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BUBBLE NEBULAE AROUND ULTRALUMINOUS X-RAY SOURCES

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RESUMEN

La naturaleza de las fuentes de rayos-X ultraluminosas (ULX) externas a los núcleos de galaxias cercanas continúa ser un misterio puesto que la cantidad de radiación a altas energías, si fuera isotrópica, rebasaría el límite de Eddington incluso de los hoyos negros estelares más masivos. Muchas de las fuentes de rayos-X ultraluminosas están rodeadas por nebulosas de emisión, las cuales muestran indicaciones de ionización tanto por choques como por rayos-X. Se pueden utilizar las nebulosas relativamente compactas ionizadas por rayos-X para inferir de manera independiente las luminosidades y por lo tanto excluir posibles efectos de enfoque hacia la visual. Las nebulosas más grandes tipo burbuja alcanzan diámetros de algunas centenas de parsecs y proporcionan información importante acerca de la formación y/o historia de pérdida de masa de las ULX. Señalamos la relación cercana que hay con los microcuasares y el sistema SS 433, anteriormente único, con su nebulosa de radio W 50.

ABSTRACT

The nature of extra-nuclear ultraluminous X-ray sources (ULX) in nearby galaxies continues to be an enigma, since their adopted isotropic high-energy output would surpass the Eddington limit of even the most massive stellar black holes. Many ultraluminous X-ray sources are surrounded by emission nebulae that show indications of both shock ionization and X-ray ionization. Relatively compact X-ray ionized nebulae can be used to independently infer the luminosities, and thus to exclude possible beaming effects into our line of sight. Larger bubble-like nebulae reach several hundred parsec diameters and provide important information on the formation and/or mass loss history of ULX. We point out the close relationship to microquasars and the previously unique SS 433 system with its radio nebula W 50.

Key Words: **H II REGIONS — ISM: JETS AND OUTFLOWS — STARS: MASS LOSS — X-RAYS: BINARIES**

1. INTRODUCTION

The study of ultraluminous X-ray sources (ULX) has for some time been among the "hot topics" in X-ray astronomy. Their interest for observers and theoreticians alike comes from the fact that their apparent luminosities appear to surpass the Eddington limit of a stellar black hole ($< 10\,M_\odot$), sometimes by large factors (e.g., Fabbiano 1989). One individual ULX might well emit more high energy radiation than the the total output of the Local Group of Galaxies! Among the possible explanations, X-ray beaming into our line of sight and the well-advertized "intermediate black holes" (Colbert & Mushotzky 1999) bridging the gap between black holes of the stellar and supermassive AGN variety have been most popular (cf. Colbert & Ptak 2002).

The discovery of large (up to several hundred parsec) ionized nebulae (hereafter ULXN) around a significant fraction of ULX (Pakull & Mirioni 2002; Mirioni 2002) has opened a new avenue for our understanding of these sources. In fact, we are reminded of the important rôle of nebular observations of H II regions and planetary nebulae (PN) for our understanding of stellar atmospheres and stellar evolution. ULXN have begun to keep their promise. We mention the relatively compact (diameter 34 pc) high-ionization nebula around Holmberg II X-1, which appears to be an upscaled version (by a factor 50) of the only previously known X-ray ionized nebula LMC X-1 (Pakull & Angebault 1986). Comparing the He II $\lambda\,4686$ Å recombination line luminosity of the ULXN ($I_{4686}/I_\beta = 0.17$) with Cloudy model nebulae, we derived an EUV/X-ray luminosity in agreement with that expected from an isotropic source (Pakull & Mirioni 2003; Mirioni 2002).

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2. ULXN BUBBLES

In this conference paper we have chosen to concentrate on the very energetic and extended nebulae, some of which have been confused with extremely luminous supernova remnants. They constitute a new class of objects that we are only beginning to understand.

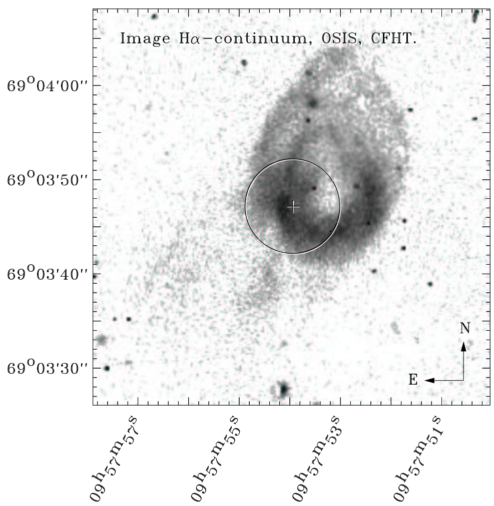

Fig. 1. Continuum subtracted Hα image of the nebula LH9/10 around the ULX M 81 X-9 (Holmberg IX X-1) shown by the error circle.

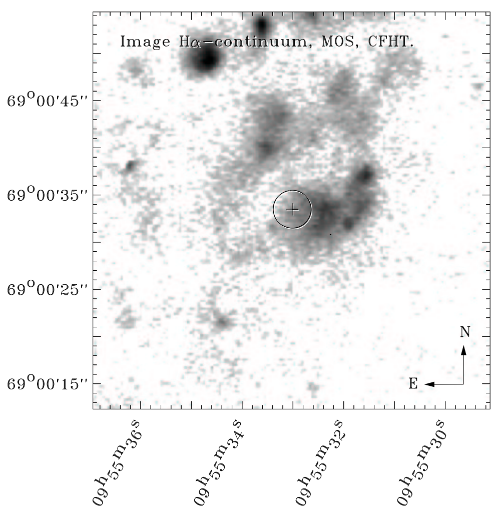

Fig. 2. Hα image of the nebular complex MF 22 (southern lobe) and MF 23 (northern lobe around the ULX M 81 X-6 marked by the *Chandra* error circle.

2.1. *Two Bubbles In and Around M 81*

A striking example is furnished by the 250×360 pc diameter barrel shaped nebula LH9/10 (Figure 1) coincident with the 10^{40} erg s^{-1} *Einstein* source M 81 X-9 (but which is really situated in its low-mass dwarf companion Holmberg IX). Miller (1995) favored an explanation in terms of hot gas in a superbubble; however, the discovery of marked X-ray variability (La Parola et al. 2001) now excludes this possibility and clearly points to a compact nature of the ULX.

In a similar way, the ULX M 81 X-6 has recently been found to be variable, and was identified with a faint stellar object (Swartz et al. 2002), whereas

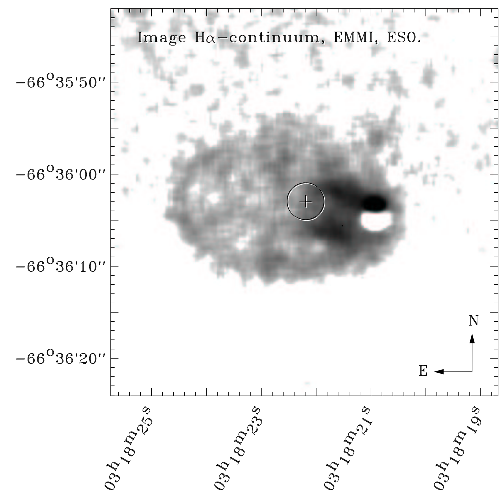

Fig. 3. The huge, 600 pc diameter Hα bubble around the ULX NGC 1313 X-2. The nebula expands with 80 km s^{-1} and is largely shock excited.

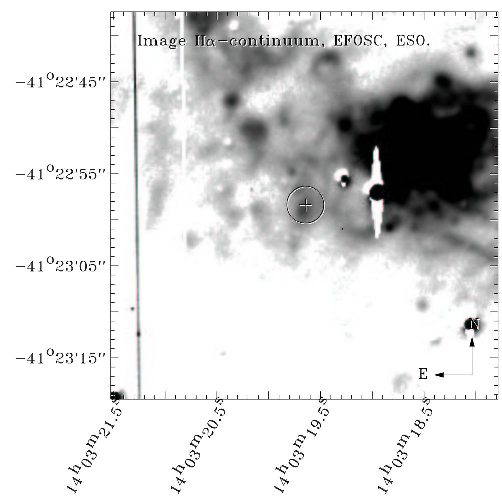

Fig. 4. The ultraluminous X-ray source in NGC 5408 (shown by *Chandra* error circle) lies close to a giant H II region complex and is centered on a small nebula which is a non-thermal radio source.

the association with a nebula showing an enhanced [S II]/Hα ratio (MF 22; Matonick & Fesen 1997) had previously suggested a supernova remnant (SNR) nature. The Hα image in Figure 2, moreover, shows that SNR candidates MF 22 and MF 23 are indeed part of a larger 260×350 pc structure, which again shows a barrel-shaped morphology.

2.2. *NGC 1313 X-2*

The southern hemisphere counterpart of the ULXN around M 81 is the 570×400 pc bubble nebula around the luminous X-ray variable source X-2 (Figure 3 in the spiral galaxy NGC 1313. It is located 9 kpc from the nucleus, far away from regions of recent star formation. Here we also have kinematic information from medium-resolution spectroscopy, pointing to an expansion velocity of some $80\,\mathrm{km\,s^{-1}}$. Using the relations beween radius, expansion velocity, interstellar density and energy of evolved SNRs (see Pakull & Mirioni 2003) we derive a kinetic energy input into the bubble of some 10^{52} to $10^{53}\,\mathrm{erg\,s^{-1}}$. This is much higher than the explosion energy for a typical supernova, and has led to the suggestion that the bubble was powered by a "hypernova" during which the black hole in the ULX was formed. Alternatively, the bubble could well be inflated by ongoing stellar wind or jet-like activity from the central ULX. In order to fulfill the energy requirements during the evolution of the bubble (some 10^6 years) such a wind has to be mildly relativistic. In fact, such a scenario is inspired by the famous jet source SS 433 and its "beam-bag" interaction with radio nebula W 50 (cf. Begelman et al. 1980).

2.3. *More Nebulae Around ULX*

The discovery of several more ULXN, such as the objects NGC 1313 X-1, IC 342 X-1 and NGC 5204 X-1, have been reported by Pakull & Mirioni (2003) and by Mirioni (2002), and the list of likely members of this class is growing.

For example, Snowden et al. (2001) showed that the X-ray luminous "hypernova remnant" MF 83 is variable and therefore compact; Bauer et al. (2001) related one of the ULX in the Circinus galaxy with a small H II region, and we note that the "ultraluminous supernova remnant complex" in NGC 6946 (cf. Dunne, Gruendl, & Chu 2000; Schlegel, Blair, & Fesen 2000) strongly resembles the ULXN, including the presence of a central stellar object that probably represents the X-ray binary system. In Figure 4 we show the position of NGC 5408 X-1, which we find to be coincident with a small nebula, and which from comparison with a 4.8 GHz radio map of Stevens, Forbes, & Norris (2002) appears to be largely nonthermal.

3. X-RAY AND SHOCK IONIZATION

There are similarities between the spectra of X-ray ionized nebulae and radiative shock-exited nebulae, which at the same time distinguish them from normal H II regions and PNs. One is the coexistence of lines of highly ionized atoms ([O III], [Ne III], He III, etc.) and strong lines of near-neutral species such as [O I] or [S II]. The latter lines are excited in extended warm ($T_\mathrm{e} = 10^4$ K) regions of low ionization, which are largely absent in Strömgren spheres.

An important difference concerns the behaviour of multiply ionized species such as the diagnostic [O III] $\lambda\,5007$ Å line: as compared to Hβ, it becomes strong in pre- and postshock regions at velocities larger than some $80\,\mathrm{km\,s^{-1}}$ (Dopita et al. 1984), whereas X-ray ionization excites this line only for relatively large ionization parameters where charge exchange reactions with H^0 are negligible. From our grid of Cloudy models we find that $\lambda\,5007$ Å emission should indeed be absent in the very extended ULXN such as the M 81 and NGC 1313 objects, and that their observed strength indicates shock excitation, in agreement with the measured expansion velocity in the latter bubble nebula.

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