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LETTER

Letter to the Editor

Luminous supersoft X-ray emission from the recurrent nova U Scorpii

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Abstract. BeppoSAX detected luminous 0.2–2.0 keV supersoft X-ray emission from the recurrent nova U Sco ~19–20 days after the peak of the optical outburst in February 1999. U Sco is the first recurrent nova to be observed during a luminous supersoft X-ray phase. Non-LTE white dwarf atmosphere spectral models (together with a ~0.5 keV optically thin thermal component) were fitted to the BeppoSAX spectrum. We find that the fit is acceptable assuming enriched He and an enhanced N/C ratio. This implies that the CNO cycle was active during the outburst, in agreement with a thermonuclear runaway scenario. The best-fit temperature is $\sim 9 \times 10^5$ K and the bolometric luminosity $(0.16\text{–}1.2) \times 10^{36}\ \mathrm{erg\,s^{-1}}\ (\mathrm{d/kpc})^2$. These values are in agreement with those predicted for steady nuclear burning on a WD close to the Chandrasekhar mass. The fact that U Sco was detected as a supersoft X-ray source is consistent with steady nuclear burning continuing for at least one month after the outburst. This means that only a fraction of the previously accreted H and He was ejected during the outburst and that the WD can grow in mass, ultimately reaching the Chandrasekhar limit. This makes U Sco a candidate type Ia supernova progenitor.

Key words: stars: binaries: close – X-rays: stars – stars: evolution – stars: white dwarfs – stars: individual: U Scorpii

1. Introduction

Recurrent novae (RN) are a small and diverse subclass of cataclysmic variables, which show multiple outbursts resembling those of classical novae, though of lesser magnitude (see Webbink et al. 1987; Sekiguchi 1995). U Scorpii (U Sco) is one of the six best known members of this class. The source underwent outbursts in 1863, 1906, 1936, 1979, 1987, and most recently on 1999 Feb 25.2 (Schmeer et al. 1999). The last two outbursts were separated by 8 and 12 years respectively. It is the RN with the shortest recurrence period known.

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Starrfield et al. (1988) applied thermonuclear runaway (TR) theory to this nova assuming a very massive white dwarf (WD).

The estimate of the distance to U Sco in the literature varies with different assumptions. Kato (1990) obtained a distance range 3.3–8.6 kpc comparing the observed visual light curve with the theoretical one and assuming a high mass ($\sim 1.38\,\mathrm{M_\odot}$) WD. If the donor star is a dwarf the distance can be 3.5 ± 1.5 kpc (Hanes 1985), however most authors recently agree instead on a *subgiant* nature of the donor, as indicated by the detection of a Mg Ib absorption feature at λ5180 in the late 1979 outburst spectrum, consistent with a K2 III spectral type (Pritchet et al. 1977). This is in agreement with a low mass ($\simeq 1\,\mathrm{M_\odot}$) subgiant secondary with M_V=+3.8 which fills the Roche lobe at an orbital period $\simeq$1.2 days (Portegies Zwart, private communication). From the apparent magnitude V=20.0 in the faint state and the visual extinction A_V=0.6 a distance $\simeq$13 kpc is derived, in rough agreement with d=14.8 kpc derived by Webbink et al. (1987) with the assumption of a G III subgiant, and with d$\simeq$14 kpc estimated by Warner (1995). In any case U Sco is at a latitude 21^o and for any distance d$\geq$ 3 kpc it belongs to the galactic halo population. It is seen through the full galactic hydrogen column of $1.4 \times 10^{21}\ \mathrm{cm^{-2}}$ (Dickey & Lockman 1990).

U Sco was observed to be an eclipsing system by Schaefer (1990). The orbital period is 1.23 days (Johnston & Kulkarni 1992; Schaefer & Ringwald 1995). $\mathrm{m_V}$ varies from 18.5 to 20. An accretion disk is required from the modeling of the optical continuum during quiescence. The maximum visual magnitude during outburst is $\mathrm{m_V} \sim 8$. U Sco shows the fastest visual decline of 0.67 magnitude per day of all known novae (Sekiguchi et al. 1988). Spectroscopically it shows very high ejection velocities of $\sim (7.5\text{–}11) \times 10^3\ \mathrm{km\ s^{-1}}$ (Williams et al. 1981; Rosino & Iijima 1988; Niedzielski et al. 1999).

Ejecta abundances have been estimated from optical and UV studies (Williams et al. 1981; Barlow et al. 1981). From the emission lines a depletion in hydrogen relative to helium with He/H~2 has been derived while the CNO abundance was solar with an enhanced N/C ratio. The strongest emission feature at maximum is the HeII $\lambda 4686$ line. Other reported lines are

Hα, HeI, HeII, NII, NIII, CIII, and CIV (Zwitter et al. 1999; Bonifacio et al. 1999). Satellite lines to Hα, HeII and HeI have also been detected (Bonifacio et al. 1999). The estimated mass of the ejected shell for the 1979 outburst is $\mathrm{M_{shell}} \sim 10^{-7}\ \mathrm{M_\odot}$ (Williams et al. 1981).

It has been suggested that the companion of U Sco may be somewhat evolved (and helium enriched) as the quiescent spectrum shows strong HeII emission lines (cf. Hanes 1985). Hachisu et al. (1999) propose an evolutionary scenario for this system assuming a secondary star which experienced a helium accretion phase. The WD may efficiently grow in mass towards the Chandrasekhar (CH) limit and explode as a SN Ia (Della Valle & Livio 1996). But if U Sco is in the galactic halo then the system belongs to an old stellar population and the evolution may be different. Helium enrichment as observed from U Sco may also be due to helium enriched winds from the WD (cf. Prialnik & Livio, 1995).

2. The BeppoSAX observation

After the optical outburst of U Sco was reported (Schmeer et al. 1999) a target of opportunity observation of U Sco was performed with the BeppoSAX X-ray satellite. According to the calculations of Kato (1996), supersoft (SSS) X-ray emission is predicted to be observed ∼10–60 days after the optical outburst. The 50 ks exposure observation was performed during 1999 March 16.214–17.425, 19–20 days after the optical outburst. Here we report the first results of an analysis of the mean X-ray spectrum observed during this observation.

The scientific payload of BeppoSAX (see Boella et al. 1997a) comprises four coaligned Narrow Field Instruments including the LECS (Parmar et al. 1997) and MECS (Boella et al. 1997b). U Sco was detected with mean LECS and MECS net count rates, after background subtraction, of $(5.67 \pm 0.23) \times 10^{-2}\ \mathrm{s^{-1}}$ and $(1.35 \pm 0.38) \times 10^{-3}\ \mathrm{s^{-1}}$ respectively. The source was not detected in the high-energy non-imaging instruments. The X-ray flux varies by a factor of ∼1.5 during the observation possibly due to orbital variations or a rise in flux.

The combined LECS and MECS spectrum was first fit with a simple blackbody spectral model. The fit is unacceptable with a χ^2 of 72 for 10 degrees of freedom (dof). We then added absorption edges due to highly ionized species of N and O expected in the hot atmosphere of a steadily nuclear burning WD. The edge energies were fixed at 0.55 keV, 0.67 keV, 0.74 keV, and 0.87 keV, corresponding to the Lyman edges of N VI, N VII, O VII, and O VIII, respectively. Only the NVI, NVII, and OVIII edges were detected at high significance with absorption depths of 4.3, 2.4, and 5.6, respectively. The OVII edge is not detected and the 90% confidence upper limit to its absorption depth is <1.6. The χ^2 is 12 for 6 dof. However, other interpretations of the spectral shape above ∼0.8 keV appear to be more likely (see below and the discussion). We independently fitted the edge energies of the N VI and N VII features and derived 90% confidence ranges of 0.524–0.555 keV and 0.630–0.669 keV, respectively and an absorbing hydrogen column density $(1.8\text{–}2.6) \times 10^{21}\ \mathrm{atom\ cm^{-2}}$.

Table 1. Best-fit values derived from spectral fits to the BeppoSAX LECS and MECS spectrum of U Sco using (a) a blackbody model with absorption edges and (b) an optically thick non-LTE WD atmosphere model (with He enriched and the N/C ratio enhanced) and an optically thin Raymond and Smith component (assuming He enriched and the ratio N/C enhanced). 90% confidence parameter ranges are given. For the edges the absorption depth at the given energies are listed

(a) Blackbody with absorption edges		
Parameter	unit	90% confidence
$\mathrm{N_H}$	$(10^{21}\ \mathrm{cm^{-2}})$	1.8–2.6
T	(eV)	102–112
	$(10^6\ \mathrm{K})$	1.2–1.30
R	$(10^7\ \mathrm{cm}\ (\mathrm{d/kpc}))$	0.50–0.66
L	$(10^{35}\ \mathrm{erg\ s^{-1}}\ (\mathrm{d/kpc})^2)$	0.39–0.88
Absorption edges		
τ N VI	0.55 keV	3.8–5.6
τ N VII	0.67 keV	1.6–3.7
τ O VII	0.74 keV	<1.6
τ O VIII	0.87 keV	4.5–7.2
(b) WD atmosphere with He enriched and ratio N/C enhanced		
$\mathrm{N_H}$	$(10^{21}\ \mathrm{cm^{-2}})$	3.1–4.8
T	(eV)	73.7–76.3
	$(10^5\ \mathrm{K})$	8.5–8.9
R	$(10^7\ \mathrm{cm}\ (\mathrm{d/kpc}))$	1.9–5.5
L	$(10^{35}\ \mathrm{erg\ s^{-1}}\ (\mathrm{d/kpc})^2)$	1.6–12
Raymond-Smith component		
kT	(keV)	0.22–0.52
EM	$(10^{55}\ \mathrm{cm^{-3}}\ (\mathrm{d/kpc})^2)$	0.44–3.2

WD atmosphere spectra have been shown to deviate strongly from simple blackbodies (e.g., Hartmann & Heise 1997). The use of sophisticated WD atmosphere model spectra is required. We applied a non-LTE WD atmosphere spectral model grid assuming a very massive (log(g)=9.5) WD with cosmic CNO abundances (see e.g., Hartmann et al. 1999). The fit was unacceptable at energies ≳0.8 keV. We added an optically thin thermal component (Raymond & Smith 1977), hereafter RS, to the model. Such a component may be due to a strong wind from the WD atmosphere and has been observed in the classical nova Cyg 1992 (Balman et al. 1998). The fit was still unacceptable with a χ^2 of 23.4 for 8 dof. We also fitted the observed spectrum with two optically thin RS components. We found that the fit was not acceptable with a χ^2 of 55.8 for 8 dof.

When the CNO cycle is active then the N/C and O/C ratios are strongly modified. A strong enrichment of N with respect to C is expected as N is involved in the slowest reaction. We calculated log g=9.5 non-LTE WD atmosphere spectral models with He and CNO (number) abundances ($\mathrm{H} = 0.5$, $\mathrm{C} = 9 \times 10^{-4}$, $\mathrm{N} = 6 \times 10^{-3}$, $\mathrm{O} = 3 \times 10^{-3}$ with respect to helium) according to values determined from optical/UV studies of the nova ejecta of U Sco (Williams et al. 1981). In addition, we applied a hot optically thin thermal component. We found that with these assumptions the fit was acceptable with a χ^2 of 10.7 for 8 dof. The best-fit atmospheric temperature is $(8.53\text{–}8.85) \times 10^5$ K (90% confidence), the atmospheric radius is $(1.9\text{–}5.5) \times$

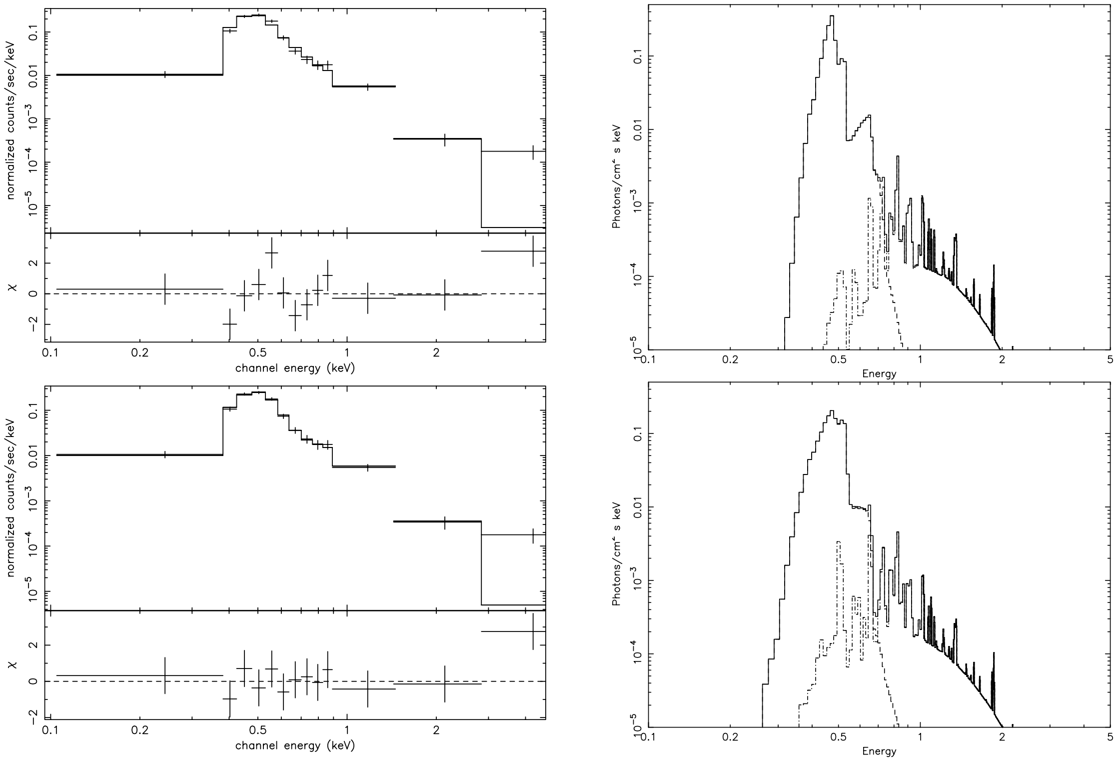

Fig. 1. Combined BeppoSAX LECS and MECS spectra of U Sco (*left*) and spectral models (*right*). Upper panels show the non-LTE WD atmosphere model using cosmic abundances, lower panels show the WD atmosphere model using He enrichment and enhanced N/C ratio

$10^7\ \mathrm{cm\ (d/kpc)}$, and the bolometric luminosity $(0.16–1.2) \times 10^{36}\ \mathrm{erg\ s^{-1}\ (d/kpc)^2}$. For the optically thin component we derive a temperature, kT, of 0.22–0.52 keV and an emission measure, EM, of $(0.42–3.2) \times 10^{55}\ \mathrm{cm^{-3}\ (d/kpc)^2}$ assuming that He is enriched and N/C enhanced. The absorbing hydrogen column density is $(3.1–4.8) \times 10^{21}\ \mathrm{atom\ cm^{-2}}$. This value is larger than the galactic absorption in the direction of U Sco of $1.4 \times 10^{21}\ \mathrm{cm^{-2}}$ (see Introduction) indicating a substantial intrinsic absorption.

3. Discussion

3.1. Supersoft X-ray emission

U Sco belongs now to those novae for which SSS X-ray emission has been discovered (cf. Orio & Greiner 1999).

The TR theory predicts two processes which can generate soft X-rays: Shock acceleration in the nova ejecta and steady nuclear burning. For Nova Cyg 1992 an optically thin component due to shocks has been detected. In addition an optically thick SSS X-ray component has been observed ∼60 days after the outburst and for ∼600 days (Krautter et al. 1996; Balman et al. 1998).

According to the calculations of Kato (1996) performed for U Sco, and assuming a massive (M_{WD}=1.377$M_\odot$) WD a SSS component is predicted to be observed from ∼10 days after the outburst. In the case of the H-rich model (He/H=0.1) the supersoft component is expected to rise till ∼50 days after the outburst to a maximum luminosity of $\sim 3 \times 10^{36}\ \mathrm{erg\ s^{-1}\ (d/kpc)^2}$. In the He-rich model (He/H=2), a maximum luminosity for the SSS component of $\sim (0.8–1) \times 10^{36}\ \mathrm{erg\ s^{-1}\ (d/kpc)^2}$ is reached ∼20 days after the optical outburst. Using the He enriched fit with the N/C ratio enhanced (Table 1), the observed bolometric luminosity ∼19–20 days after the optical outburst is $\sim (0.16–1.2) \times 10^{36}\ \mathrm{erg\ s^{-1}\ (d/kpc)^2}$. Assuming a distance ≃14 kpc (see Introduction) a bolometric luminosity of $\sim (0.3–2.4) \times 10^{38}\ \mathrm{erg\ s^{-1}}$ is derived. The luminosity is in agreement with the bolometric luminosity of $\sim 10^{38}\ \mathrm{erg\ s^{-1}}$ predicted for novae (Mc Donald et al. 1985). The temperature of $(8.7–8.9) \times 10^5$ K and the luminosity of $\leq 2.4 \times 10^{38}\ \mathrm{erg\ s^{-1}}$ derived from the X-ray spectral fit requires a very massive $M_{WD} > 1.2\ M_\odot$ WD consistent with an almost CH mass WD (e.g. Kato 1997).

3.2. Spectrally hard component

In addition to the optically thick SSS X-ray model spectrum, the spectral fits require a spectrally hard component. A similar component in addition to a SSS component was used by Balman et al. (1998) for X-ray spectral fits to the classical nova Cyg 1992. Using an optically thin thermal model we derive a temperature of $0.22–0.52$ keV, an emission measure $\mathrm{EM} = (0.4–3.2) \times 10^{55}\ \mathrm{cm^{-3}\ (d/kpc)^2}$ if He is enriched and the ratio N/C enhanced.

If we assume a terminal wind velocity of $\mathrm{v}_\infty \approx 10^8\ \mathrm{cm\,s^{-1}}$ the wind mass loss rate for a He/H=2 mixture can be estimated from $\dot{\mathrm{M}} \approx 14.5\ \mathrm{m_H}\ \mathrm{v}_\infty\ \sqrt{\mathrm{EM\,r}}$. Here r is the typical radius of the emitting region. We assume $\mathrm{r} = 10^{11}$ cm, the radius of the Roche-lobe, and use the result of the spectral fit assuming He is enriched. We then obtain a wind mass loss rate of $\dot{\mathrm{M}} = (2.4\text{–}6.9) \times 10^{-8}\ \mathrm{M_\odot\ yr^{-1}}\ (\mathrm{d/kpc})$. For a distance to U Sco of 14 kpc, we derive a wind mass loss rate of $(3.4\text{–}9.7) \times 10^{-7}\ \mathrm{M_\odot\ yr^{-1}}$. A near-CH mass WD at $\mathrm{T} = 9 \times 10^5$ K experiences an envelope mass loss of $\sim 1.2 \times 10^{-6}\ \mathrm{M_\odot\ yr^{-1}}$ due to both steady nuclear burning and a wind from the WD. The steady nuclear burning mass loss can be estimated to be $\sim 6 \times 10^{-7}\ \mathrm{M_\odot\ yr^{-1}}$ (Hachisu et al. 1999). The mass loss due to the wind is $\sim 6 \times 10^{-7}\ \mathrm{M_\odot\ yr^{-1}}$. This value is in agreement with the range we derived above. For a duration of the steady nuclear burning phase plus wind mass loss phase of ∼0.1 year (Kato 1996) we derive a mass loss from the WD envelope of $\sim 1.2 \times 10^{-7}\ \mathrm{M_\odot}$ of which $\sim 6 \times 10^{-8}\ \mathrm{M_\odot}$ is due to the wind. In addition the predicted post-outburst envelope mass is $\sim 8 \times 10^{-8}\ \mathrm{M_\odot}$ (Hachisu et al. 1999). This would mean that 70% of the envelope mass has remained on the WD allowing it to increase in mass. Williams et al. (1981) derive from the UV lines (for 14 kpc and $\mathrm{r} > 6.5 \times 10^{11}$ cm) a wind mass loss rate $\dot{\mathrm{M}} > 5.4 \times 10^{-8}\ \mathrm{M_\odot\ yr^{-1}}$ which differs significantly from our value, although it is subject to many uncertainties, and differences between outbursts cannot be accounted for.

If the helium fraction is indeed large ($\mathrm{He/H} \approx 2$) only part of the accreted He/H envelope might have been ejected and steady nuclear burning proceeded for at least one month. This result is consistent with the analytical model of Kahabka (1995). Assuming an X-ray on-time of 0.1 years and a recurrence period of 10 years, we constrain the WD mass to $\mathrm{M_{WD}} \geq 1.36\ \mathrm{M_\odot}$. U Sco and RN in general are therefore probably SN Ia progenitors (cf. Li & van den Heuvel 1997; for a recent review on SN Ia, see Livio 1999).

4. Conclusions

For the first time a RN (U Sco) has been detected in a SSS X-ray phase with the BeppoSAX X-ray satellite ∼20 days after an optical outburst. This observation confirms the theoretical predictions that RN have a SSS X-ray phase (Yungelson et al. 1996; Kato 1996). He enhanced non-LTE WD atmosphere model spectra, with a high N/C ratio (using abundances derived from the ejecta) are required to fit the BeppoSAX X-ray spectrum of U Sco. This is evidence that the outburst of U Sco was triggered by a TR and that the CNO cycle was active. From the temperature of the optically thick SSS component of $\sim 9 \times 10^5$ K, we constrain the WD to be very massive ($> 1.2\ \mathrm{M_\odot}$) and consistent to be close to the CH limit.

Besides the SSS emission we observe an additional optically thin component. We explain this hard component as emission from a strong shocked wind from the WD with a mass loss rate of $\dot{\mathrm{M}} = (2.4\text{–}6.9) \times 10^{-8}\ \mathrm{M_\odot\ yr^{-1}}\ (\mathrm{d/kpc})$. Such a component is consistent with the theoretical predictions for a WD with a mass just below the CH mass (Hachisu et al. 1999). According to their calculations U Sco emerged from an optically thick wind phase when the BeppoSAX observation was performed and it cannot last longer than 20 days for a mass just below the CH limit.

U Sco, and therefore RN in general, can be considered to be progenitors of SN Ia. The condition that the WD can grow in mass is achieved if the accreted and accumulated material is enriched in He and not all the envelope was ejected. This condition may occur if the donor star has experienced a previous helium accretion phase, if it is somewhat evolved (a subgiant), or if helium rich material has been mixed into the accreted envelope.

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References

Balman S., Ögelman H., Krautter J., 1998, ApJ 499, 395
Barlow M.J., Brodie J.P., Brunt C.C., et al., 1981, MNRAS 195, 61
Boella G., Butler R.C., Perola G.C., et al., 1997a, A&AS 122, 299
Boella G., Chiappetti L., Conti G., et al., 1997b, A&AS 122, 327
Bonifacio P., Molaro P., Selvelli P., 1999, IAU Circ. No. 7129
Della Valle M., Livio M., 1996, ApJ 473, 240
Dickey J.M., Lockman F.J., 1990, ARA&A 28, 215
Hachisu I., Kato M., Nomoto K., 1999, ApJ 519 (astro-ph/9902303)
Hanes D.A., 1985, MNRAS 213, 443
Hartmann H.W., Heise J., 1997, A&A 322, 591
Hartmann H.W., Heise J., Kahabka P., et al., 1999, A&A 346, 125
Johnston H.M., Kulkarni S.R., 1992, ApJ 396, 267
Kahabka P., 1995, A&A 304, 227
Kato M., 1990, ApJ 355, 277
Kato M., 1996, in Greiner, "Supersoft X-ray sources", LNP 472, Springer, p. 15
Kato M., 1997, ApJS 113, 121
Krautter J., Ögelman H., Starrfield S., et al., 1996, ApJ 456, 788
Li X-D., van den Heuvel E.P.J., 1997, A&A 322, L9
Livio M., 1999, in proceedings of Type Ia Supernovae: Theory and Cosmology (astro-ph/9903264)
McDonald J., Fujimoto H., Truran J.W., 1985, ApJ 294, 263
Niedzielski A., Tomov T., Munari U., 1999, IAU Circ. No. 7115
Orio M., Greiner J., 1999, A&A 344, L13
Parmar A.N., Martin D.D.E., Bavdaz M., et al., 1997, A&AS 122 309
Prialnik D., Livio M., 1995, PASP 107, 1201
Princhet C., van den Bergh S., 1977, ApJS 34, 101
Raymond J., Smith B.H., 1977, ApJS 35, 419
Rosino L., Iijima T., 1988, A&A 201, 89
Schaefer B.E., 1990, ApJ 335, L39
Schaefer B.E., Ringwald F.A., 1995, ApJ 447, L45
Schmeer P., Waagen E., Shaw L., et al., 1999, IAU Circ. No. 7113
Sekiguchi K., Feast M.W., Whitelock P.A., et al., 1988, MNRAS 234, 281
Sekiguchi K., 1995, Ap&SS 230, 75
Starrfield S., Sparks W.M., Shaviv G., 1988, ApJ 325, L35
Warner B., 1995, Cataclysmic Variables, Cambridge University press
Webbink R.F., Livio M., Truran J.W., Orio M., 1987, ApJ 314, 653
Williams R.E., Sparks W.M., Gallagher J.S., et al., 1981, ApJ 251, 221
Yungelson L., Livio M., Truran J.W., et al., 1996, ApJ 466, 890
Zwitter T., Munari U., 1999, IAU Circ. No. 7118