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Letter to the Editor

Optical identification of the supersoft X-ray source 1E 0035.4–7230 in the Small Magellanic Cloud

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Abstract. We report the identification of the optical counterpart of the SMC super-soft X-ray source 1E0035.4-7230 with a variable star of magnitude B=19.9–20.2 within the 40" *Einstein* error box. The star shows strong UV excess, a hot, blue continuum and weak lines of high ionization. The lines are redshifted by 3–4 Å, indicating SMC membership. This object appears similar to CAL 83 and CAL 87 and is probably a binary system hosting an accreting, hydrogen burning white dwarf.

Key words: Accretion, accretion disks – Stars: binaries: close; white dwarfs – X-rays: stars.

1. Introduction

Wang & Wu (1992) examined the X-ray sources detected by *Einstein* in a 32 square degree field in the Small Magellanic Cloud (hereafter SMC) and reported the detection of two new *supersoft* X-ray sources. One of them is the planetary nebula N67 and the other is 1E0035.4-7230. In this work we present the optical identification of this second source.

The empirical definition of *supersoft sources* (hereafter SUSO's) is used for objects emitting X-rays, but predominantly below the 0.5 KeV energy range of soft X-ray telescopes. Thus they were never observed before in the galaxy because of the high absorption in the galactic plane that prevented detections. According to recent findings, many SUSO's belong to a new class of X-ray binaries, unique in their very high X-ray luminosity (often close to the Eddington luminosity for a 1 $M_\odot$ star). Their X-ray emision is fitted satisfactorly by a black-body with typical temperature in the range 1.5–5 $\times 10^5$ K and *not* by thermal brehmstrahlung or any of the non-thermal mechanisms that produce X-rays. Therefore they are among the hottest stellar objects. Such characteristics were first found for CAL 83 and CAL 87, two Large Magellanic Cloud (LMC) sources discovered by *Einstein* (Long et al 1981, Brown et al 1994 and references therein). *Rosat* recently discovered eleven other sources of this kind; five are in the LMC (Greiner et al 1992, 1994, Orio & Ögelman 1993, Schaeidt et al 1993, Cowley et al 1993) three in the SMC (Kahabka et al 1994), and three in the galactic plane, namely the post novae GQ Mus (Ögelman et al 1993) and Nova Cyg 1992 (Krautter et al 1994) and the symbiotic nova RR Tel that we include in the group despite a slightly lower X-ray luminosity (a few $10^{\simeq 35}$ ergs, see Jordan et al 1993). The two classical novae seemed to fade below the *Rosat* detection threshold respectively in 10 and 1.5 years (Shanley et al, 1994, and Krautter et al, 1994); other SUSO's seem to be variable (see for instance Schaeidt et al 1993). Other objects exhibiting SUSO's characteristics are two galactic PG 1159 stars that emit supersoft X-ray radiation at about 1 % of the Eddington luminosity. They are most likely recently formed white dwarfs that have lost all the H and He rich envelope of the central star because of a He flash (Nousek et al 1986, Werner 1991, Motch et al 1993). CAL 83 and CAL 87 are both eclipsing binaries. Pakull et al (1988) discovered that CAL 87 is a low mass eclipsing binary and Cowley et al (1990) measured its orbital period of 10.6 hours. Optical spectra of CAL 83 revealed emission lines typical of an accretion disk and a sinusoidal variation of the radial velocity with periodicity 1.0436±0.0044 days (Crampton et al, 1983, Smale et al 1988). So far only one of the *Rosat* LMC sources, RXJ0513.9-6951 , has been identified optically and it is described as "remarkably similar to CAL 83", with optical and UV spectra showing narrow H, HeII and OIV emission lines, absence of strong CIV λ1548,51 and shallow P Cygni absorption components in the hydrogen lines (see Pakull et al, 1993, Cowley et al, 1993). Radial velocity variations suggest a binary system. The three galactic SUSO's mentioned above and one in the SMC are post-outburst classical novae or symbiotic novae. In short, most SUSO's seem to be close binaries and some definitely host a white dwarf as the compact object.

In section 2 we proceed to present photometric and spectroscopic observations of the proposed optical counterpart of 1E0035.4-7230 . A discussion follows in section 3.

2. The observations

2.1. Photometry

We observed the field of 1E0035.4-7230 photometrically on November 8 and 10, 1993 with a Thompson CCD detector at the the 1.5 m Danish telescope of the European Southern Observatory (ESO) at La Silla. The first four frames were obtained in the R,V,B and U Johnson colours and the following

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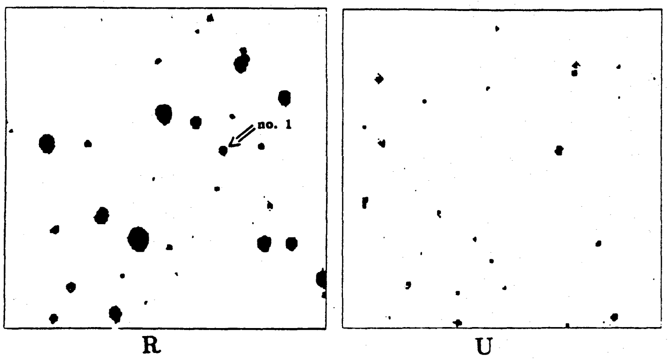

Fig. 1. The field of 1E0035.4-7230 as it appeared on November 8 1993 with the Thompson CCD at the 1.5 m danish ESO telescope in R and U filters. The star marked as no. 1 is at 1950 coordinates α = 00, 35, 19.256 and δ = -72, 30, 43.37.

exposures were all with the B filter. We took several exposures of the field in the "B" colour during two intervals of time. From the first to the last exposure 1 hour and 46 minutes elapsed on November 8 and 1 hour and 35 minutes on November 10. What immediately appeared striking is that the star that we mark as no. 1 in Fig. 1, 3.9" NW of the *Einstein* HRI position, has a significant UB excess (see Fig. 1 for the comparison of R and U). The error radius at 90 % confidence level for the *Einstein* HRI position is 40", but there are no other stars with a UB excess in the error box. To obtain an absolute calibration of the magnitudes in B, V and R we observed the field again on February, 18, 1994 with the Dutch 90 cm telescope at ESO, a TK512CB CCD and the ESO filters number 419, 420 and 421. In order to transform the instrumental magnitudes in the Johnson-Kron-Cousins system we observed 15 standard stars (from Landolt, 1992). Good photometric conditions of the sky on that night allowed determination of the colour and extinction coefficients. Using these calibration data, reduced with the ESO standard software package MIDAS and with the photometric software packages DAOPHOT and ROBIN (see respectively Stetson, 1987, Lanteri, 1994), we estimated the absolute magnitudes of the candidate star no. 1 in the frames of November 8 1993 (the Danish 1.5 m telescope allowed higher precision for this star, which appeared faint). A point spread function was fitted to the stars' profiles. The resulting V magnitude of star no. 1 is V = 20.25 ±0.05. We conclude that this object is very likely to be the one mentioned by Jones et al. (1985), who remarked that a V$\simeq$21 star in the field might be the optical counterpart of 1E0035.4-7230 . Assuming for the SMC a distance modulus 18.80 (van den Bergh, 1992) and a reddening E(B-V)=0.043 (Burstein & Heles, 1984) we obtain an absolute magnitude M_v=1.31±0.05. From the R image and the third B image of the same night we computed the Johnson colour indexes B–V = –0.29 ± 0.07 and V–R = –0.01 ± 0.10.

Analysis of the B exposures with DAOPHOT to detect time variability did indeed show that the object is variable. During the second night the luminosity decreased by about 0.2 mag (see Fig. 2 a and b). The error bars shown in the figures are obtained with the relative photometry. The accuracy is better than that of the external calibration. We estimated these errors calculating a weighted mean of the differences relative to eight stars that appeared at a constant luminosity level in the different frames. The errors vary, but do not exceed 0.03 mag for the second data set, so the variation of $\simeq$0.2 mag is indeed significant. Obviously much more observing time is needed to detect a periodicity, but the light curve in Fig. 2b suggests that an eclipse might have occurred. The portion of the light curve that we monitored resembles the light curves of CAL 87 near eclipse (see Cowley et al. 1990, Pakull et al. 1988). Judging from the two last observations, the star became 0.2 mag fainter in 40 minutes. It is interesting to notice that this is about the time for the first decrease of 0.2 mag in the major eclipse of CAL 87 (the depth of the whole eclipse is 1.2 mag and it is complete in about 2.5 hours). In the time interval covered by the data of Fig. 1a on the other hand the brightness did not vary significantly, but also CAL 87 appeared at constant luminosity level for time intervals of 2–2.5 hrs (see Cowley et al. 1990).

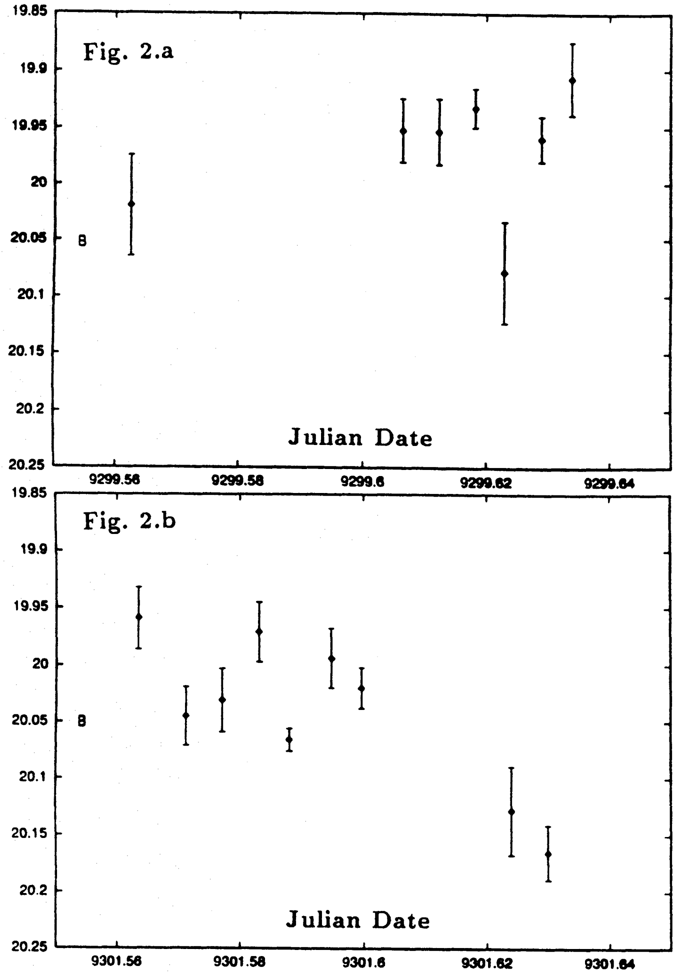

Fig. 2. The light curve of star no. 1 on November 8 1994 (2a) and on November 10 1994 (2b). Each point represents a 10 min exposure.

2.2. Spectroscopy

On the night of November 10, 1994 we also obtained the spectrum of star no. 1 shown in Fig. 3 with the ESO 3.6 m telescope and the imaging spectrograph EFOSC (Eso Faint Object Spectrograph and Camera), covering the wavelengths 3500-7000 Å with 14 Å resolution. The main characteristics, in common with CAL 83 and 87, are the very blue continuum and the

Table 1. The flux and full width at half maximum for each of the emission lines appearing in the spectrum in Fig.3.

Observed λ (Å)	identification	flux in 10^{-16} ergs/cm^2/s	fwhm
4077.5	blend of NII(38), OII(10), CII(36)	3.3	35
4118	OII(37)	2.2	15
4690	HeII(1)	1.6	14
4864	Hβ	1.2	22
4971	OI(14)	2.4	35.0
6069	NII (27)	0.83	30.84
6566	Hα	1.70	30.85

presence of some weak emission lines. Only the HeII λ 4686 feature is well pronounced. In Table 1 we report the flux and full width at half maximum of the lines. The NIII $\lambda\lambda$4634–41 complex seems to be missing for the candidate optical counterpart of 1E0035.4-7230 , although it is conspicuous in the case of CAL 83. We notice that the full width at maximum of Hα and of the NII λ6069 line is twice the instrumental width, suggesting the possibility of a doubly peaked but non resolved emission. The gaussian fit to the lines of Table 1 shows that they are red-shifted by 3–4 Å, so that the SMC membership is verified. Since we did not observe standard stars for absolute calibration in the U band, we estimated the U-B colour index from the spectrum as U–B = -0.50 ± 0.10, while the value of B–V did not seem significantly different from the value measured two nights before.

3. Discussion

The serendipitous finding of several SUSO's in the Magellanic Clouds shows that these objects might be quite common. They are likely to be often missed because of variability (see the dramatic variations of RXJ0513.9-6951 in Schaeidt et al 1993) or the variable count rate of RXJ0527.8-6954 (Orio & Ögelman 1993), moreover galactic absorption plays a very strong selection effect against their discovery. Different hypothesis were formulated for the nature of SUSO's. Cowley et al (1990) inferred a very high mass function from radial velocity measurements of the He II λ4686 in CAL 87, and suggested the possibility that its compact object is is a black hole candidate. However, van den Heuvel et al (1992) found evidence that this line is not formed in the vicinity of the disk, but most likely in the extended region of hot disk corona produced by a wind. Other more conservative explanations for SUSO's involve binaries containing neutron stars (e.g. Smale et al, 1988). Some authors (Pakull 1988, van den Heuvel et al 1992, Ögelman et al 1993, Orio & Ögelman 1993) suggest instead that all binary SUSO's might be white dwarfs on which hydrogen burning is occurring in a shell of hydrogen material accreted from a companion, although in systems with different parameters. Since the post novae GQ Mus and N Cyg 1992, the planetary nebula N67 and the symbiotic novae SMC 3 and RR Tel belong to the SUSO's group, there is no doubt that hydrogen burning in a shell indeed produces the type of X-ray emission detected by *Einstein* or *Rosat* .

Nova remnants are expected to appear as super-soft X-ray sources if part of the accreted hydrogen rich envelope is not ejected and continues to burn (e.g. Prialnik 1986). They should be observed at the same luminosity level for even 100 years, but this is *not* confirmed by *Rosat* observations (Orio 1993). It was also recently shown that classical novae might reach effective temperatures as high as a few 10^5 K for centuries *before* the outburst if the accreting white dwarf is close to the Chandrasekhar mass, thereby being observable as SUSO's (Prialnik & Kovetz 1994). However, not all SUSO's can be novae. In the first place, the orbital periods of CAL 83 and 87 are definitely too long. Moreover, the LMC was well monitored for nova search in the last 50 years, but none of the known sources is close to the position of a known nova (Orio 1993). According to van den Heuvel et al (1992) CAL 83 and 87 are binary systems with a white dwarf and a near main sequence companion of the order of 1–2 $M_\odot$, accreting and burning 10^{-7} $M_\odot$ yr^{-1}. Pakull et al (1993) even explain the brightening of a factor 20 in X-rays that occourred for RXJ0513.9-6951 with variable mass accretion rate on a white dwarf. Theoretical models recently calculated for SUSO's therefore imply hydrogen burning on top of a white dwarf with a thin atmosphere, with (Shaham et al 1993) or without (Sion & Starrfield 1993) irradiation induced mass transfer playing a role refuelling the burning envelope.

The X-ray observations of the two PG 1159 stars mentioned in the introduction and of the planetary nebula N 67 imply that there is range of possible conditions in which white dwarfs appear as SUSO's. It can happen when the white dwarfs are simply "just being born" either because they are still extremly hot (and depleted of hydrogen and helium) or because they still burn hydrogen in a shell. The "SUSO condition" occurs, however, also as an end product of a complex binary evolution, if hydrogen is burning at very high rate in an accreted shell.

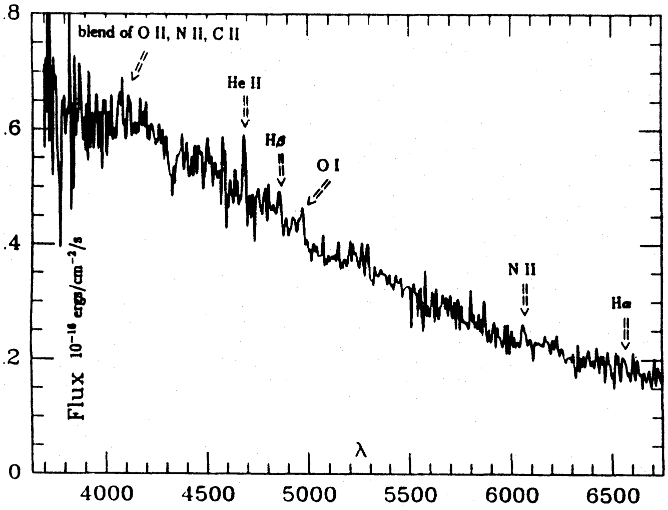

Fig. 3. Mean flux calibrated spectrum of the proposed optical counterpart of 1E0035.4-7230

For the intriguing binary SUSO's, before developing the models further we need to acquire and fully understand the optical data that provide constraints for the nature of the systems. In Table 2 we report the dereddened magnitudes and intrinsic color indexes of the optical counterparts found for 1E0035.4-7230 and for other SUSO's. For the SMC we assumed E(B-V)=0.045 to obtain the intrinsic colour indexes, as mentioned in Section 2.1. For the LMC sources we assumed

Table 2. Mean absolute magnitudes, reference paper, color indexes, amplitude of brightness modulations for five sources. *The references are: 1) Crampton et al, 1987, data of November 1985; 2) Smale et al, 1988, data of December 1984; 3) Smale et al, 1988, data of August 1984; 4) Cowley et al, 1990, data of November/December 1985; 5) Pakull et al, 1988, data of March 1986; 6) Pakull et al, 1993, 7) Diaz & Steiner, 1989, data of March 1988, with E(B−V)=0.45, d=4.8 Kpc, as Krautter et al, 1984.*

Source	ref	M_v	<V-R>	<B-V>	<U-B>	Δ(m)
1E0035.4-7230		+1.31±0.05	-0.04±0.10	-0.34±0.07	-0.50±0.10	≥0.2
CAL 83	1	−1.43±0.03		-0.090±0.034		≃0.2
	2	−1.84±0.1				0.22
	3	−2.39±0.01				
CAL 87	4	+0.248±0.196	+0.090±0.043	+0.075±0.043	-0.700±0.075	1.2
	5	+0.19±0.300	+0.09±0.06	+0.24±0.06		
RXJ0513.9-6951	6	−2.01		-0.16±0.04		
GQ Mus	7	+2.66		-0.3	-1.1	≃0.5

a distance modulus 18.5 (Panagia et al., 1991) and reddening E(B-V)=0.065 (Burstein & Heiles, 1984). In Table 2 also the amplitude modulation of the sources is indicated, if it is known. The first thing that appears striking concerns the absolute magnitudes. Supposing that the white dwarf radiates as a black body at $T\simeq350000$ K, the optical luminosity would be at most a fraction of order 10^{-4} of the total bolometric luminosity ($L_{opt} \leq 10^{34}$ ergs/s). The absolute visual magnitude would be in the range M_v=+3–M_v=+4. A near main sequence secondary of 1–2 $M_\odot$ as suggested by van den Heuvel et al. (1992), would have M_v=+2 to M_v=+4.8. GQ Mus is an exception with a secondary oft $M_v \simeq +13$ (its mass is ≤ 0.2 $M_\odot$).

The colour indexes in Table 2 give additional significant physical information, being due to the inclination of the disk, to the mass of the secondary and to the extent of the irradiated region. For the proposed counterpart of 1E0035.4-7230 , the B–V and V–R colour indexes are consistent with a large region at a temperature above 25000 K (a fact that again seems to be well explained by X-ray irradiation). The U–B value inferred from the spectrum implies, however, a lower temperature, a fact that cannot be understood with a simple model. We intend to monitor this star photometrically and spectroscopically in the future, in order to compare it with the other systems. Not only for 1E0035.4-7230 , but for all SUSO's much work is still needed to determine the physical parameters. These objects might have great astrophysical significance, being possible progenitors of type Ia SNe (Della Valle & Livio 1994) or eventually undergoing an accretion induced collapse. It seems therefore that this complex but challenging study should be pursued further.

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