Astronomy
&
Astrophysics

HST observations of the nebula around the central compact object in the Vela Jr. supernova remnant⋆
(Research Note)

R. P. Mignani[1], A. De Luca[2,3], and A. Pellizzoni[4]

[1] Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Dorking, Surrey, RH5 6NT, UK
 e-mail: rm2@mssl.ucl.ac.uk
[2] Istituto Universitario di Studi Superiori Viale Lungo Ticino Sforza 56, Pavia 27100, Italy
[3] INAF, Istituto di Astrofisica Spaziale, via Bassini 15, Milan 20133, Italy
 e-mail: deluca@iasf-milano.inaf.it
[4] INAF, Osservatorio Astronomico di Cagliari, Localitá Poggio dei Pini, Strada 54, Capoterra, Cagliari 09012, Italy
 e-mail: apellizz@oa-cagliari.inaf.it

ABSTRACT

Context. A handful of young (a few thousand years) supernova remnants (SNRs) host point-like X-ray sources, dubbed central compact objects (CCOs), which are thought to be radio-silent isolated neutron stars formed by the supernova explosion. So far, no CCO has been firmly detected at other wavelengths. However, ground-based observation in the H_α band detected a nebula around CXO J085201.4−461753, the CCO in the Vela Jr. SNR. The nebula has also been detected in deep *R*-band observations performed with the *Very Large Telescope* (*VLT*). Interestingly, both its extension and its flux in the *R* band are consistent with those measured in H_α, suggesting that the nebula spectrum is dominated by line emission, possibly produced by a velocity-driven bow-shock in the interstellar medium (ISM) or by its photo-ionisation from the neutron star.
Aims. The aim of this work is to resolve the morphology of the H_α nebula around the CCO to verify the proposed interpretations.
Methods. We performed high-resolution imaging observations of the nebula with the *Wide Field Planetary Camera 2* (*WFPC2*) of the *Hubble Space Telescope* (*HST*) through the *656N* filter, almost exactly centred on the rest wavelength of the H_α line.
Results. Surprisingly enough, we did not detect the nebula in our *WFPC2* image down to a 3σ flux limit of $\sim 3 \times 10^{-15}$ erg cm^{-2} s^{-1}. This limit is a factor of 10 fainter than the nebula flux measured in the discovery ground-based observations which were, however, performed with redder and broader H_α filters.
Conclusions. The non-detection of the nebula in the narrower and bluer *WFPC2 656N* filter suggests that the peak of the emission might actually be at longer wavelengths. One possibility, compatible with the bow-shock scenario only, is that the H_α line is red-shifted by $\sim 10–60$ Å due to the neutron star motion with a radial velocity $450 \lesssim V_r \lesssim 2700$ km s^{-1}. The other possibility is that the nebula is a knot of [NII] emission ($\lambda = 6583.6$ Å) unrelated to CXO J085201.4−461753 and possibly associated with the nearby star Wray 16-30. High-resolution spectroscopy observations will help to settle the nature of the nebula.

Key words. stars: neutron – ISM: supernova remnants – ISM: clouds

1. Introduction

X-ray observations performed over the last 30 years led to the discovery of about ten puzzling radio-silent, isolated neutron stars (INSs) at the centre of young ($\sim 0.3–20$ kyears old) supernova remnants (SNRs), hence dubbed central compact objects (CCOs; Pavlov et al. 2004). Their thermal-like X-ray spectra and lack of pulsar-wind nebulae (PWNe) indicate a low level of magnetospheric activity, which clearly sets CCO apart from most young INSs (see De Luca 2008 for a recent review). X-ray pulsations have been measured only for 1E 1207−5209 in PKS 1209−52 ($P = 424$ ms; Zavlin et al. 2000), CXOU J185238.6+004020 in Kes 79 ($P = 105$ ms; Gotthelf et al. 2005), and RX J0822.0−4300 in Puppis A ($P = 112$ ms; Gotthelf & Halpern 2009). In all three cases, the upper limits on the period derivatives (Gotthelf & Halpern 2007;

Halpern et al. 2007; Gotthelf & Halpern 2009) suggest magnetic fields $B \lesssim 10^{11-12}$ G, rotational energy losses $\dot{E} \lesssim 10^{32-35}$ erg s^{-1}, and spin-down ages a factor of $\gtrsim 1000$ larger then the SNR age. This suggests a scenario where CCOs are born spinning close to their present period and with very low magnetic fields, perhaps enabling polar cap accretion from a debris disc. So far, no CCO has been detected outside the X-ray band (see De Luca 2008, and references therein). One possible exception is the CCO in the RX J0852.0−4622 (G266.1−1.2) SNR. In the optical, CXO J085201.4−461753 is embedded in a compact ($\sim 6''$ diameter) nebula detected in H_α both in an archival *ESO/MPG 2.2 m* observation and in a digitised UK Schmidt Telescope (*UKST*) plate (Pellizzoni et al. 2002). Recent *Very Large Telescope* (*VLT*) observations clearly detected the nebula also in the *R* band (Mignani et al. 2007a,b) with an extension and a flux consistent with those measured in H_α, suggesting that its spectrum is dominated by line emission. The most likely interpretations favour either a velocity-driven bow-shock nebula,

as observed in a handful of other INSs (see, e.g. Pellizzoni et al. 2002, and references therein), or a photo-ionisation nebula produced by the ultraviolet (UV) radiation from the neutron star. The nebula was undetected in more recent *VLT* infrared (IR) observations which, instead, pinpointed a faint ($K_{\rm s} \sim 21.4$) candidate counterpart to the CCO (Mignani et al. 2007b).

Here, we present high resolution H_α imaging observations of the nebula around CXO J085201.4−461753 taken with the *Hubble Space Telescope* (*HST*). The observations and data analysis are described in Sect. 2, while the results are discussed in Sect. 3.

2. Observations and results

As a back-up after the failure of the *Advanced Camera for Survey (ACS)* on January 2007, CXO J085201.4−461753 was re-scheduled for observations with the *Wide Field Planetary Camera 2* (*WFPC2*). We obtained a set of four 500 s exposures during the allocated spacecraft orbit on January 12th 2008. In order to exploit the maximum spatial resolution of the *WFPC2* we centred the target in the *planetary camera* (*PC*) chip ($0\farcs045$/pixel). The spacecraft pointing and orientation were fine-tuned in order to place two bright and nearby field stars, HD 76060 ($V = 7.9$; $\approx35''$ northeast) and Wray 16-30 ($V = 13.8$; $\approx25''$ southwest), out of the *PC* field of view. The observations were performed using the *656N* filter which has a central wavelength $\lambda = 6564$ Å and a full width half maximum (*FWHM*) $\Delta\lambda = 22$ Å. We retrieved the data from the *HST* science data archive after on-the-fly re-calibration, performed to remove instrument signatures (bias and flat-field correction). Flux calibration was performed as a part of the *WFPC2* standard pipeline processing. Single exposures were finally combined and averaged using the *STSDAS* task `combine` to filter cosmic ray hits.

As a reference for the CXO J085201.4−461753 position we used the *Chandra* coordinates re-computed in Mignani et al. (2007b), i.e. α(J2000) = 08$^{\rm h}$52$^{\rm m}$01.37$^{\rm s}$, δ(J2000) = −46°17′53$\farcs$50, with a nominal 90% error circle of $0\farcs6$. For consistency with Mignani et al. (2007b), we checked the astrometric calibration of the *WFPC2* image against the positions of stars in the *2MASS* catalogue (Skrutskie et al. 2006). We used the mosaic of the four *WFPC2* chips since it provides a large enough field of view to include a sufficient number of *2MASS* stars. We produced the mosaic image with the *STSDAS* task `wmosaic` which also accounts for the correction of the geometric distortions of the four chips. Then, we measured the pixel coordinates of the *2MASS* stars through gaussian fitting with the *Graphical Astronomy and Image Analysis* (*GAIA*) tool[1] and we computed the pixel-to-sky coordinates transformation using the code `ASTROM`[2]. This yielded an rms $\sigma r \approx 0\farcs13$ in the astrometric fit. Finally, we added in quadrature the uncertainty in the registration of the *WFPC2* image on the *2MASS* reference frame ($\sigma_{\rm tr} = 0\farcs055$)[3]. Thus, the overall accuracy of the *WFPC2* astrometry is $0\farcs14$ (1σ). By adding in quadrature this value to the $0\farcs6$ accuracy of the *Chandra* coordinates we obtained an uncertainty of $\sim0\farcs62$ on the CXO J085201.4−461753 position on the *WFPC2* image.

No point or extended source is visible at or close to the CCO position (Fig. 1). In order to increase the signal-to-noise ratio we rebinned the image by a factor of 2 and applied a smoothing
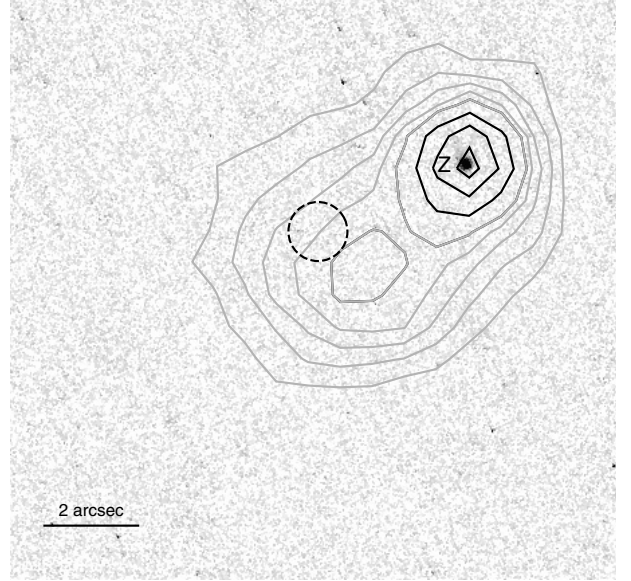
Fig. 1. $13'' \times 13''$ part of the combined 2000 s *WFPC2* image of the CXO J085201.4−461753 field obtained through the *656N* filter. The circle ($0\farcs62$ radius) corresponds to the computed uncertainty of the CCO position on the *WFPC2* (see Sect. 3). Star Z of Pavlov et al. (2001) is labelled. *North to the top, East to the left.* The isophotal contours from the *UKST* H_α image of Pellizzoni et al. (2002) overplotted (light grey contours: linear spacing; dark grey contours: logarithmic spacing).

over 3×3 pixel cells. Still, our result did not change. We thus conclude that the CXO J085201.4−461753 nebula was not detected in our images. We evaluated the upper limit to the flux of the undetected nebula from the number of background counts over regions with a size comparable to that of the nebula. We thus estimated that a 3σ detection would correspond to a count rate of 0.92 cts s^{-1} over such an area. According to the *WFPC2* absolute flux calibration, this corresponds to a flux limit of $\sim 3 \times 10^{-15}$ erg cm^{-2} s^{-1}. Assuming pure H_α emission, the flux of the nebula measured by Pellizzoni et al. (2002) in the *UKST* image, where it is detected at $\gtrsim50\sigma$, is a factor 10 brighter than our 3σ upper limit. This huge difference is far larger than any of the different flux calibration between the *UKST* and of the *WFPC2* images. Thus, we exclude that the non-detection of the nebula can be attributed to an exposure shallower than expected, possibly ascribed to a decrease in the efficiency of the *WFPC2* detector.

3. Discussion

The non-detection of the nebula in the *WFPC2 656N* image can be explained, in principle, by invoking a decrease in brightness since the epoch of the *ESO/MPG 2.2m* and of the *UKST* observations. However, this possibility is unlikely since the brightness measured in both ground-based observations is consistent with a steady emission. Besides, it would be difficult to explain on physical grounds such a large variability of the H_α emission in both the bow-shock and the photo-ionisation nebula scenarios. It is possible that the non-detection of the nebula in the *WFPC2 656N* image is purely an effect of the different characteristics of the filters used in the different observations. In particular, the H_α filter of the *ESO/MPG 2.2m Wide Field Imager* (*WFI*) has a central wavelength $\lambda = 6588.27$ Å and a *FWHM* $\Delta\lambda = 74.31$ Å[4], very similar to those of the H_α filter of the

UKST (λ = 6590 Å and a *FWHM* $\Delta\lambda$ = 70 Å; Parker & Phillips 1998). Thus, both filters are centred at wavelengths longer than the rest wavelength of the H$_\alpha$ line (λ = 6562.8 Å) which, however, is still encompassed by their relatively large band widths. Instead, the *WFPC2 656N* filter (λ = 6564 Å; $\Delta\lambda$ = 22 Å) is narrower and almost exactly centred on the rest wavelength of the H$_\alpha$ line. Consequently, it is possible that the nebula is detected through the broader and redder ground-based H$_\alpha$ filters, but not through the narrower and bluer *WFPC2 656N* because the emission peaks at a longer wavelength.

One possibility is that the H$_\alpha$ line is red-shifted by $\gtrsim$10 Å. However, since H$_\alpha$ emission is indeed detected in the broader ground-based filters, the line can not be red-shifted by more than ~60 Å. This corresponds to a red-shift 0.0015 $\lesssim z \lesssim$ 0.009 and it would imply that the nebula is either moving or expanding asymmetrically, with a radial velocity V_r = 450−2700 km s^{-1}.

In the bow-shock scenario, the first case would be compatible with both the CCO and the shock front moving along the radial direction. This would be consistent with the shape of the nebula which features a somewhat spherical symmetry (Pellizzoni et al. 2002; Mignani et al. 2007b) instead of the more typical arc-like one. On the other hand, a nebula expanding asymmetrically would be incompatible with the fact that the shock front is expected to be almost stationary with respect to the neutron star. An asymmetric nebula expansion would also be incompatible with the photo-ionisation scenario, unless the radiation pressure from the neutron star improbably sweeps the ISM in the radial direction only. This means that a red-shifted H$_\alpha$ line would be compatible with the bow-shock scenario only. In this case, we could constrain the CXO J085201.4−461753 rotational energy loss from its spatial velocity and from the H$_\alpha$ luminosity of the nebula (Chatterjee & Cordes 2002). We inferred the radial velocity V_r from the assumed red-shift of the H$_\alpha$ line, while we derived the transverse velocity V_t from the CCO displacement from the SNR centre ($\approx$5′) which, for a distance of ~1 kpc (Slane et al. 2001) and for an age of ~1000−3000 years (Katsuda et al. 2009), implies a value of 500−1500 km s^{-1}. This corresponds to a spatial velocity V = 700−3000 km s^{-1}, large but not unheard of for a neutron star, as it is shown by the Guitar Nebula pulsar PSR B2224+65 (see, e.g. Chatterjee & Cordes 2002, 2004). For an H$_\alpha$ luminosity of ~4 × 10^{30} erg s^{-1}, computed for a SNR distance of 1 kpc, and for a fraction of neutral hydrogen in the ISM $X \lesssim$ 1, the bow-shock formation requires that $\dot{E} \times V \gtrsim 7 \times 10^{36}$ erg km s^{-2} (see Fig. 3 of Pellizzoni et al. 2002). Thus, our limits on the CXO J085201.4−461753 spatial velocity translates into lower limits on its rotational energy loss of $\dot{E} \gtrsim 10^{34}$ erg s^{-1} and $\dot{E} \gtrsim 2 \times 10^{33}$ erg s^{-1}, respectively. We note that the lower bound on the $\dot{E}$ of CXO J085201.4−461753 would be still compatible with the $\dot{E}$ upper limits of both CXOU J185238.6+004020 in Kes 79 (Halpern et al. 2007) and of RX J0822.0−4300 in Puppis A (Gotthelf & Halpern 2009), and so be consistent with the emerging picture of CCOs as young, low-energetic INSs.

A second possibility is that the emission line is indeed [NII] (λ = 6583.6 Å). In this case, the nebula would neither be produced by a velocity-driven bow-shock nor by photo-ionisation from the neutron star. Most likely, it would be a fore/background emission knot in the SNR or in the diffuse emission structures observed close to the CXO J085201.4−461753 position (see, e.g. Fig. 1 of Pellizzoni et al. 2002 and Fig. 2). At this stage, we can only speculate on the nebula origin. Because of its proximity, the nebula might be associated with Star Z. This possibility is also suggested by the isophotal contours of
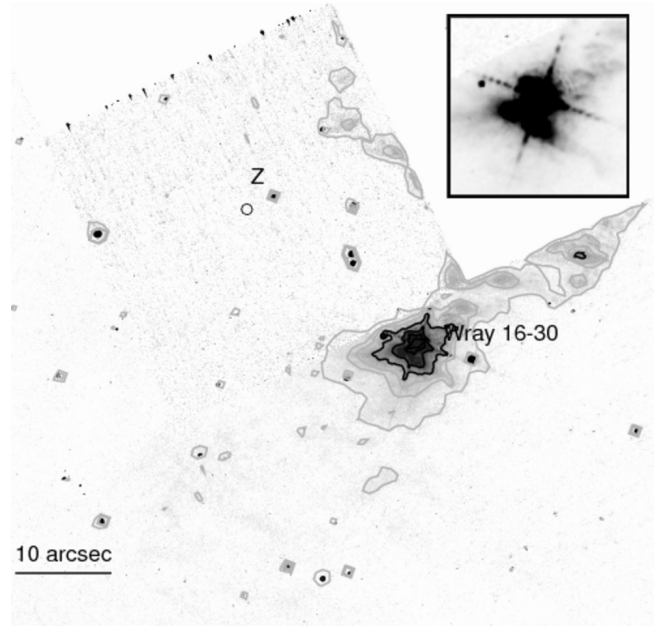

Fig. 2. 65″ × 65″ part of the mosaic *WFPC2* image around the CCO position (circle). Star Z and Wray 16-30 are labelled. *North to the top, East to the left*. Contours are colour-coded as in Fig. 1. Inset: 10″ × 10″ zoom of Wray 16-30.

the *UKST* H$_\alpha$ image (Fig. 1) which, within their 1″ angular resolution, do not allow to exclude a physical connection between the two. The classification of Star Z is, however, uncertain. For instance, based on its *B* and *R*-band magnitudes Pavlov et al. (2001) concluded that it might be an early G-type background star at a distance of 2.3 kpc, for an A_V ~ 1.7. Diffuse emission around main sequence stars could, in principle, be produced by gas outflows from the outer shells. However, if associated with Star Z, the nebula structure would require an unipolar outflow, difficult to explain for a main sequence star. Recently, Reynoso et al. (2006), based on 13 and 20 cm radio observations of the Vela Jr. SNR, suggested that star Wray 16-30 is actually a planetary nebula (PN). One could then argue whether the putative [NII] nebula seen around CXO J085201.4−461753 might be an emission knot of the external rim of the PN. However, a physical association between the two is not so evident since neither the ground-based images of Pellizzoni et al. (2002) nor our *WFPC2* image (Fig. 2) show evidence of extended structures connecting Wray 16-30 to the CXO J085201.4−461753 position. We investigated the morphology of Wray 16-30 in our *WFPC2* image. Thanks to the *WFPC2* spatial resolution (0.″1 for the *wide field camera* chips), we could resolve for the first time the structure of Wray 16-30. We found that part of the object structure is indeed consistent with that of a bright, saturated, star. However, we also resolved an extended, clumpy emission structure south of it. It is not clear whether this is associated with Wray 16-30 or is part of the much more extended diffuse emission structures west/north-west of it, observed in the ground-based images and also partially visible in our *WFPC2* image. Thus, from the object morphology we can not confirm the identification of Wray 16-30 as a PN.

4. Summary

Our *HST*/*WFPC2* observations of the CXO J085201.4−461753 field with the *656N* filter, almost exactly centred on the rest

wavelength of the H$_\alpha$ line (λ = 6562.8 Å), did not detect its nebula down to a 3σ flux limit of ~3 × 10^{-15} erg cm^{-2} s^{-1}, which is a factor of 10 fainter than the flux measured by Pellizzoni et al. (2002). This is probably to be ascribed to the narrower and bluer pass band of the *656N* filter with respect to those used in the ground-based observations (see Sect. 3), which would make the nebula undetectable if the peak of the emission is at a longer wavelength. One possibility, compatible with the bow-shock scenario only, is that the H$_\alpha$ line is red-shifted by ~10−60 Å due to the neutron star motion with a radial velocity 450 ≲ V_r ≲ 2700 km s^{-1}. An alternative possibility is that the nebula flux is almost entirely ascribed to [NII] (λ = 6583.6 Å) rather than to H$_\alpha$ emission. Such a picture would then argue against its physical association with CXO J085201.4−461753. The nebula could instead be part of the complex patterns of diffuse emission that are seen in the field of CXO J085201.4−461753, possibly associated with Star Z or (at least in part) with the nearby (25″) star Wray 16-30, whose nature is debated (a peculiar planetary nebula? see Reynoso et al. 2006). High-resolution, spectroscopy observations of the nebula will help to determine its nature and to establish its association with CXO J085201.4−461753.

References

Chatterjee, S., & Cordes, J. M. 2002, ApJ, 575, 407
Chatterjee, S., & Cordes, J. M. 2004, ApJ, 600, L51
De Luca, A. 2008, in 40 Years of Pulsars: Millisecond Pulsars, Magnetars and More, AIP, 983, 311
Gotthelf, E. V., & Halpern, J. P. 2007, ApJ, 664, L35
Gotthelf, E. V., & Halpern, J. P. 2009, ApJ, 695, L35
Halpern, J. P., Gotthelf, E. V., Camilo, F., & Seward, F. D. 2007, ApJ, 665, 1304
Katsuda, S., Tsunemi, H., & Mori, K. 2009, ASpR, 43, 895
Lattanzi, M. G., Capetti, A., & Macchetto, F. D. 1997, A&A, 318, 997
Mignani, R. P., Bagnulo, S., De Luca, A., et al. 2007a, Ap&SS, 308, 203
Mignani, R. P., de Luca, A., Zaggia, S., et al. 2007b, A&A, 473, 883
Parker, Q. A., & Phillips, S. 1998, PASA, 15, 28
Pavlov, G. G., Sanwal, D., Kiziltan, B., & Garmire, G. P. 2001, ApJ, 559, L131
Pavlov, G. G., Sanwal, D., & Teter, M. A. 2004, in Young Neutron Stars and Their Environments, ASP, 239
Pellizzoni, A., Mereghetti, S., & De Luca, A. 2002, A&A, 393, L65
Reynoso, E. M., Dubner, G., Giacani, E., et al. 2006, A&A, 449,243
Skrutskie, M. F., Cutri, R. M., Stiening, et al. 2006, AJ, 131, 1163
Slane, P., Hughes, J. P., Edgar, R. J., et al. 2001, ApJ, 548, 814