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The unusual supernova remnant surrounding the ultraluminous X-ray source IC 342 X-1

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ABSTRACT

We report the results of an observation of a large diameter (110 pc) supernova remnant (SNR) found to encircle the position of the ultraluminous X-ray source (ULX) IC 342 X-1. The inferred initial energy input to the SNR is at least $2-3$ times greater than the canonical energy for an "ordinary" supernova remnant. Two regions on the inside of the shell are bright in [OIII] λ5007 emission, possibly as the result of X-ray photoionization by the ULX. If this is the case, then the morphology of this nebulosity implies that the X-ray emission from the ULX is anisotropic. The presence of the ULX, most probably a black hole X-ray binary, within an unusually energetic supernova remnant suggests that we may be observing the aftermath of a gamma-ray burst, though other origins for the energetic nebula are discussed.

Key words: Galaxies: individual: IC 342 – ISM: supernova remnants – X-rays: galaxies – X-rays: binaries – Black hole physics

1 INTRODUCTION

Ultraluminous X-ray Sources (ULX) are the most luminous point-like extra-nuclear X-ray sources found in nearby galaxies, with observed X-ray luminosities in excess of 10^{39} erg s^{-1}. Whilst some recent supernovae can appear as ULX (e.g. SN 1986J, Bregman & Pildis 1992; SN 1979C, Immler et al. 1998), the majority of ULX are believed to be accreting systems, and indeed *ASCA* studies have shown that many ULX display the characteristics of accreting black holes (e.g. Makishima et al. 2000; Mizuno, Kubota & Makishima 2001). Several competing models currently provide plausible physical descriptions of these systems, and explain how they apparently reach, and in many cases greatly exceed, the Eddington luminosity for a 10 $M_\odot$ black hole. These include accretion onto a new class of 10^2-10^5 $M_\odot$ intermediate-mass black holes (e.g. Colbert & Mushotzky 1999; Miller & Hamilton 2002), possible examples of which were recently inferred to be present in the globular clusters G1 and M15 (Gebhardt, Rich & Ho 2002 and references therein); truly super-Eddington X-ray emission from "ordinary" X-ray binaries (Begelman 2002); and anisotropic emission from X-ray binaries (King et al. 2001), perhaps relativistically beamed if we are looking down the jets of microquasars (e.g. Körding, Falcke & Markoff 2002). Current observations do not rule out any of these models, but they do suggest a heterogeneous population, with ULX associated with both the nascent stellar populations found in star forming regions, and the old stellar population found in elliptical galaxies (c.f. Roberts et al. 2002; Sarazin, Irwin & Bregman 2001 - see King 2002 for further discussion).

IC 342 X-1 is one of the nearest and most comprehensively-studied ULX[1]. It was originally detected in an *Einstein* IPC observation of IC 342 with a 0.2 – 4 keV X-ray luminosity of 3.0×10^{39} erg s^{-1} (Fabbiano & Trinchieri 1987). A subsequent *ROSAT* observation also detected the source in an ultraluminous state (Bregman, Cox & Tomisaka 1993; Roberts & Warwick 2000). An *ASCA* observation obtained in September 1993 showed IC 342 X-1 to be in a very luminous state ($L_X > 1.5\times10^{40}$ erg s^{-1}, 0.5 - 10 keV), in which it displayed large amplitude, short timescale ($\sim$ 1000 s) variability (Okada et al. 1997), and possessed an X-ray spectral form characteristic of black hole accretion disc spectra in the high/soft state (Makishima et al. 2000). Conversely, a deep follow-up *ASCA* observation in February 2000 showed the ULX to have dimmed to 6×10^{39} erg s^{-1} (0.5 - 10 keV) and undergone a spectral transition into a low/hard state, similar behaviour to that observed in many

[1] The precise distance to IC 342 remains quite uncertain, due to high foreground obscuration. Previous X-ray analyses assume distances of $\sim$ 4 Mpc, consistent with the distance of 3.9 Mpc quoted by Tully (1988), which is itself supported by a later analysis placing the IC 342/Maffei group at a distance 3.6 ± 0.5 Mpc (Krismer, Tully & Gioia 1995). However, other studies have placed the galaxy much closer. For example, photometry of supergiant stars in IC 342 imply a distance of only 2.1 Mpc (Karachentsev & Tikhonov 1993). In this paper we assume a distance of 3.9 Mpc.

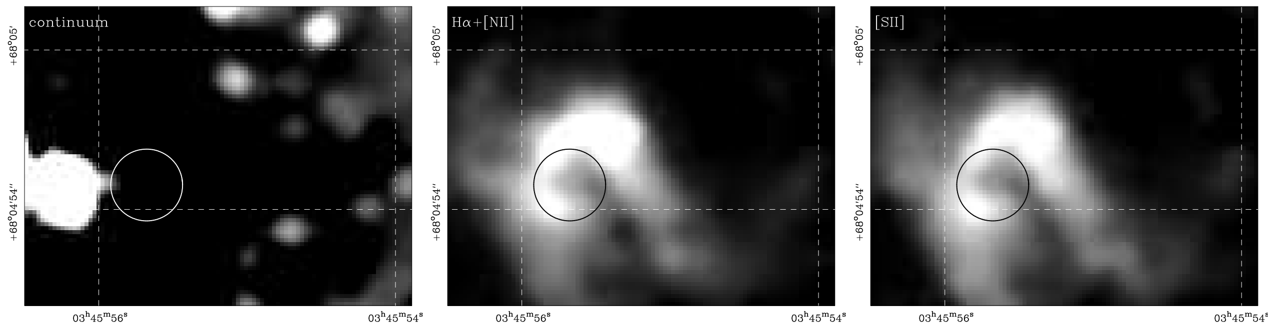

Figure 1. INTEGRAL images of the IC 342 X-1 field. The greyscale is in units of observed surface brightness, and ranges between 0 (black) and 2.5×10^{-17} erg cm^{-2} s^{-1} Å^{-1} arcsec^{-2} (white) for the 5300 - 5500 Å continuum and [SII] images, and 0 to 5×10^{-17} erg cm^{-2} s^{-1} Å^{-1} arcsec^{-2} for the Hα+[NII] image. The circle represents the uncertainty in the position of IC 342 X-1.

Galactic and Magellanic black hole binary systems (Kubota et al. 2001; Mizuno, Kubota & Makishima 2001). An alternate view is that IC 342 X-1 could have been in the very high/anomalous state during this observation, which is also seen in many Galactic black hole binaries (Kubota, Done & Makishima 2002). IC 342 X-1 is therefore one of the best candidates for a *bona fide* black hole X-ray binary ULX.

Multi-wavelength studies are crucial to understanding the nature of ULX, through the identification of potential counterparts and the investigation of their immediate environment. Several ULX have been shown to be associated with structures apparent in other bands. For example, a star forming complex on the edge of NGC 4559 is host to the luminous ULX NGC 4559 X-7 (Vogler, Pietsch & Bertoldi 1997), and M81 X-9 is located within a shock-heated giant nebula, possibly a supershell formed by one very energetic supernova, or multiple supernovae (Miller 1995; Wang 2002). However, the precise identification of possible counterparts, or the exact location of ULX within larger structures, has only been possible in the new era of sub-arcsecond X-ray astrometry provided by *Chandra*. This has led to the first identification of possible stellar counterparts to ULX, in particular with the identification of three young ($<$ 10 Myr old) compact stellar clusters associated with NGC 5204 X-1 (Roberts et al. 2001; Goad et al. 2002), the coincidence of a ULX in NGC 4565 with a faint globular cluster (Wu et al. 2002), and the identification of an O-star counterpart to M81 X-6 ($\equiv$ NGC 3031 X-11; Liu, Bregman & Seitzer 2002).

The presence of optical emission-line nebulae at, or close to, the positions of several ULX has recently been reported in a conference proceedings paper by Pakull & Mirioni (2003a; hereafter PM03). This includes the identification of a nebula coincident with the *ROSAT* HRI position of IC 342 X-1, that they christen the "tooth" nebula on the basis of its morphology. Their optical spectroscopy shows the nebula to display "extreme SNR-like emission line ratios: [SII]/Hα = 1.2 and [OI]λ6300/Hα = 0.4". In this letter we report new X-ray and optical observations that locate the suspected black hole X-ray binary ULX IC 342 X-1 at the heart of this unusual nebula.

2 OBSERVATIONS & RESULTS

The optical data were obtained on the night of 2001 February 1 using the INTEGRAL field spectrograph on the William Herschel Telescope (Arribas et al. 1998). A summary of the instrumental set-up is given in Roberts et al. (2001) and the data analysis will be detailed in Roberts et al. (in preparation). In short, the INTEGRAL data provided us with spectroscopy in 189 fibres and, through the relative fibre positions, simultaneous imaging within a $16.5'' \times 12.3''$ field-of-view. The IC 342 X-1 follow-up observation was targetted on $03^h45^m55.2^s, +68°04'56''$, which is the *ROSAT* HRI position after applying an astrometric correction, calculated from the field X-ray source positions and their possible optical counterparts in the USNO catalogue[2].

A new 9.9 ks *Chandra* X-ray observation of IC 342 X-1 was obtained on 2002 April 29. The ULX was positioned on the ACIS-S3 chip, which was operated in the 1/8 sub-array mode to mitigate the anticipated effects of pile-up. Initial analysis of the cleaned data (reduced using CIAO v2.2) detected IC 342 X-1 at a position $03^h45^m55.68^s, +68°04'54.9''$. An investigation of the radial profile of the source indicates that it is point-like at the $0.5''$ resolution of *Chandra*. Unfortunately, only one other source was detected on the S3 chip (at $03^h46^m32.90^s, +68°03'56.0''$), and this faint source does not have an optical counterpart, hence a direct check of the astrometry was not possible. We therefore adopt the *Chandra* position for IC 342 X-1, and assume a conservative accuracy of $\pm 1''$ for the X-ray position (c.f. Goad et al. 2002). We defer further analysis of the X-ray emission of IC 342 X-1 to a future paper; for the remainder of this letter we concentrate upon the interpretation of the INTEGRAL data in the context of the precise determination of the X-ray position.

Several optical continuum sources and an emission-line nebula are evident in the INTEGRAL field-of-view. We show a continuum image, plus continuum-subtracted emission-line images in Hα+[NII] and [SII] in Figure 1. The nebula is characterised by a shell-like morphology, and has a high [SII]/Hα emission-line flux ratio of ~ 1.1 throughout its extent, hence we interpret it as a supernova remnant (SNR), consistent with the comments of PM03 (c.f. Matonick & Fesen 1997 and references therein). This remnant was not reported in a previous search for such objects in IC 342 by D'Odorico, Dopita & Benvenuti (1980). In Figure 1 we illustrate the uncertainty in the position of IC 342 X-1 using a circle of radius $1.5''$; this is a conservative estimate

[2] All co-ordinates in this letter are quoted in epoch J2000.

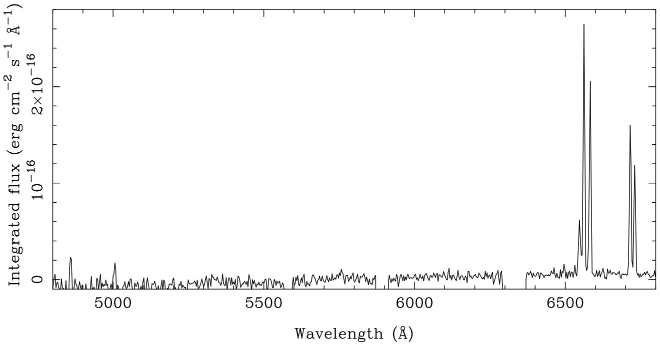

Figure 2. The total flux-calibrated INTEGRAL spectrum of the SNR. This spectrum is **not** corrected for Galactic extinction. Small portions of the spectrum are excluded around the Na-D, HeI and [OI] sky lines to remove residual contamination.

Table 1. Integrated emission-line fluxes, corrected for reddening.

Species	λ (Å)	Flux ($\times10^{-15}$ erg cm^{-2} s^{-1})
Hβ	4861	1.7 ± 0.5
[OIII]	4959	0.4 ± 0.2
	5007	1.2 ± 0.2
[NII]	5755	0.4 ± 0.2
	6548	1.6 ± 0.2
	6583	4.6 ± 0.2
Hα	6563	5.8 ± 0.1
[SII]	6717	3.7 ± 0.1
	6731	2.6 ± 0.1

based on the intrinsic *Chandra* astrometry error discussed above, with an additional contribution of $\pm1''$ corresponding to the uncertainty in the INTEGRAL astrometry. The ULX is clearly not associated with the bright continuum source at the eastern edge of the image, but is in fact positionally coincident with the central regions of the supernova remnant. This raises the intriguing possibility that the ULX may be physically related to the supernova remnant.

In Figure 2 we show the INTEGRAL spectrum of the supernova remnant, integrated over the whole spatial extent of the nebulosity (58 out of 189 fibres) within the field-of-view. It is immediately obvious that the spectrum suffers from a high degree of reddening; in fact the line-of-sight to IC 342 has an extinction of $E(B-V) = 0.6$, a consequence of its low Galactic latitude ($b \sim 10°$). This severely limits the sensitivity at the blue end of our spectrum. The residual contamination from sky lines is removed from Figure 2. Large positive residuals were found in the data at the positions of the [OI] $\lambda6300$ and $\lambda6363$ lines, but the relatively low spectral resolution (~ 6 Å) of the data and the added complication of excluding spatially-variable sky lines from fibre data implies that any physical measurements from these residuals would be very uncertain. We therefore remove them from our analysis. The reddening-corrected integrated fluxes of the diagnostically important emission lines are given in Table 1.

The inferred characteristics of the supernova remnant are listed in Table 2. Both the radius of the bright northern

Table 2. The properties of the supernova remnant.

Radius	R_{neb}	55 pc
Shell velocity	V_s	< 180 km s^{-1}
Age	τ_{neb}	> 92000 yr
Initial energy ($\times10^{51}$ erg)	E_{51}	> 2
Ambient ISM density	n_0	> 0.12 cm^{-3}
Electron density ^{a}	N_e	< 40 cm^{-3}
Electron temperature ^{b}	T_e	$< 3 \times 10^4$ K

Notes: ^{a} from [SII] $\lambda6731/\lambda6717 = 1.4 \pm 0.1$.
^{b} From [NII] $(\lambda6548 + \lambda6583)/\lambda5755 < 15.5$.

part of the supernova shell[3], R_{neb}, and the velocity of the material in the shell, V_s, are directly derived from our INTEGRAL observations (V_s is a 3σ upper limit on the velocity of the Hα emitting region, determined from a comparison of the Hα line FWHM with that of the sky lines). However, the low [OIII]/Hβ ratio of ~ 1 suggests that the actual velocity may indeed be lower, probably < 100 km s^{-1} (Dopita et al. 1984). To derive the age of the SNR and its initial explosion energy we follow the method shown in PM03, who use the pressure-driven snowplough phase equations of Cioffi, McKee & Bertschinger (1988) to describe the current expansion of an old, very large SNR. As with PM03, this relies on an estimate of the ambient ISM density around the supernova progenitor as determined from the total radiative Hβ flux of the nebula (in our case a luminosity of 3×10^{36} erg s^{-1}), using the equations of Dopita & Sutherland (1995). The limits derived from these equations are shown in Table 2. We also show limits on the electron density and temperature in the shocked region calculated from the [SII] $\lambda6731/\lambda6717$ (density) and [NII] $(\lambda6548 + \lambda6583)/\lambda5755$ (temperature) ratios, as per Osterbrock (1989). Table 2 indicates that the supernova remnant is unusually large, having a projected diameter of at least 110 pc. For comparison, Matonick & Fesen (1997) argue that a typical single supernova remnant will not remain visible once it has expanded beyond a diameter of 100 pc, for a canonical energy input of 10^{51} erg. One way in which a single supernova remnant could reach the observed size is if the initial explosion energy exceeds 10^{51} erg, which appears to be the case for this nebula since we calculate a lower limit on the initial energy input of $\sim 2 \times 10^{51}$ erg. We discuss this possibility further in Section 4.

3 EVIDENCE FOR AN X-RAY IONIZED NEBULA INSIDE THE SUPERNOVA REMNANT?

A remarkable spatial feature of this supernova remnant is revealed upon closer inspection of the continuum-subtracted emission-line images. Whilst the Hα, [NII] and [SII] images all trace the same shell structure, an image created from the faint [OIII] line shows a distinctly different morphology,

[3] We conservatively use the brightest (and hence the densest) part of the shell, since it provides the best emission line constraints. We note that the lower surface brightness extension of the nebula, particularly to the south of the shell structure, may be due to density gradients in the ambient ISM allowing faster expansion in this direction.

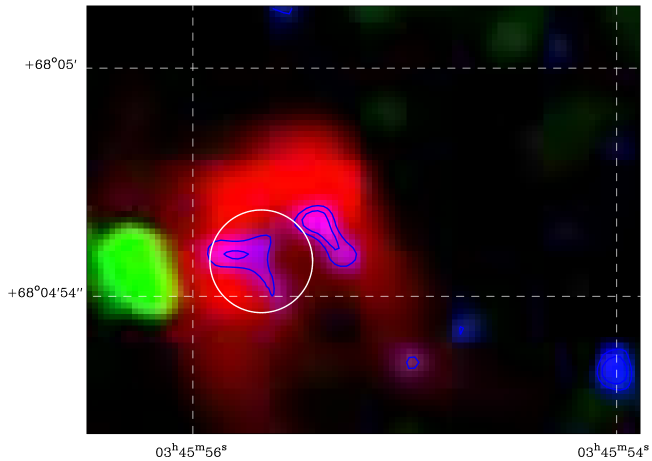

Figure 3. The unusual ionization structure of the IC 342 X-1 SNR. The three colours represent 5300 – 5500 Å continuum emission (green), continuum-subtracted Hα+[NII] emission (red), and continuum-subtracted [O III] emission (blue). The [O III] emission is highlighted by blue contours showing the 3 and 3.5σ confidence levels above the background noise. The uncertainty in the position of IC 342 X-1 is shown by the circle.

illustrated in Figure 3. The faint [OIII] emission appears concentrated on the inside of the supernova remnant, and traces the inside of the shell, both within the positional error circle of the ULX and to the north-west of this position. However, this [OIII] nebula does not appear to follow the entire structure of the inside of the shell, with no emission detected along the inside of the northern part of the shell. The presence of enhanced [OIII] emission on the inner-edge of the shell is confirmed by extracting spectra from individual fibres in both the [OIII] region and to the north of this position, which confirm a higher average [OIII]/Hβ ratio in the former (1.0 vs 0.5 in the respective reddening-corrected ratios)[4]. It therefore appears that there is a concentration of highly-excited oxygen located on the inside of the much larger supernova remnant. Furthermore, given that the shock front passed through this region of the nebula at least half the SNR lifetime ago (assuming a physically unrealistic constant expansion velocity), and that the [OIII] recombination time is much shorter than the age of the nebula ($\tau_{rec} > 150$ years for $N_e < 40$ cm^{-3})[5], it is possible that a process other than the supernova blast wave may be energising the [OIII] emission. If this is so, what could be producing it?

One possibility is that this high-excitation emission is produced by the ULX. In particular, it could potentially be photoionized by the $> 10^{39}$ erg s^{-1} X-ray flux to produce an "X-ray ionized nebula" (XIN). Relatively few examples of this phenomenon are currently known. Two examples are the XIN associated with the high-mass X-ray binary LMC X-1 (Pakull & Angebault 1986) and the supersoft X-ray source CAL 83 (Remillard, Rappaport & Macri 1995), both in the Large Magellanic Cloud. Also, an XIN was recently discovered associated with the ULX in Holmberg II (PM03). On first appearances, our [OIII] nebula bears remarkable similarities to the [OIII] nebula surrounding CAL 83, which is also located on the inside of an incomplete Hα shell. However, our observed [OIII]/Hβ flux ratio is much smaller than that observed around CAL 83, which has a ratio [OIII]/H$\beta = 15 \pm 2$, indicative of a very high excitation state (though see footnote [4]). This difference may perhaps be a result of the very different X-ray spectra of CAL 83 and IC 342 X-1. CAL 83 is a classic supersoft X-ray source, with a very soft X-ray spectrum that produces a large flux of UV and very soft X-ray photons, that are ideally suited to photoionizing its immediate environment (Remillard et al. 1995), whereas IC 342 X-1 displays the much harder X-ray spectrum characteristic of a black hole X-ray binary. Also, in the case of CAL 83 the surrounding medium is very different, with the XIN being produced in the ISM in the vicinity of the X-ray source, as opposed to in the inner parts of a supernova shell.

It is therefore informative to consider other possible signatures of X-ray ionization. The XIN around LMC X-1 and the Holmberg II ULX were primarily identified by the presence of relatively faint HeII λ4686 lines in their optical spectra. Unfortunately, the high extinction towards IC 342 means that our INTEGRAL spectrum is dominated by noise at short wavelengths, so we are not sensitive to faint line emission below Hβ. The observational evidence for the [OIII] nebula being X-ray ionized is therefore inconclusive, at least on the basis of the INTEGRAL data alone.

Another method of addressing whether the [OIII] nebulosity is an XIN is simply to consider whether we would expect the ULX to create a photoionized zone consistent with the size of the nebula. We estimate the number of available photoionizing X-ray photons using the best-fit to the *ASCA* data for IC 342 X-1 in its high state, namely a multi-colour disc blackbody model (Kubota et al. 2001). By extrapolation this gives a hydrogen ionizing flux of $Q = 2.3 \times 10^{48}$ photon s^{-1} in the 13.6 – 300 eV range, originating in the ULX and not escaping the nebula (calculated in XSPEC, assuming a hydrogen density of of 0.12 atom cm^{-3} in the nebula, and that the nebula becomes essentially transparent to X-ray photons at 300 eV). This ionizing flux will create a Stromgren sphere in Hα up to 170 pc in radius for a low density (0.12 atom cm^{-3}, $\equiv n_0$), homogeneous medium. However, for IC 342 X-1 we should consider the case in which a higher density medium (the SNR shell) surrounds a low density cavity. Assuming that IC 342 X-1 is located in the centre of the cavity, placing it ~ 20 pc from the nebula, and that the cavity is essentially empty whilst the edge of the nebula has a density of e.g. 3 atom cm^{-3}, then a similar calculation shows that the ULX will photoionize the surface of the nebula, penetrating up to 7 pc into the denser gas. Of course, in reality the density of 3 atom cm^{-3} is higher than the predicted post-shock density[6], and the edge of the nebula may not be tightly de-

[4] These [OIII]/Hβ ratios are not indicative of high excitation regions. However, given the spatial resolution of $\sim$ 20 pc per fibre, this of course does not preclude smaller parsec-scale high-excitation regions within the nebula.

[5] We note that N_e may be a factor 100 smaller, and thus τ_{rec} 100 times larger, if the temperature exceeds 15000 K. This is still much less than the age of the remnant.

[6] The density in the post-shock regions may be estimated as $N_S = 4n_0$ (Osterbrock 1989), implying $N_S \sim 0.5$ cm^{-3} in this case.

fined, which should act to increase the physical size of the ionized zone. Finally, we note that following the well-known relation L(Hα) $= 1.3 \times 10^{-12} Q$ erg s^{-1} implies that a maximum Hα luminosity of $\sim 3 \times 10^{36}$ erg s^{-1} originates in the XIN, though this probably has a large error margin due to the uncertainty inherent in extrapolating the ULX spectrum below 300 eV, and in using a relation that is strictly valid for stellar EUV sources. This is below the observed Hα luminosity of 1×10^{37} erg s^{-1}, supporting the scenario in which an XIN sits on the inner edge of a larger SNR which has produced the bulk of the Hα excitation.

An alternative interpretation is that the large uncertainty in the errors could be consistent with the entire Hα luminosity originating in X-ray ionization. It would imply the whole nebula is X-ray ionized, and not a supernova remnant. In this paper we interpret the object as a supernova remnant on the basis of a high [SII]/Hα ratio implying a shock excited nebula. We note that Pakull & Mirioni (2003b) suggest that X-ray ionized nebulae may contain an extended warm ($T_e = 10^4$K) low-ionization region which would excite strong lines of near-neutral species such as [OI] and [SII], thereby mimicking the emission-line ratios of a shock-excited nebula. Further work to confirm this model would be of great importance.

The above discussion assumes that the X-ray emission of the ULX is isotropic. In this case the morphology of the photoionized nebula should reflect the distribution of the surrounding material. However, the discrepancy between the bi-modal [OIII] distribution and the half-shell distribution in the supernova remnant suggests that the nebula is not seeing an isotropic photoionizing source. This implies that the X-ray emission of the ULX is anisotropic, as has been suggested to explain the apparent super-Eddington luminosities of ULX (King et al. 2001).

A potential alternative source of ionization for the [OIII] nebulosity is one or more young stars. The presence of the supernova remnant and the ULX suggest that young stars exist in this region of IC 342 (a link between many ULX and young stellar populations appears increasingly likely; see e.g. Roberts et al. 2002). The total [OIII] luminosity in the central regions of the supernova remnant ($L_{[OIII],\lambda5007} \sim 9 \times 10^{35}$ erg s^{-1}) is consistent with the observed luminosities of nearby HII regions in our Galaxy. Indeed, the Orion nebula has a luminosity of $L_{[OIII],\lambda5007} \sim 2 \times 10^{37}$ erg s^{-1} (Pogge, Owen & Atwood 1992), with the ionisation originating in a single O7V star, θ^1 Ori C, possessing an ionising flux of $Q = 10^{49-50}$ photon s^{-1} (Ferland 2001). Curiously, if ULX are black-hole X-ray binaries containing a young secondary star (c.f. King et al. 2001), then it is plausible that the [OIII] excitation might originate in the secondary star in the ULX system, though we note that the morphology of the [OIII] nebula might argue against a single stellar excitation source. The presence of one or more O-stars is not ruled out by our continuum images, which only probe down to $M_V \sim -9$ in IC 342 due, in part, to the heavy line-of-sight reddening. Deeper optical continuum observations of the environment of IC 342 X-1 will provide the crucial constraints on the presence of young stars.

4 A BLACK HOLE FORMED IN A HYPERNOVA EXPLOSION?

As alluded to in Section 2, the idea that the ULX may be causally related to an unusually energetic supernova remnant is an intriguing one. The case for a physical link (as opposed to a line-of-sight coincidence) between the two is made stronger if we can attribute the [OIII] nebular emission within the SNR to the ULX at its centre. As discussed in the introduction, this particular ULX is one of the best candidates for a *bona fide* black hole X-ray binary, hence we have a scenario in which a black hole system sits inside an energetic supernova remnant. This appears to satisfy the conditions for the aftermath of a gamma-ray burst, in which the collapse of a massive star to a black hole triggers a supernova explosion with an unusually high input energy, i.e. a "hypernova" (e.g. Paczyński 1998; Fryer & Woosley 1998). If so, this system may be direct evidence that gamma-ray bursts do form black holes.

This hypothesis requires further examination. In particular, it is important to establish that this supernova remnant really is a hypernova remnant (assuming even that it is a supernova remnant - see previous section). Following the methods adopted by PM03 we derived an initial input energy of $E_{51} > 2$ (see Section 2), assuming a velocity of 180 km s^{-1}. If the actual velocity is < 100 km s^{-1}, as suggested by the [OIII]/Hβ ratio, then E_{51} increases, though only to > 3. If we accept the same convention as Chen et al. (2002) and define a hypernova remnant as a supernova remnant possessing an input energy in excess of 10^{52} erg, the supernova remnant clearly does not meet this strict criterion (though it could be met if the actual nebular density is closer to the value of < 40 cm^{-3} inferred from the [SII] ratio than the assumed density in Table 2). However this remnant, if it originates in a single supernova explosion, still appears to be more energetic than an "ordinary" supernova by a factor at least 2 – 3.

Other scenarios for the creation of this energetic supernova remnant should also be considered. In particular, this remnant is morphologically very similar to the shell surrounding the ULX M81 X-9, albeit smaller in size (c.f. Miller 1995), which is suggested to be the result of multiple supernovae. A "superbubble" of this size might be distinguishable from a single energetic supernova remnant by their contrasting velocities ($\ll 100$ km s^{-1} for a superbubble; c.f. Chen et al. 2002). In this case a minimum of only 2 – 3 "ordinary" supernova events occuring inside the bubble within a relatively short time ($\sim 10^5$ years) could inject sufficient energy to expand the bubble to its current size. This relatively high incidence of supernovae would require a population of young stars to reside inside the bubble, which again should be unveiled by deeper optical observations.

A further source of power that could expand the nebula is a jet and/or stellar wind originating from the ULX system. If we follow PM03, who note that the total energy requirements and lifetime of a system inflated by such a process would be quantitatively similar to that from a SNR, then the energetics of the nebula imply that an average of $\sim 10^{39}$ erg s^{-1} would need to be injected over its lifetime. This would require a mechanical energy of the wind similar to the radiation energy of the ULX. This is consistent with the average energy input of 3×10^{39} erg s^{-1} estimated to be required to inflate the W50 system in our own galaxy, probably originating in the relativistic jets of the microquasar SS 433 (Dubner et al. 1998). PM03 also note that mildly relativistic jets, similar to those of SS 433, could be responsible for inflating many of the nebulae in their sample. This scenario could therefore constitute a very credible alternative to an energetic supernova event.

Finally, is the presence of the ULX consistent with a black hole possibly formed only $\sim 10^5$ years ago? If the black hole has formed in isolation it could be accreting directly from the ISM in its vicinity via Bondi-Hoyle accretion. However, this accretion mode is unlikely to produce the required X-ray luminosity, even if any "kick" it received on formation was sufficient to move the black hole into the denser nebular regions (c.f. Miller & Hamilton 2002). It is therefore much more likely that the black hole is in an accreting binary system. Such a system might expect to receive a kick on its formation in a supernova explosion. If we assume a similar kick to that experienced by the Galactic black hole system GRO 1655-40 of ~ 100 km s^{-1} (Mirabel et al. 2002), then it will have travelled no more than ~ 10 pc. It should clearly still be located close to the centre of the supernova remnant, which is consistent with Figures 1 & 3. However, to produce a luminous accreting binary system $\sim 10^5$ years after the black hole was formed requires that both the primary (black hole progenitor) and the secondary (donor) stars have very similar, large initial masses (c.f. Verbunt & Van den Heuvel 1995). The formation of such a binary system appears unlikely to occur in isolation, and may imply the presence of a young, dense cluster similar to those seen close to ULX in NGC 5204 (Goad et al. 2002) and the Antennae (Zezas et al. 2002), albeit one not bright enough to be detected in our observation of this field.

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