Mem. S.A.It. Suppl. Vol. 9, 378
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Memorie della
Supplementi

Ultraluminous X-ray Sources in Nearby Galaxies

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Abstract. The observation of nearby galaxies with Einstein, ROSAT, ASCA, XMM-Newton and Chandra has revealed a novel class of point-like, off-nuclear X-ray sources with isotropic luminosity largely in excess of the Eddington limit for one solar mass. From the available X-ray and multiwavelength observations, these ultraluminous X-ray sources turn out to be a composite population. The majority of them (probably all those found in star-forming galaxies) are accreting binaries, likely high mass X-ray binaries. The current debate is centered on understanding whether the compact objects is an intermediate mass ($M > 100 M_\odot$) black hole emitting isotropically or a stellar mass black hole with beamed emission. A short review of the topic is presented.

Key words. X-rays: binaries – X-rays: galaxies – X-rays: stars

1. X-ray properties

First revealed by the Einstein Observatory (see e.g. Fabbiano 1989), the population of ultraluminous X-ray Sources (ULXs) has increasingly grown up in the last decade mainly thanks to the observations of ROSAT (e.g. Colbert & Ptak 2002; Liu & Bregman 2005), XMM-Newton (e.g. Foschini et al. 2002a) and Chandra (e.g. Swartz et al. 2004). These point-like sources have X-ray luminosities $L_X \gtrsim 10^{39}$ erg s^{-1}, largely in excess of the Eddington limit for one solar mass. Variability in the X-ray flux on timescales of months is observed in about half of the ROSAT ULXs with multiple observations (Colbert & Ptak 2002), while about 5-15% of the Chandra ULXs show variability during a single observation (Swartz et al. 2004).

The first ASCA spectra of ULXs were fitted with a standard accretion disk model (MCD; Makishima et al. 2000). More recent XMM (e.g. Foschini et al. 2002a) and Chandra (e.g. Zezas et al. 2002) spectra can be successfully fitted with a power-law or a power-law plus a MCD component with photon index $\Gamma \sim 1 - 1.5$ and temperature $kT \sim 1$ keV. Very soft MCD components have been recently identified in several good quality ULX spectra with typical temperatures $kT \sim 100$ eV ($\Gamma \sim 1.5 - 2$; e.g. Miller et al. 2003; Cropper et al. 2004). This is 5-10 times lower than the typical MCD temperatures observed in Galactic X-ray binaries (XRBs). Finally, correlated luminosity-spectral variability has also been reported (e.g. M 81 X-9, La Parola et al. 2001; M 51 X-7, Liu et al. 2002; 9 ULXs in the Antennae, Fabbiano et al. 2003a).

Another approach to study the nature of ULXs is through X-ray time variability. The first ULX where a QPO has been discovered is M82 X-1 (Strohmayer & Mushotzky 2003). The QPO has a frequency of 54.4 mHz and

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a FWHM of 11.4 mHz. The total fractional rms of the QPO in the 2-10 keV band is 8.4%. Recently, Fiorito & Titarchuk (2004) reported the identification of a similar QPO at 106 mHz from RossiXTE data. A recent analysis by Mucciarelli et al. (2005) shows that the properties of the QPO in M82 X-1 are similar to those of the type-C, low frequency QPOs detected in Galactic black hole XRBs.

2. Radio and optical counterparts

Multiwavelength observations are a powerful tool to investigate the nature of ULXs. Radio emission, when present, gives important clues on the geometry, energetics and lifetime of ULXs (Kaaret et al. 2003; Miller et al. 2005).

Optical observations are crucial to identify ULX counterparts and clean up the sample from the contamination of known X-ray sources. Some ULXs were identified with background AGNs through optical follow-up spectroscopy (Foschini et al. 2002b; Masetti et al. 2003). Up to now only a very small number of ULXs have been convincingly associated with stellar objects (e.g. Liu et al. 2002, 2004; Kaaret et al. 2004; Zampieri et al. 2004). The great majority of these ULXs are hosted in star-forming regions and their optical counterparts have properties consistent with those of early type O-B stars. In these systems X-ray reprocessed emission may contribute to the optical light. Only two positive identifications of ULXs in non star-forming galaxies have been reported, both coincident with globular clusters (Angelini et al. 2001; Wu et al. 2002). They have luminosities in the lower range of those exhibited by ULXs ($L \sim 10^{39}$ erg s^{-1}).

Some ULXs in star-forming galaxies are associated to optical emission nebulae (Pakull & Mirioni 2002), that are typically young ($\lesssim 1$ Myr) and very extended (few hundreds parsecs in diameter). These nebulae show supernova remnant-like line ratios (e.g. [SII]/Hα, [OI] λ6300/Hα) and have similar morphologies on radio images. The energy needed to power them ($\sim 10^{52}$ erg) is about one order of magnitude larger than that typically released in a single supernova event. The detection of the He λ4686 line in some nebulae (Pakull & Mirioni 2002; Kaaret et al. 2004) indicate that they are likely to be X-ray photoionized.

3. Statistical properties and the ULX population

Studies on the statistical properties of ULXs rely mainly on ROSAT HRI (Colbert & Ptak 2002; Liu & Bregman 2005) and Chandra (Swartz et al. 2004) observations for accurate celestial positions.

In the recent Chandra survey by Swartz et al. (2004), a total of 154 ULXs out to 3400 sources were detected, among which 57/97 in elliptical/spiral galaxies ($\sim$ 2 per galaxy). Power-law X-ray spectral fits show that the spectral indices of ULXs have a gaussian distribution with $< \Gamma >= 1.9 - 2.0$, similar to that of non-ULXs sources. Also the location and spatial distribution of ULXs and less luminous X-ray field sources are similar. More luminous ULXs tend to occur preferentially in spiral galaxies (2/3 have $L > 2 \times 10^{39}$ erg s^{-1}, while only 1/3 of the ULXs in ellipticals are this luminous). There exists also a strong correlation between the ULXs properties and the host galaxy far-IR luminosity in spirals.

From the available observations, ULXs turn out to be a composite population. Swartz et al. (2004) found that a large fraction ($\sim$ 25%) are, in fact, background AGNs (of which 44%/14% occur in ellipticals/spirals) and that $\lesssim$ 22% are supernovae interacting with the circumstellar medium (e.g. SN 1978K, SN 1993J). A contamination from very soft, thermal sources (similar to Galactic Super-Soft Sources, e.g. Di Stefano & Kong 2003) is also present. Finally, it has been suggested that some ULXs may be young, Crab-like pulsars, powered by rotation (Perna & Stella 2004). However, for the majority of ULXs, the X-ray variability (on hours, months, years timescale), spectra and correlated luminosity/spectral variability are strongly suggestive of accreting binaries.

4. Intermediate mass black holes or beamed X-ray binaries?

Among the debated issues on ULX properties, a number of open questions stand out: What type of accreting binaries are ULXs? Are they isotropic or beamed emitters? How have ULXs formed?

The large inferred isotropic luminosity ($10^{39} - 10^{41}$ erg s^{-1}) and the very low temperature of the soft MCD component observed in the X-ray spectra of several ULXs ($\sim$ 100 eV) can be easily accounted for assuming that they host an intermediate mass black hole (IMBH) of $\gtrsim 100 M_\odot$ (e.g. Colbert & Mushotzky 1999). In fact, assuming that at maximum luminosity ULXs emit at the Eddington limit, one obtains

$$M_{BH} \sim 75\,(L/10^{40}\,\mathrm{erg\,s^{-1}})\,M_\odot\,. \quad (1)$$

Similarly, assuming that the temperature of the soft MCD component is the characteristic temperature of a standard accretion disk, it is possible to derive an independent order-of-magnitude estimate of the black hole (BH) mass

$$M_{BH} \gtrsim 100\,(T/200\mathrm{eV})^{-4}\,M_\odot\,. \quad (2)$$

An interpretation of ULXs obeying Occams razor principle is that they are ordinary XRBs in short-lived evolutionary stages. The emission may be beamed because the accretion disk is geometrically thick and radiation escapes only through funnels formed along the rotation axis (mechanical beaming; King et al. 2001; King 2002). If b is the beaming factor (funnel opening angle divided by 4π), the total emitted luminosity is then bL, where L is the isotropic luminosity. For $b \sim 0.1$, the BH mass inferred from the Eddington limit is $M_{BH} \sim 7\,(L/10^{40}\mathrm{erg\,s^{-1}})\,M_\odot$, consistent with that of stellar mass BHs and similar to that of some Galactic XRBs. The large inferred accretion rates and short timescales require a short episode of super-Eddington accretion, identified with the thermal-timescale mass transfer occurring when the donor has a radiative envelope and is somewhat more massive than the accretor (Cyg X-2 is believed to be a survivor of such an episode). An interpretation in terms of physical (relativistic) beaming of the emitted radiation by high velocity jets has also been proposed (Körding et al. 2002; Georganopoulos et al. 2002).

The beamed XRB interpretation is supported by the fact that the statistical properties of ULXs appear to be indistinguishable from those of less luminous X-ray sources in the same galaxy fields (Swartz et al. 2004). Also the correlation of ULXs with active star forming regions (association with massive stars, presence of emission nebulae, correlation with the far-IR luminosity in spirals) has been taken as evidence in favor of this interpretation. The relativistic beaming interpretation is supported mainly by the X-ray spectrum and multiwavelength spectral energy distribution of one source (NGC 5408 X-1; Kaaret et al. 2003). However, the beamed XRB interpretation can not explain why several ULXs show a very high luminosity and, at the same time, a very low temperature of the accretion disk. This fact is not consistent with the behavior of Galactic BH XRBs where high luminosities are associated to high disk temperatures ($kT \sim 1$ keV). Also the extended radio emission around some ULXs (e.g. Holmberg II X-1; Miller et al. 2005) is not in agreement with the beamed interpretation (especially in the case of relativistic beaming where a compact morphology would be expected). It has been suggested that the very soft X-ray spectral components in ULXs may be produced by optically thick winds (King & Pounds 2003), similarly to what proposed for Super-Soft ULXs (e.g. M 101 X-1, Mukai et al. 2003; a ULX in the Antennae, Fabbiano et al. 2003b).

On the other hand, the IMBH interpretation offers a straigthforward interpretation of both the very high luminosity *and* low disk temperature of ULXs (e.g. Miller et al. 2004). Also the association with very massive OB companions is consistent with this interpretation, especially if mass transfer occurs via Roche-lobe overflow on the main sequence (Patruno & Zampieri, in preparation). Furthermore, the presence of uniformly X-ray irradiated emission nebulae and extended radio counterparts suggests a rather isotropic illumination of the surrounding interstellar medium by the ULX.

In M82 X-1 recent combined spectral and timing data provide evidence for a BH with a mass between a few tens and 1000 $M_{\odot}$ (Mucciarelli et al. 2005). However, the IMBH interpretation leaves some important open questions, chiefly among them how such a system may have formed. In fact, such massive BHs would require a different formation mechanism with respect to stellar BHs in XRBs and supermassive BHs in AGNs. It has been suggested that IMBHs may be relics of Population III stars (Madau & Rees 2001), may form in globular clusters (Miller & Hamilton 2002) or may be generated through gravitational interactions in stellar super-clusters (Portegies Zwart et al. 2004). Further observational and theoretical work is needed in order to shed light on the ULX properties and understand their nature. In particular, investigating the X-ray timing properties to estimate the BH mass, searching for X-ray emission lines to constrain the ULX environment, and computing binary evolution models to test different interpretations will be of key importance to advance our knowledge in this field.

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