shortly after outburst, while V1016 Cyg and HM Sge showed emission line spectra at the same stage of postoutburst evolution, suggesting at the very least a significant difference in the circumstellar or circumbinary envelopes between these two pairs of systems. Note that it was the emission-line profiles in V1016 Cyg and HM Sge that provided some of the motivation for the development of the colliding winds model (Wallerstein et al. 1984).

In summary, PU Vul and FG Ser displayed similar optical behavior shortly after outburst, and at least one of these systems (FG Ser) had an X-ray luminosity much lower than that of a symbiotic nova of the same postoutburst "age" (HM Sge). PU Vul's X-ray luminosity was found to be at a higher level, comparable to other symbiotic novae, after more time (≈10 yr) had elapsed since its outburst. It would be valuable to obtain X-ray observations of FG Ser in 2002, when it will be at the same time after outburst as PU Vul during our 1992 *ROSAT* observation. Such an observation could both separate geometric effects from possible orbital obscuration in the case of PU Vul as well as provide an additional check on the time-development of the X-ray emission from FG Ser. It would also be valuable in determining the effect of orbital obscuration to monitor the changes with time of the X-ray flux from symbiotic novae (particularly PU Vul) before, during, and after an eclipse.

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APPENDIX: *ROSAT* OBSERVATION OF V SAGITTAE

V Sge, an eclipsing nova-like cataclysmic variable (CV), was serendipitously located 31 arcmin off-axis in the field of our *ROSAT* observation of PU Vul. V Sge has an orbital period of 12.34 hr (Ritter 1990) and is located at a distance of roughly 2.7 kpc (Patterson 1984). Herbig et al. (1965) conducted an extensive photometric and spectroscopic study of this star. They found that the brightness of the system varied between $V \approx 9-13$, and that the Balmer and He II λ4686 emission lines were narrow when the star was faint and broad when it was bright. A radial-velocity curve solution for the system parameters suggested that the secondary (cool) star is the more massive of the two, which is the opposite case from what is expected in a normal CV. Koch et al. (1986) found a wide variety of high-excitation lines of C, N, and O in *IUE* spectra of V Sge. Further inspection of

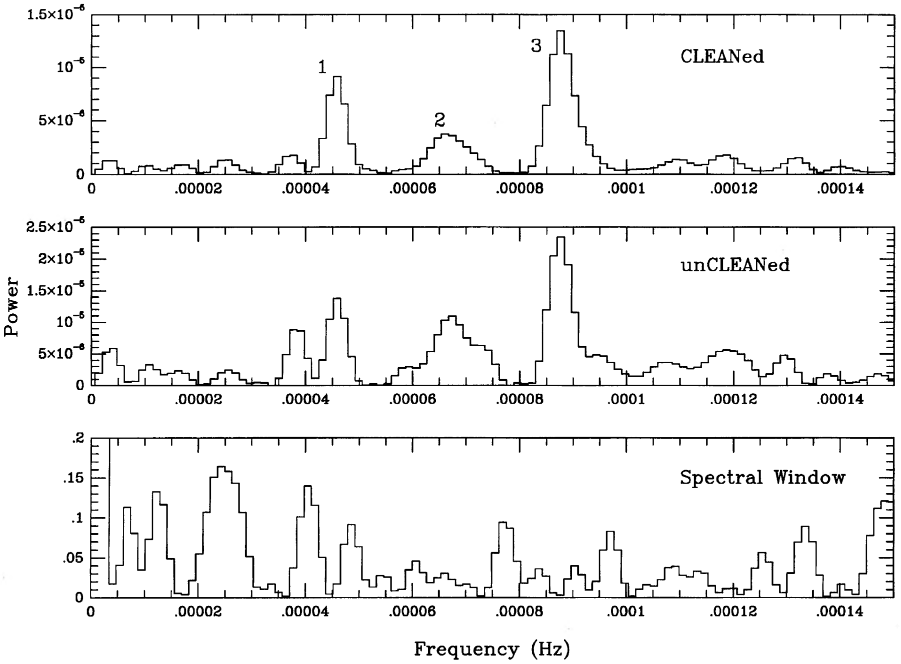

FIG. 4—The spectral window (bottom), dirty power spectrum (middle), and cleaned power spectrum (top) of V Sge's X-ray light curve. The three labeled peaks correspond to periods of (1) 6.0, (2) 4.2, and (3) 3.2 hr.

archival *Einstein* X-ray observations led them to suggest that the massive component may be a neutron star.

Williams et al. (1986) obtained time-resolved spectra of V Sge during primary eclipse. They observed that the average wavelengths of the Balmer and He II λ4686 lines shifted first to the red and then to the blue as the eclipse progressed. This "Z-wave" pattern is the characteristic behavior during eclipse of emission lines originating in a rotating accretion disk. The side of the disk moving towards us is eclipsed first during ingress (redshifting the peak wavelength) and uncovered first during egress (blue-shifting the peak wavelength). This led Williams et al. (1986) to conclude that the primary star in V Sge is surrounded by a disk of accreting matter.

The three *Einstein* IPC observations of V Sge, which we retrieved from the public archive, are from 1979–80 and total approximately 13,900 s. They show that the star is a soft X-ray source with a count rate of about 0.02–0.04 cts s^{-1}. Eracleous et al. (1991) reexamined one of these observations, an 8747 s exposure from 1979 May 2 UT, and found V Sge to have a count rate of 0.018 ± 0.002 cts s^{-1}. They fit a single-component thermal bremsstrahlung model to the source spectrum with final parameters: temperature <1.5 keV, $N_H<8\times10^{20}$ atoms cm^{-2}, and $L_x(0.1-3.5\ \mathrm{keV})=3(+2/-1)\times10^{32}$ ergs s^{-1} (for a distance of 2.7 kpc).

The number of counts in a circular aperture of radius 3′.4 around the position of V Sge in our *ROSAT* image was measured with *imcnts*, then background-subtracted via the counts/pixel measured from a concentric annulus of inner radius 3′.5 and outer radius 4′.0. The net source counts are 248.5 ± 56.6. The vignetting-corrected exposure time for V Sge is 19,273 s, giving a count rate of 0.013 ± 0.003 cts s^{-1}, which is comparable to that measured in the 1979 *Einstein* observations. The *ROSAT* hardness ratios of V Sge were calculated as in Sec. 3.1.1, and found to be $\mathrm{HR1}=-0.56\pm0.19$ and $\mathrm{HR2}=-0.43\pm0.53$. This indicates a very soft X-ray source; in fact, over 50% of the photons were detected at energies less than 0.5 keV. This is also in agreement with the *Einstein* results. Due to the problematic nature of working with a far-off axis source, as well as the agreement of the count rate and hardness with previous data, we did not fit a spectral model to our observation of V Sge.

The PROS task *ltcurv* was used to determine the net count rate in 300 s bins for the duration of the *ROSAT* observation. A power spectrum was calculated from this light curve using the DFOURT routine, then deconvolved from the spectral window using the CLEAN algorithm (Roberts et al. 1984). The deconvolution from the spectral window was performed in a fairly conservative manner: the iterations of the CLEAN algorithm were halted when the maximum residual was still ≈50% of the peak value in each power spectrum. The spectral window, and dirty (i.e., uncleaned) and cleaned power spectra are shown in Fig. 4. Three peaks are apparent in the power spectrum, at frequencies of (1) 4.6×10^{-5} Hz, (2) 6.6×10^{-5} Hz, and (3) 8.8×10^{-5} Hz. These correspond to periods of 6.0, 4.2, and 3.2 hr, respectively. Relative to the known 12.34 hr orbital period of V Sge, these periods fall in the ratio 2.1:2.9:3.9, which suggests that they are actually just the 2:3:4 harmonic series of the orbital frequency.

Whether or not the X-ray period actually differs from the optical period is beyond the sensitivity of this data. It is interesting to note, however, that there is no sign of a peak in the power spectrum at 2.25×10^{-5} Hz (i.e., 12.34 hr) itself. This suggests that the X-ray source is probably obscured twice during each orbital period, at opposite phases. The

X-rays could be originating from a fixed location between the two stars, such that they are blocked by the secondary star during the primary optical eclipse and by the primary star (and its associated accretion disk) half an orbit later during the secondary optical eclipse.

REFERENCES

Allen, D. A. 1980, MNRAS, 192, 521
Allen, D. A. 1981, MNRAS, 197, 739
Belyakina, T. S., et al. 1984, A&AL, 132, L12
Belyakina, T. S., et al. 1989, A&A, 223, 119
Bopp, B. W. 1977, IBVS No. 1327
Burstein, D., and Heiles, C. 1978, ApJ, 225, 40
Diplas, A., and Savage, B. D. 1994, ApJ, 427, 274
Dokuchaeva, O. D. 1976, IBVS No. 1189
Eracleous, M., Halpern, J., and Patterson, J. 1991, ApJ, 382, 290
Feibelman, W. A., Bruhweiler, F. C., and Johansson, S. 1991, ApJ, 373, 649
Garnavich, P. M., and Trammell, S. R. 1994, IAU Circ., No. 6089
Gochermann, J. 1991, A&A, 250, 361
Groenewegen, M. A. T., and Lamers, H. J. G. L. M. 1989, A&AS, 79, 359
Gutiérrez-Moreno, A., Moreno, H., and Feibelman, W. A. 1992, ApJ, 395, 295
Glass, I. S., Catchpole, R. M., Feast, M. W., Whitelock, P. A., and Reid, I. N. 1987, Late Stages of Stellar Evolution, ed. S. Kwok and S. R. Pottasch (Dordrecht, Reidel), p. 51
Hawley, S. L., Jeffreys, W. H., Barnes III, T. G., and Lai, W. 1986, ApJ, 302, 626
Herbig, G. H., Preston, G. W., Smak, J., and Paczynski, B. 1965, ApJ, 141, 617
Honda, M., as reported by Kozai, Y. 1979, IAU Circ., No. 3348
Jordan, S., Mürset, U., and Werner, K. 1994, A&A, 283, 475
Kallrath, J., and Linnel, A. P. 1987, ApJ, 313, 346
Kenyon, S. J. 1986, The Symbiotic Stars (Cambridge, Cambridge University Press)
Kenyon, S. J., Mikolajewska, J., Mikolajewski, M., Polidan, R. S., and Slovak, M. H. 1993, AJ, 106, 1573
Klein, A., Bruch, A., and Luthardt, R. 1994, A&AS, 104, 99
Koch, R. H., Corcoran, M. F., Holenstein, B. D., and McCluskey, Jr. G. E., 1986, ApJ, 306, 618
Kolotilov, E. A., Munari, U., and Yudin, B. F. 1995, MNRAS, 275, 185
Kurochkin, N. E. 1993, A&AS, 3, 295
Kuwano, Y., as reported by Kozai, Y. 1979, IAU Circ., No. 3344
Kwok, S., and Leahy, D. A. 1984, ApJ, 283, 675
Lampton, M., Margon, B., and Bowyers, S. 1976, ApJ, 208, 117
Liller, M. H., and Liller, W. 1979, AJ, 84, 1357
McCuskey, S. 1965a, IAU Circ., No. 1916
McCuskey, S. 1965b, IAU Circ., No. 1917
Merrill, P. W., and Burwell, C. G. 1950, ApJ, 112, 72
Mihalas, D., and Binney, J. 1981, Galactic Astronomy: Structure and Kinematics, 2nd Edition (New York, Freeman)
Morrison, R., and McCammon, D. 1983, ApJ, 270, 119
Munari, U. 1988, IAU Circ., No. 4622
Munari, U., and Whitelock, P. A. 1989, MNRAS, 239, 273
Munari, U., and Whitelock, P. A., Gilmore, A. C., Blanco, C., Massone, G., and Schmeer, P. 1992, AJ, 104, 262
Mürset, U., and Nussbaumer, H. 1994, A&A, 282, 586
Mürset, U., Jordan, S., and Walder, R. 1995, A&A, 297, L87
Nussbaumer, H., and Vogel, M. 1995, A&A preprint
Patterson, J. 1984, ApJS, 54, 443
Ritter, H. 1990, A&AS, 85, 1179
Roberts, D. H., Lehar, J., and Dreher, J. W. 1987, AJ, 93, 968
Sanduleak, N., and Stephenson, C. B. 1973, ApJ, 185, 899
Schweitzer, E. 1990, IBVS No. 3476
Schmid, H. M. 1989, A&A, 211, L31
Taranova, O. G., and Yudin, B. F. 1985, Soviet Astron. Lett., 11, 23
Thackeray, A. D. 1950, MNRAS, 110, 45
Thackeray, A. D. 1977, MNRAS, 83, 1
Tomov, T., Zamanov, R., Iliev, L., Mikolajewski, M., and Georgiev, L. 1991, MNRAS, 252, 31p-5
Trümper, J., et al. 1983, Adv. Space Res., 2, 241
Vogel, M., and Nussbaumer, H. 1992, A&A, 259, 525
Vogel, M., and Nussbaumer, H. 1994, A&A, 284, 145
Wallerstein, G., Willson, L. A., Salzer, J., and Brugel, E. 1984, A&A, 133, 137
Wallerstein, G., Gilroy, K. K., Willson, L. A., and Garnavich, P. 1993, PASP, 105, 859
White, N. E., Giommi, P., and Angelini, L. 1994, IAU Circ., No. 6100
Whitelock, P. A. 1987, PASP, 99, 573
Whitelock, P. A. 1995, private communication
Whitelock, P. A., and Munari, U. 1992, A&A, 255, 171
Whitney, C. A. 1979, IAU Circ., No. 3348
Williams, G. A., King, A. R., Uomoto, A. K., and Hiltner, W. A. 1986, MNRAS, 219, 809
Willson, L. A., Wallerstein, G., Brugel, E. W., and Stencel, R. E. 1984, A&A, 133, 154
Wood, P. R., Moore, G. K. G., and Hughes, S. M. G. 1991, in The Magellenic Clouds: IAU Symposium 148, ed. R. Haynes and D. Milne (Dordrecht, Kluwer), p. 259
Yamashita, Y., Norimoto, Y., and Yoo, K. H. 1983, PASJ, 35, 521