Letter to the Editor

The identification of the long–period X–ray pulsar 1WGA J1958.2+3232 with a Be-star/X-ray binary[⋆]

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Abstract. We present the results of optical observations performed between May and September 1998 of the stars within the position error circle of the recently discovered $\sim$12 min pulsating X–ray source 1WGA J1958.2+3232. Based on photometry and slitless spectroscopy, we selected a likely optical counterpart, which was subsequently determined to be a m_V=15.7 B0Ve star, the spectral properties of which are in good agreement with the X–ray results. The proposed optical counterpart shows several H, He and Fe emission–lines, while the interstellar absorption spectral features place the star at a distance of $\sim$ 800 pc. The inferred X–ray luminosity for this distance is $\simeq 10^{33}$ erg s^{-1} in the 2–10 keV band. We conclude that 1WGA J1958.2+3232 is a likely new long–period low–luminosity accreting neutron star in a Be–star/X–ray binary system.

Key words: stars: binaries: general – stars: emission-line, Be – stars: neutron – stars: pulsars: individual: 1WGA J1958.2+3232 – X-rays: stars

1. Introduction

The X–ray source 1WGA J1958.2+3232 was serendipitously detected on May 1993 within the field of view of the Position Sensitive Proportional Counter (PSPC; 0.1–2.4 keV) in the focal plane of the ROSAT X–ray telescope. Highly significant pulsations at a period of 721±14 s were discovered in the ROSAT data (Israel et al. 1998). An ASCA observation performed on May 1998 detected 1WGA J1958.2+3232 at the flux level expected from the ROSAT pointing and confirmed the presence of a strong periodic signal at 734±1 s (Israel et al. 1999). A luminosity of $\sim 10^{33}(d/1\,\mathrm{kpc})^2$ erg s^{-1} in the 2–10 keV energy band was obtained (assuming an absorbed power–law model). Due

to the large uncertainty in the period determined by ROSAT, it was not possible to determine whether the system contains an accreting magnetic white dwarf or a neutron star, based on the period derivative. Even the spectral characteristics were consistent with both scenarios. Accreting neutron stars in binary systems are often associated with O–B stars, while cataclysmic variables with K–M main sequence companion stars; in both cases strong emission–lines are expected to be detected. So far no unambiguous association of an accreting white dwarf to an OB star has been found. Expected X–ray luminosities are in the $\leq 10^{32}$ erg s^{-1} range for wind accretors. Identifying the optical counterpart of 1WGA J1958.2+3232 and studying its spectrum provides decisive clues on the nature of system.

We present here the results of an optical program aimed at studying the stars included in the X–ray $30''$ radius error circle of 1WGA J1958.2+3232. The observations were performed between May and September 1998 at the Loiano Astronomical Observatory. In order to select objects with peculiar emission–lines, as expected from the companion star of this kind of binary systems, slitless multiobject spectroscopy as described by Polcaro & Viotti (1998) was used. This method allows to obtain a good spectrum for a large number of stars and quickly select stars with strong emission–lines, down to magnitudes of $m_V \leq$ 16–18. Moreover the absence of a slit eliminates the light loss due to poor seeing, while sky and nebular lines are spread out over the whole image, resulting only in a small increase of the background level.

A Be spectral–type star was found well within the X–ray error circle. The probability of finding by chance a Be star with V$\leq$16.0 mag within the small position uncertainty region is $\sim 10^{-6}$. Therefore the Be star represents a very likely optical counterpart of 1WGA J1958.2+3232, making this source one of the few accreting X–ray pulsars with a pulse period P > 500 s in a Be/X–ray binary system.

2. Observations and results

The observations were all performed with the 1.52 m "Cassini" telescope equipped with the Bologna Faint Objects Spectrom-
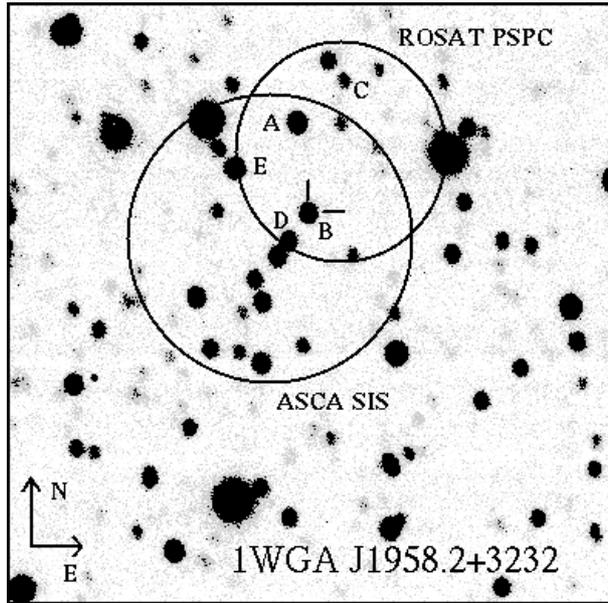

Fig. 1. 2 min image (filter R) of the field of 1WGA J1958.2+3232. The H_α emitter position is marked (Cand B). The position uncertainty circles of ROSAT PSPC (30″) and ASCA SIS (40″) are also shown.

Table 1. Position and V magnitude of the studied stars within the uncertainty region.

Star	R.A. (2000)[a] (hh mm ss)	DEC (2000)[a] (deg ′ ″)	V[b] mag
A	19 58 14.7	+32 33 07	15.4
B	19 58 14.4	+32 32 42	15.7
C	19 58 13.6	+32 33 16	17.0
D	19 58 16.0	+32 32 54	16.6
E	19 58 14.9	+32 32 34	16.0

[a] calibrated with DSS1 plates. Uncertainty 1″.
[b] calibrated with DSS1 plates. Uncertainty 0.1 mag.

Table 2. Journal of the slit spectroscopic observations.

Date	UT	Wavelenght Range (Å)	Dispersion (Å/pixel)
1998 May 30	23:40	3900–7900	3.8
”	00:30	”	”
”	01:00	”	”
”	01:30	”	”
1998 May 31	23:30	”	”
”	00:15	”	”
1998 June 01	00:10	6200–7900	1.7
”	01:00	3900–7900	3.8
1998 July 27	23:11	3800–9000	2.5
1998 July 28	00:09	”	”
1998 July 30	20:25	”	”
1998 July 31	22:56	”	”
1998 Sep. 14	20:32	”	”
1998 Sep. 15	18:38	”	”

eter and Camera *BFOSC* (Bregoli et al. 1987, Merighi et al. 1994). During the first run (May 1998) the camera was equipped with the Thomson 1024×1024 CCD with 0.56″ pixel size and $\sim 9.6 \times 9.6$ field of view (FOV). On July and September 1998 a Loral 2048×2048 CCD detector with 0.41″ pixel size and a FOV of $\sim 13.5 \times 13.5$ was used instead. We performed V, R and I photometry, and low–resolution spectroscopy. The data were reduced using standard *ESO–MIDAS* and *IRAF* procedures for bias subtraction, flat–field correction, and one dimension stellar and sky spectra extraction. Cosmic rays were removed from each image and spectrum and the sky–subtracted stellar spectra were obtained, corrected for atmospheric extinction and flux calibrated (when possible).

2.1. Photometry and spectroscopy

V, R, and I images of the whole 9.6×9.6 wide 1WGA J1958.2+3232 field were first obtained on 1998 May 30. In Fig. 1 the ROSAT PSPC error circle is shown together with the ASCA error circle (Israel et al. 1998, 1999). Note that at the time of the first optical observation only the ROSAT PSPC position uncertainty was known. Photometry for each stellar object in the image was derived with the DAOPHOT II package (Stetson 1987), and Color-Magnitude Diagrams (CMDs) were then computed for all color combinations. By the analysis of the V-R vs. V CMD a well defined main sequence is clearly visible (Fig. 2), as expected in an area projected along the galactic plane like the one of 1WGA J1958.2+3232 ($l^{II} \sim 69°$; $b^{II} \sim 2°$). However, a number of objects with peculiar colors (redder or bluer) with respect the bulk of the stars were selected; three of them (stars A, B and C) were found to lie within the ROSAT position uncertainty region (see Table 1). Comparison between

photometry obtained at the beginning and the end of the run showed no signs of variability to a limit of ~ 0.2 mag for any of the selected objects. A comparison between May and September 1999 gave similar results.

On 1998 May 30 we obtained a low–resolution (20 Å) slit-less spectroscopic image of the field with an R filter and a large band grism covering the spectral region (4000–8000 Å). We note that, in general, the choice of the grism, filter and time exposure depends on the grism dispersion and CCD size (which set the maximum spectral range allowed), and the crowding level of the field (which sets the maximum number of non–overlapping spectra to be analysed). The selected filter and grism combination gives a bandpass of ~ 1000 Å, centered on Hα. A detailed analysis of the spectra obtained in this way allowed us to single out a relatively strong Hα emission line associated to one (star B) of the three stars previously selected.

Slit spectroscopy was performed over selected stars on 1998 May 30–June 2, July 27–31, and September 14–15 (see Table 2).

2.2. Results

The spectra of star A are undoubtfully those of a classical OB star. However neither emission–lines or other peculiarities are
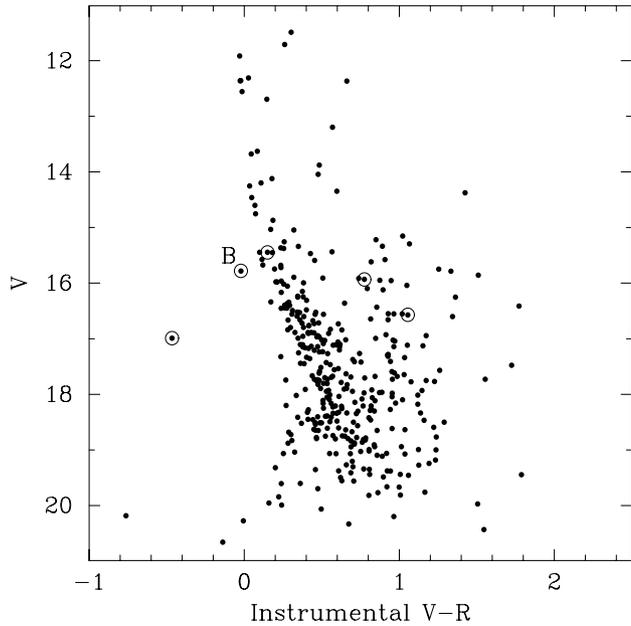
Fig. 2. Color–Magnitude diagram in filter V and R for 1WGA J1958.2+3232. Big circles mark the five stars within the X–ray position uncertainty region, while the letter B represents the likely optical counterpart.

Table 3. List of the strongest spectral lines identified in the likely optical counterpart of the 1WGA J1958.2+3232 star.

Line ID	Wavelength (Å)	EW (Å)
H_δ	4101	1.6
H_γ	4340	5.3
H_β	4861	14.4
H_α	6563	45.2
HeI	4471	2.2
HeII	4686	2.5
HeI	4922	3.7
HeI	5876	2.5
HeI	6678	6.0
HeI	7066	6.2
FeII	4990	2.2
FeII	5466	8.0
CrI	5297–8	2.5

present that would associate this star with the X–rays source. Similar results were obtained for stars D and E for which a slitless spectrum was obtained on May 1998.

Due to its faintness (R=17.0) star C is more difficult to study. Even after a 1.5 h exposure spectrum, the S/N ratio of the spectrum barely reached the unity with our instrumental set–up. The steep rise of its spectrum in the UV argues for a very hot object. However, it is unlikely that it is to be associated with the X–ray source since no obvious emission features are present. Moreover, after the ASCA observation, its position lies outside the intersection region of the two X–ray error circles.

We note that at the border of the ROSAT error circle lies a bright (V≃12) star. Its 4000–8000 Å spectrum ($\Delta\lambda$=5.5 Å) was taken in an earlier observation (June 1996) also from the Loiano Observatory using the *BFOSC*; the star resulted to be a strongly reddened B8V spectral–type star, without any spectral peculiarity.

The spectrum of star B clearly shows a very high ionization state (see Fig. 3). The Balmer series lines are all in emission, up to the blue edge of our spectrogram as well as many He I ($\lambda\lambda$ 4471, 4922, 5875, 6678, 7065, 8361 Å) and He II ($\lambda\lambda$ 4686, 5412 Å). An emission feature centered at 4634 Å is present, that could be attributed to the N III 4634–40 Å doublet, but we cannot exclude the possibility that these feature is mainly due to Fe II lines. The presence of He II emission rules out a classical Be star, whereas the presence of emissions up to H7 exclude that of an Of star (see e.g. Jaschek & Jaschek, 1987).

Table 3 gives the parameters of the strongest emission lines. These lines (Hα, Hβ, Hγ, He I 5875 Å, He II 4686 Å) show extended and asymmetric profiles, with a red wing more pro-

nounced than the blue wing. At our spectral resolution, this might indicate a line splitting, possibly due to the presence of a disk. The absence of forbidden lines rules out the possibility of a pre–main sequence object or a cataclysmic variable. All this evidence clearly point to the association of this object with the X–ray source.

3. Discussion

The spectrum of star B is similar to those of massive Be/X–ray binaries. As usual, a more detailed spectral classification is made more difficult by the fact that most of the classical criteria are unusable, since the H and most of the He lines are in emission and the Fe II complex masks most of the stellar atmospheric features. However, the presence of N III, C III and O II lines, and the ~ 0.1 Å equivalent width of the Mg II 4481 Å line suggest a B0 spectral type (see e.g. Jaschek & Jaschek, 1987). The few absorption lines that are clearly visible are wide, thus suggesting a main sequence star. We can thus conclude that most probably the optical companion of the collapsed object is a B0V star.

The equivalent width ≃0.5 Å of the interstellar Na II (5890 Å) indicates an intermediate reddening ($E_{B-V} \simeq 0.6$; following Hobbs, 1974), corresponding, in the Cygnus region to a distance of ~ 800 pc (Ishida, 1969). We also note that a $E_{B-V} \simeq 0.6$ translates into a hydrogen column of $\sim 3 \times 10^{21}$ cm^{-2} (Zombeck 1990), which is in good agreement with the N_H values inferred from the spectral analysis of the merged ROSAT and ASCA data ($N_H \sim 4 \times 10^{21}$ cm^{-2}; Israel et al. 1999). This result implies a 1–10 keV X–ray luminosity of 1.2 $\times 10^{33}$ erg s^{-1}. Even though the optical data argue against an accreting white dwarf, only a measurement of the spin period derivative will firmly asses the nature of the accreting object. If the system hosts an accreting neutron star, than it would be one of the faintest Be/X–ray pulsars. Its closest analogue would be X Per which shows a 1–10 keV X–ray luminosity of 0.7–3.0 $\times 10^{34}$ erg s^{-1} in its low state (Haberl et al. 1998). Two recently identified Be/X–ray pulsars, namely RX J0440.9+4431/BSD 24–491 and RX J1037.5–564/LS 1698
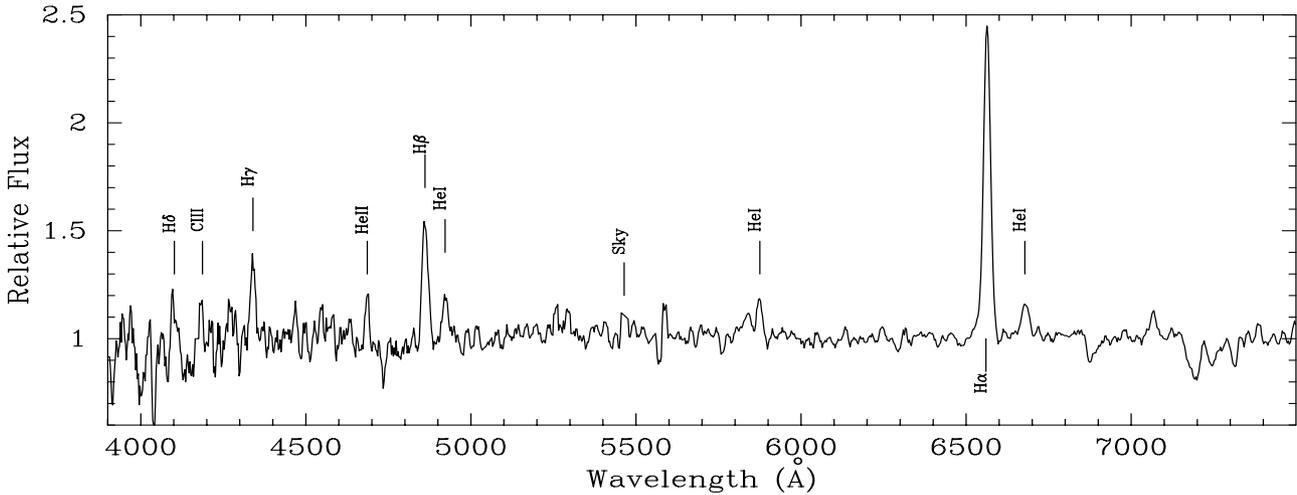
Fig. 3. 5 hr low–resolution normalised spectrum of 1WGA J1958.2+3232 obtained on July 1998. The strongest emission lines detected in the spectrum are marked.

(Reig & Roche, 1999), also share similar optical and X–ray characteristics with 1WGA J1958.2+3232. If the accreting object is a white dwarf, 1WGA J1958.2+3232 would be the first example of a Be/white dwarf interacting binary system.

4. Conclusion

Based on the optical results we obtained for the stars within the error circle of 1WGA J1958.2+3232, we conclude that star B, a B0Ve spectral–type star, represents the very likely optical counterpart of 1WGA J1958.2+3232. We compared the optical findings with recent ASCA X–ray data obtained for this source (Israel et al. 1999), other similar X–ray sources (Haberl et al. 1998; Reig & Roche, 1999), and the current knowledge on accreting white dwarfs. We conclude that 1WGA J1958.2+3232 is a new likely faint Be/X–ray pulsar, probably belonging to a new subclass of Be X–ray binary systems with long periods, persistent, low luminosities X–ray emission, and small flux variations. If the accreting white dwarf interpretation proves instead correct, than 1WGA J1958.2+3232 would be the first unambiguous example of a Be/white dwarf binary system.

References

Bregoli, G., Federici, L., Merighi, R., et al., 1987, in: ESO–OHP Workshop on the Optimization of the Use of CCD Detectors in Astronomy, Saint–Michel–l'Observatoire, France, June 17–19, 1986, Proceedings (A88–13301 03–89). Garching, ESO, Germany, p. 177

Haberl, F., Angelini, L., Motch, C. et al. 1998, A&A, 330, 189

Hobbs, L.M., 1974, ApJ, 191, 381

Ishida, K., 1969, MNRAS, 144, 55

Israel, G.L., Angelini, L, Campana, S., et al., 1998, MNRAS, 298, 502

Israel, G.L., et al., 1999, in preparation

Jaschek, C., Jaschek, M., 1987, "The Classification of Stars", Cambridge University Press

Merighi, R., Mignoli, M., Ciattaglia, C., et al., 1994, Bologna Technical Reports 09,-1994,-05

Polcaro, V.F., Viotti, R., 1998, in: "Astronomical Data Analysis Software and Systems VII", ASP Conference Series, Vol. 145, Eds. R. Albrecht, R. N. Hook & H. A. Bushouse

Reig, P., Roche, P., 1999, MNRAS, in press (astro–ph/9902221)

Stetson P.B. 1987, PASP, 99, 191

Zombeck, M.V., 1990, in "Handbook of space astronomy & astrophysics", Cambridge University Press