A ULX IN NGC 4559: A “MINI-CARTWHEEL” SCENARIO?

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RESUMEN

ABSTRACT

We have studied an ultraluminous X-ray source (ULX) in NGC 4559 with XMM-Newton, and its peculiar star-forming environment with HST/WFPC2. The X-ray source is one of the brightest in its class ($L_x \approx 2 \times 10^{40}$ erg s$^{-1}$). Luminosity and timing arguments suggest a mass $\sim 50 M_\odot$ for the accreting black hole. The ULX is located near the rim of a young (age $< 30$ Myr), large (diameter $\approx 700$ pc) ring-like star forming complex possibly triggered by the impact of a dwarf satellite galaxy through the gas-rich outer disk of NGC 4559. We speculate that galaxy interactions (including the infall of high-velocity clouds and satellites on a galactic disk) and low-metallicity environments offer favourable conditions for the formation of compact remnants more massive than “standard” X-ray binaries, and accreting from a massive Roche-lobe filling companion.

Key Words: GALAXIES: SPIRAL — GALAXIES: INDIVIDUAL: NAME: NGC 4559 — GALAXIES: INTERACTIONS — X-RAYS: GALAXIES

1. A “CANONICAL” ULX IN NGC 4559

Located at a distance of $\approx 10$ Mpc (Sanders 2003), the late-type spiral NGC 4559 hosts two ultraluminous X-ray sources (ULXs) with isotropic luminosities $\gtrsim 10^{40}$ erg s$^{-1}$ (Vogler, Pietsch & Bertoldi 1997). Its low foreground Galactic absorption ($n_H \approx 1.5 \times 10^{20}$ cm$^{-2}$;Dickey & Lockman 1990) makes it a suitable target for X-ray and optical studies aimed at determining the nature of these sources, and their relation with the host environment. A study of the X-ray timing and spectral properties of the two brightest X-ray sources in NGC 4559, based on XMM-Newton and Chandra data, is presented in Cropper et al. (2004). We focus here on the brighter of the two sources, X7 (using the naming convention of Vogler et al. 1997), which presents some of the “canonical” features of ULXs in star-forming galaxies. It has an isotropic luminosity $L_x \approx 2 \times 10^{40}$ erg s$^{-1}$ in the 0.3–10 keV band, suggesting a mass $\sim 10^2 M_\odot$ for the accreting object. Its X-ray spectrum is well modelled by a power-law (photon index $\Gamma = 2.2$) with a “soft-excess” below 0.7 keV. If the soft component is modelled as a simple blackbody or multicolor blackbody (standard disk spectrum), we obtain a characteristic temperature $kT_{bb} \approx 0.12$ keV, similar to what is found in some other bright ULXs. Furthermore, we detect a feature at $\sim 30$ mHz in its power-density spectrum, which may be another indication of a high mass, $\gtrsim 50 M_\odot$ (Cropper et al. 2004).

2. A PECULIAR STAR-FORMING COMPLEX NEAR THE X7 ULX

X7 is located in a large (diameter $\approx 700$ pc), isolated star-forming complex, at the outer edge of the stellar disk of NGC 4559 (Fig. 1). From HST/WFPC2 observations, we infer (Soria et
consistent with low (SMC-type) metal abundance (Langer & Maeder 1995). This is in agreement with the low metal abundance inferred from our X-ray study (Cropper et al. 2004). A CHFT Hα observation (Fig. 4) shows more clearly the structure of this HII complex. The shell-like structure suggests that an expanding wave of star formation has recently moved from a centre (which appears to be near but not coincident with the ULX) outwards. Continuous star formation at a rate of $\sim 10^{-2} M_\odot$/yr over the last 30 Myr would account for the integrated luminosity and the observed number of O stars (from Starburst99 models, Leitherer et al. 1999). We estimate a mass in stars of a few $10^5$–$10^6 M_\odot$, depending on the assumed IMF. The total mass (stars plus swept-up gas) is probably an order of magnitude higher.

Was the ULX somehow responsible for triggering this peculiar star-forming complex, or are they both consequences of another external factor? Large, isolated shell- or ring-like star-forming complexes of comparable size (500–1000 pc) and age (10–30 Myr) have been found in other nearby spiral galaxies: for example in NGC 6946 (eg, Larsen et al. 2002), and, on a smaller scale, in M83 (Comerón 2001). Gould’s Belt in the Milky Way is also similar. From our preliminary analysis of the HST data, we estimate an integrated magnitude $M_B \approx -13.5$ for the star-forming complex in NGC 4559, a factor of two brighter than Gould’s Belt and a factor of four fainter than the NGC 6946 complex. The latter has a young super-star cluster at its centre, while Gould’s Belt and the complex in M83 contain only OB associations. None of them has a ULX. This suggests that the ULX is not the cause or the driving force of the star-forming complex in NGC 4559.

Possible explanations for the initial triggering of such star-forming complexes are (Elmegreen, Efremov & Larsen 2000; Larsen et al. 2002): the collapse of a "supergiant molecular cloud" at the end of a spiral arm; a hypernova explosion (which in our case might also have been the progenitor of NGC 4559 X7); or the infall of a high-velocity HI cloud or satellite galaxy through the outer galactic disk. In all cases, the initial perturbation creates a radially expanding density wave or ionization front, which sweeps up neutral interstellar medium. Clustered star formation along the expanding bubble rim is triggered by the gravitational collapse of the swept-up material (eg, Elmegreen & Lada 1977; Whitworth et al. 1994).

The large size of the complex in NGC 4559, its location in the outer disk, the lack of other star-
The impact of an supernova model (Tenorio-Tagle et al. 1986, 1987). It seems to favour the collision hypothesis over the X-ray emitting gas inside the star-forming complex forming regions nearby, and the absence of diffuse X-ray emitting gas inside the star-forming complex, as it plunged through the gas-rich outer disk of NGC 4559 some 30 Myr ago.

form regions nearby, and the absence of diffuse X-ray emitting gas inside the star-forming complex seem to favour the collision hypothesis over the supernova model (Tenorio-Tagle et al. 1986, 1987). The impact of an $\approx 3 \times 10^5 M_\odot$ HI cloud on the Milky Way disk was simulated (Comerón & Torra 1994) to explain the formation of Gould’s Belt. They show that, after $\approx 30$ Myr, the mass of the cold swept-up material is comparable or larger than the mass of the impacting cloud.

3. A DWARF GALAXY PLUNGING THROUGH THE DISK?

Perhaps the most intriguing result of our optical study of the X7 environment is that we do indeed see an object that could have plunged through the gas-rich disk of NGC 4559, triggering the expanding density wave. The culprit could be the yellow galaxy located $\approx 7''$ north-west of the ULX (Fig. 3). This object cannot be a large background elliptical, because its isophotes are too irregular. Its shape, size and luminosity are consistent with a dwarf irregular (or, possibly, a tidally-disturbed dwarf elliptical) at approximately the same distance as NGC 4559. We cannot presently rule out the possibility that it is a chance line-of-sight coincidence, but we suggest that the most natural interpretation is a small satellite galaxy of NGC 4559. Existing HI radio observations (WHISP survey) do not show any large-scale velocity distortions, but the satellite dwarf is perhaps too small to influence the galactic kinematics significantly. We are planning optical spectroscopic observations to determine the kinematics and distance of the dwarf galaxy.

If the dIrr galaxy is indeed physically associated with the star-forming complex, its integrated luminosity is $M_B \approx -10.7$, with color indices $B - V \approx 0.47$ and $V - I \approx 0.73$. These colors are typical of a population dominated by F5–F8 main-sequence stars, suggesting an old age. Assuming a single burst of star formation, we infer (using Starburst99, Leitherer et al. 1999) a mass of $\approx 10^6 M_\odot$ for the galaxy and an age $\gtrsim 10^8$ yr for the dominant component of its stellar population.

On top of this old component, the galaxy shows two bright clusters and a few more, much fainter lumps. The two brightest clusters have luminosities $M_B \approx -7.2$ and $M_B \approx -7.1$, and colors consistent with an age $\sim 10^7$ yr and masses of $\sim$ a few $\times 10^9 M_\odot$. Their brightness and morphology is consistent with the bright star-forming complexes often found in dIrr galaxies (Parodi & Binggeli 2003). We obtain that the percentage of flux in the $B$ band due to these star-forming complexes (“lumpiness index”) is $\approx 7\%$ of the total $B$-band flux, the same value found for a large sample of irregulars and spirals regardless of Hubble type and galactic mass (Elmegreen & Salzer 1999; Parodi & Binggeli 2003). Thus, the lumpiness index is thought to be a measure of star-formation efficiency. These considerations support the idea that the bright lumps are indeed clusters in the dIrr satellite galaxy and not simply background or foreground stars in NGC 4559. It is possible that this later episode of star formation in the dIrr satellite may have been triggered as this small galaxy passed through the disk of NGC 4559, shocking its gas and creating the expanding star-forming wave. The non-spherical appearance of the large star-forming complex in NGC 4559 may be due to an oblique impact, probably from the south-east to the north-west direction (because the oldest stars in the field are found in the south-east sector, with ages $\geq 20$ Myr; Soria et al. 2004). The relative masses of the “bullet” and swept-up gas are also consistent with the results of Comerón & Torra (1994) for the case of Gould’s Belt. The projected distance of the dIrr from the centre of the star-forming ring or bubble is $\approx 400$ pc, corresponding to a projected relative velocity of $\approx 30$ km s$^{-1}$ over 15 Myr.

Thus, we could view the star-forming complex in NGC 4559 as a small-scale version of the Cartwheel...
galaxy, where many young ULXs have been detected in the expanding, star-forming ring (Gao et al. 2003). Apart from the different time and length scales involved, the main difference between the two systems is that, in the Cartwheel, the initial perturbation causing the expanding density wave is due to the gravitational interaction between the two galaxies; in the case of NGC 4559, it is more likely due to the hydrodynamical interaction between the gas in the satellite galaxy and the gas-rich disk.

4. ENVIRONMENTAL CONDITIONS FAVOURABLE TO ULX FORMATION

NGC 4559 X7 offers an example of a bright ($L_x > 10^{40}$) ULX in a low-metallicity environment disturbed by close galaxy interactions. At least one or both of these elements seem to be a common feature for many of the galaxies hosting ULXs (eg, galactic interactions for the Antennae, the Cartwheel, the M81/M82 galaxy group: low metal abundance for the Cartwheel ring, the M81 group dwarfs, IZw18). A connection between ULX formation and low-Z environment was already suggested in Pakull & Mirioni (2002).

Assuming that most ULXs can be explained by accreting black holes more massive ($\approx 50–100 M_\odot$) than those found in nearby X-ray binaries, we speculate that these two environmental conditions may be most favourable for producing massive remnants:

- galaxy mergers and close interactions, and collisions with satellite galaxies and high-velocity HI clouds favour clustered star formation. The core of young star clusters may be an environment where massive remnants are formed (through the Spitzer instability, runaway core collapse and merger of the O stars; see Portegies Zwart & McMillan 2002; Rasio, Freitag, & Gürkan 2003). One of the open questions is what type of cluster (ie, what mass range) offers the best chance for the core collapse/stellar coalescence process to occur within the lifetime of its O stars: super-star clusters ($M \gtrsim 10^5 M_\odot$) or smaller clusters ($10^4 < M \lesssim 10^5 M_\odot$)?

- low metal abundance implies a lower mass-loss rate in a wind ($M_w \sim Z^{0.6}$) for the black hole progenitor, leading to a larger core and a more massive remnant. Metallicity also affects the evolution of the donor star (for example, metal-poor stars spend a longer fraction of their lifetime as red supergiants) and the orbital separation of the binary components (which increases for a higher mass-loss rate in a wind, that is, for a higher non-conservative mass transfer). This may affect the timescale in which the donor star fills the Roche lobe (that is, the timescale for the ULX phase).

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REFERENCES

Comerón, F. 2001, A&A, 365, 417
Comerón, F., & Torra, J. 1994, A&A, 281, 35
Cropper, M. S., Soria, R., Mushotzky, R. F., Wu, K., Markwardt, C. B., & Pakull, M. 2004, MNRAS, in press (astro-ph/0311302)
Dickey, J. M., Lockman, F. J. 1990, 1990, ARA&A, 28, 215
Elmegreen, B. G., Efremov, Y. N., & Larsen, S. 2000, ApJ, 535, 748
Elmegreen, B. G., & Lada, C. J. 1977, ApJ, 214, 725
Elmegreen, D. M., & Salzer, J. J. 1999, AJ, 117, 764
Langer, N., & Maeder, A. 1995, A&A, 295, 68
Larsen, S. S., Efremov, Y. N., Elmegreen, B. G., Alfar, E. J., Battinelli, P., Hodge, P. W., & Richtler, T. 2002, ApJ, 567, 896
Leitherer, C., Schaerer, D., Goldader, J. D., Delgado, R. M. G., Robert, C., Kune, D. F., de Mello, D. F., Devost, D., & Heckman, T. M. 1999, ApJS, 123, 3
Pakull, M. W., & Mirioni, L. 2002, to appear in the proceedings of the symposium 'New Visions of the X-ray Universe', 26-30 November 2001, ESTEC, The Netherlands (astro-ph/0202488)
Parodi, B. R., & Binggeli, B. 2003, A&A, 398, 501
Portegies Zwart, S. F., & McMillan, S. L. W. 2002, ApJ, 576, 899
Rasio, F. A., Freitag, M., & Gürkan, M. A. 2003, in "Carnegie Observatories Astrophysics Series, Vol. 1: Coevolution of Black Holes and Galaxies," ed. L. C. Ho (Cambridge: Cambridge Univ Press)
Sanders, D. B., Mazzarella, J. M., Kim, D.-C., Surace, J. A., & Soifer, B. T. 2003, AJ, 126, 1607
Soria, R., Cropper, M., Pakull, M., et al. 2004, MNRAS, in preparation
Tenorio-Tagle, G., Bodenheimer, P., Rozyczka, M., & Franco, J. 1986, A&A, 170, 107
Tenorio-Tagle, G., Franco, J., Bodenheimer, P., & Rozyczka, M. 1987, A&A, 179, 219
Vogler, A., Pietsch, W., & Bertoldi, F. 1997, A&A, 318, 768
Whitworth, A. P., Bhattal, A. S., Chapman, S. J., Disney, M. J., & Turner, J. A. 1994, A&A, 290, 421
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