The Unusual Supernova Remnant Surrounding the Ultraluminous X-Ray Source IC 342 X-1

T. P. Roberts[1], M. R. Goad[2], M. J. Ward[1], R. S. Warwick[1]

1: University of Leicester. 2: University of Southampton.

WHT/INTEGRAL observations have shown a large-diameter (110 pc) supernova remnant to encircle the position of the Ultraluminous X-ray Source (ULX) IC 342 X-1 (Roberts et al., 2003). We infer a remarkable initial energy input to the SNR, at least 2–3 times greater than the canonical value for an 'ordinary' SNR of 10^{51} erg. In addition, two regions on the inside of the SNR shell are bright in [OIII] λ5007 emission, possibly as the result of photoionization by the ULX. If this is the case, the morphology of the nebulosity implies that the X-ray emission of the ULX is anisotropic. The presence of the ULX, likely to be a black hole X-ray binary, within an unusually energetic SNR suggests that we may be observing the aftermath of a gamma-ray burst.

Background

Ultraluminous X-ray sources are the most luminous point-like extra-nuclear X-ray sources located coincident with nearby galaxies, displaying X-ray luminosities in excess of 10^{39} erg s^{-1}. Whilst some ULXs are known to be associated with recent supernovae, the majority appear to show the characteristics of accreting black holes (Makishima et al., 2000). However, at their observed X-ray luminosities they match, or in many cases greatly exceed, the Eddington limit for accretion onto a stellar-mass (~$10 M_{\odot}$) black hole. ULXs may therefore provide observational evidence for accretion onto a new, 10^2–10^5 $M_{\odot}$ intermediate-mass class of black hole (e.g. Colbert & Mushotzky, 1999). Alternatively, they could constitute the extreme end of the accreting stellar-mass black hole population, with their high apparent luminosities a result of either truly super-Eddington X-ray emission (Begelman, 2002), or an anisotropic radiation pattern (e.g. King et al., 2001).

One method of investigating the nature of ULXs is through detailed multi-wavelength follow-up observations. We have undertaken one such programme using the integral field unit INTEGRAL on the William Herschel Telescope to obtain optical spectro-imaging data, through 189 fibres over a 16.5×12.3 arcsecond^2 field-of-view, of the immediate environment of fourteen nearby ULXs. A crucial element of this programme is that we use sub-arcsecond X-ray astrometric data from NASA's *Chandra* X-ray observatory to locate the ULXs, which dramatically reduces the confusion problems inherent to older, less accurate X-ray positions. This programme has already borne fruit with the detection of the first stellar optical counterpart to an ULX; a young stellar cluster coincident with NGC 5204 X-1 (Roberts et al., 2001; Goad et al., 2002), which suggests that this ULX may be an extremely luminous high-mass X-ray binary. Here, we outline the results of an observation of the environment of a second ULX, IC 342 X-1, which reveals a very different optical counterpart.

The IC 342 X-1 Nebula

The first observation, on February 1st 2001, highlighted a shell-like emission-line nebula in the immediate environment of IC 342 X-1 (Figure 1; this nebula, and its SNR-like line ratios, was also detected by Pakull & Mirioni (2003a), who christen it the "tooth" nebula due to its distinctive morphology). A high [SII]/Hα emission-line ratio of ~1.1 is seen over the extent of the nebula, a classic indicator that the nebula is a supernova remnant (SNR). Our new *Chandra* position clearly locates the ULX in the central regions of the nebula, raising the intriguing possibility that the two may be physically related.

By utilising both the imaging and spectroscopic measurements provided by INTEGRAL, and assuming the SNR is in the pressure-driven snowplough phase (c.f. Cioffi, McKee & Bertschinger, 1988), we were able to place the constraints on the SNR properties shown in Table 1. The SNR appears unusually large, with a projected diameter of at least 110 pc. For comparison, Matonick & Fesen (1997) argue that a typical single SNR with an initial energy E_{51}=1 should not remain visible once it has expanded beyond a diameter of 100 pc. The

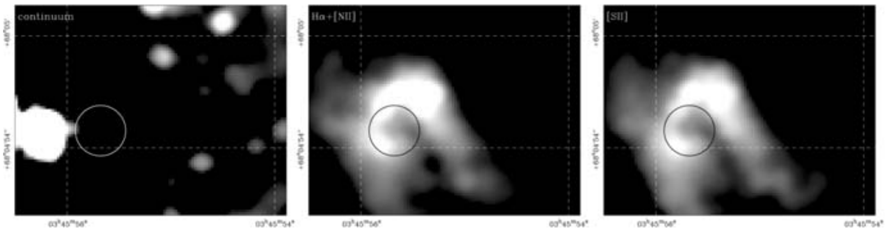

Figure 1. Narrow-band INTEGRAL images of the environment of IC 342 X-1 in the 5300–5500 Å continuum band (left), continuum-subtracted Hα+[N II] (centre), and continuum-subtracted [S II] (right). The circle represents the uncertainty in the ULX position relative to the INTEGRAL data, and each panel is 16.5×12.3 arcsecond^2 in size.

unusual size of this SNR can be attributed to an extraordinary initial energy (assuming a single explosion) of at least $2\times E_{51}$.

Radius (for d = 3.9 Mpc):	$R_{neb}=55$ pc
Shell velocity:	$V_s<180$ km s^{-1}
Age:	$\tau_{neb}>92{,}000$ yr
Initial energy (×10^{51} erg):	$E_{51}>2$
Ambient ISM density:	$n_0>0.12$ cm^{-3}
Electron density:	$N_e<40$ cm^{-3}
Electron temperature:	$T_e<3\times10^4$ K

Table 1. The properties of the SNR.

[O III] Nebulosity

A second remarkable feature of this nebula is demonstrated in Figure 2. The morphology of its [O III] emission is distinctly different to the other emission-lines, appearing to sit in two patches on the inside of the larger nebula. Importantly, the [O III] recombination time for the inner edge of the nebula is far less than its age, implying that a process other than the supernova blast wave must have energised the [O III] emission. One possibility is that the excitation originates in the high-energy emission of the ULX. Unfortunately our observation is not sensitive to the He II λ4686 line, the classic signature of an X-ray Ionised Nebula (XIN; Pakull & Angebault, 1986). However, calculations show that the ULX can produce a photoionizing flux sufficient to excite at least the inner regions of the SNR shell. If the excitation is due to the ULX, then its morphology strongly suggests that the X-ray emission of the ULX is anisotropic, consistent with the beamed X-ray binary models of King et al. (2001).

A Hypernova Remnant?

The location of a probable black hole X-ray binary within an unusually energetic supernova remnant appears to satisfy the conditions for a hypernova remnant, i.e., the aftermath of a gamma-ray burst in which a massive star has collapsed to a black hole triggering a very energetic supernova explosion. If so, this observation provides direct evidence that gamma-ray bursts do occur when black holes are formed.

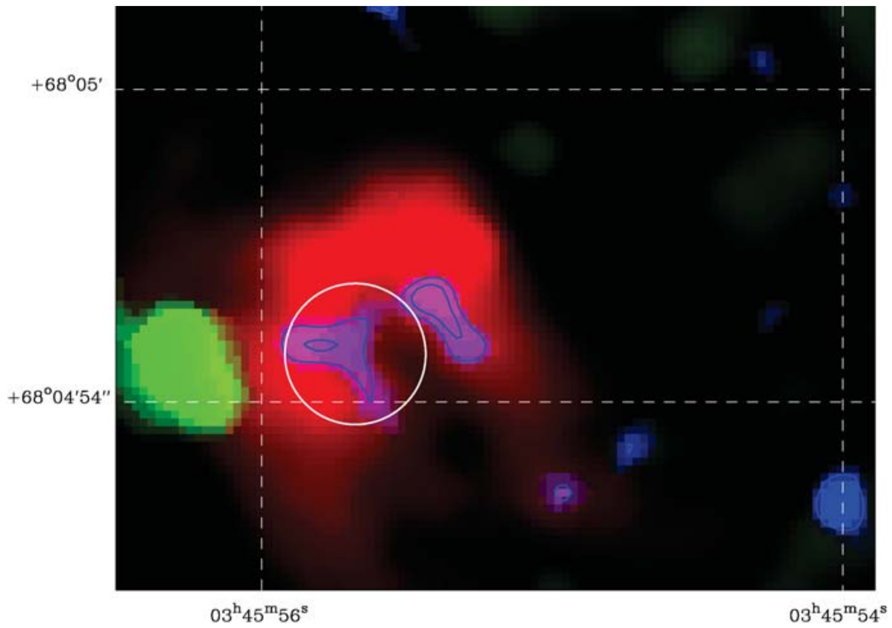

Figure 2. The unusual ionization structure of the IC 342 X-1 SNR. The three colours show 5300–5500 Å continuum emission (green), continuum-subtracted Hα +[N II] emission (red), and continuum-subtracted [O III] (blue, highlighted by contours). The uncertainty in the position of IC 342 X-1 is again shown by the circle.

However, there are other possible origins for the nebula. It might be the result of multiple supernovae occurring in a relatively short space of time (~10^5 yr). This would require a population of young stars within the nebula, which future deep optical continuum observations would detect if present. A second alternative origin could be in jets originating in the ULX. A Galactic analogue of such a system is the W50 nebula, thought to be inflated by the relativistic jets of the microquasar SS 433 (Dubner et al., 1998), which has similar energetic requirements to the IC 342 X-1 nebula. Finally, it is possible that the entire nebula could be X-ray ionised. Pakull & Mirioni (2003b) suggest that XIN should contain an extended warm low-ionisation region with strong characteristic lines such as [S II], which would mimic a SNR spectrum.

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Tim Roberts (tro@star.le.ac.uk)