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The nature of the ultraluminous X-ray sources inside galaxies and their relation to local QSOs

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Abstract. It is suggested that many of the ultraluminous compact X-ray sources now being found in the main bodies of galaxies, particularly those that are active, like M 82, NGC 3628 and others, are "local" QSOs, or BL Lac objects, with high intrinsic redshifts in the process of being ejected from those galaxies. Evidence bearing on this hypothesis is summarized.

Key words. galaxies: active – quasars: general – X-rays: galaxies – X-rays: stars

1. Introduction

It is generally agreed that there are two types of compact X-ray sources whose properties are well established. The first objects of this kind are the X-ray sources that arise in stellar binary systems. These are clearly associated with accretion disks around highly evolved stars, neutron stars and black holes. Since there is much evidence that the upper end of the stellar mass function is close to 100 $M_\odot$, it is clear that there is a luminosity limit of $\sim 10^{39}$ erg s^{-1} that can be expected from any X-ray binary system which has arisen from a normal stellar system.

The second type of compact X-ray source is that associated with active galactic nuclei and quasi-stellar objects. These sources have much greater luminosities, which in the conventional view are attributed to the presence of much more massive black holes in the centers of galaxies and in QSOs.

In studies of comparatively nearby galaxies ROSAT began to find nuclear sources with $L \simeq 10^{39}-10^{40}$ erg s^{-1}, corresponding to black hole accretion sources with masses in the range 10^3-10^4 $M_\odot$. However, in recent years, a number of studies have shown that X-ray sources with this range of luminosity are often present in the main bodies of spiral and irregular galaxies and not just in the nuclei. These discoveries, due to the high resolution properties of Chandra and XMM Newton, show that ultraluminous sources are present in NGC 1073, M 82, 3628, 4038-39, 4151, 4565, 4698, 5204 and other galaxies (Strickland et al. 2001; Fabbiano et al. 2001; Foschini et al. 2002a,b; Kaaret et al. 2001; Makishima et al. 2000; Wu et al. 2002; Colbert & Ptak 2002). A recent study of a sample of nearby Seyfert galaxies with XMM-Newton has shown that they also contain many off-center compact X-ray sources with luminosities in the range $10^{39}-10^{40}$ erg s^{-1} (Foschini et al. 2002b).

Several proposals to explain these sources have been made, the main one being the suggestion that intermediate size black holes with masses 10^2-10^4 $M_\odot$ are responsible and the energy release is again through accretion. Alternatively it has been proposed that some of these sources are background QSOs or BL Lac objects. However, for those which lie very close to the nuclei of the galaxies the chance that they are background sources is very small.

In this note we propose that these sources are (local) low luminosity QSOs which are in the process of being ejected from their places of birth in the nuclei of the galaxies. In the following section we summarize evidence in support of this hypothesis.

2. Evidence for clustering of QSOs about galaxies

Following the early work based on statistical evidence for the physical association between nearby galaxies and bright high redshift QSOs, and individual examples, which has been extensively summarized elsewhere (cf. Burbidge et al. 1971; Arp 1967, 1987; Burbidge 2001; Hoyle et al. 2000) there have been a number of recent investigations which strongly suggest that QSOs can be detected as they are ejected from low redshift active galaxies. Some of these are as follows:

– 1. Two compact X-ray QSOs ejected symmetrically along an axis of NGC 4258 (distance 7 Mpc) (Pietsch et al. 1994; Burbidge 1995);

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- 2. Two compact X-ray emitting QSOs apparently ejected from NGC 2639 (Burbidge 1997);
- 3. Two pairs of X-ray emitting QSOs, one pair with almost equal values of the redshift (z = 1.25 and 1.26) associated with Arp 220 (Arp et al. 2001);
- 4. A number of QSOs with morphological connections and a configuration strongly suggesting recent ejection in NGC 3628 with some QSOs exceedingly close to the nucleus of the galaxy (Arp et al. 2002).
- 5. Five QSOs aligned along an axis associated with NGC 3516 (Chu et al. 1998).

These are only some of the many cases which have now been found which provide strong circumstantial evidence that QSOs originate in the centers of active galaxies and are ejected from them.

Evidence based on a sample of 39 X-ray emitting QSOs associated with active galaxies, including some of the cases listed above, suggests that the line of sight components of the velocities of ejection average about 12 000 km s^{-1} (both redshifted and blueshifted) (cf. Burbidge & Napier 2001). Of course the QSOs, since they are at the distances of the galaxies and have typical apparent magnitudes in the range $17^{\rm m}$–$20^{\rm m}$, are much fainter than the galaxies. Thus at the distance of NGC 4258 (7 Mpc) the absolute magnitudes of the ejected QSOs are only about $M = -10$; i.e. they are no brighter than the brightest O stars. However, the detected QSOs associated with Arp 220, using its redshift $z = 0.018$ and $H_0 = 60$ km s^{-1} Mpc^{-1} lie at a distance of ~90 Mpc. Thus they are much more luminous with $M = -16$.

In the cases in which QSOs have been found to be clustered about active galaxies the scale of the clustering is $\sim5'$–$50'$. Thus it is clear that there will be an effect that must be taken into account, associated with the fact that since there is a considerable range in the distances of the parent galaxies, we shall identify intrinsically faint QSOs close to nearby galaxies, but only the brighter QSOs will be seen to be associated with parent galaxies which are much farther away. For the more distant parent galaxies, the intrinsically fainter QSOs will not be detected.

For example, if NGC 4258 was at the same distance as Arp 220, the two QSOs would have $m \simeq 24$, and they would lie less than 40 arcsec from the center of the galaxy. Thus they would not be detected. Correspondingly, if QSOs as bright as those detected around Arp 220 have been ejected from NGC 4258 they will lie at angular distances of 1–2 degrees and thus they will not be thought to be associated with the galaxy.

In general, we suppose that dispersing clouds of QSOs with a wide range of luminosities exist around most active galaxies, and they range in luminosity in X-rays and/or optical flux from values $\sim10^{39}$ erg s^{-1} upward. Since they are born in the nucleus, and eventually are found outside, it is reasonable to suppose that some of them will be detected in the main body of the galaxy, as they travel out. Thus it is clear also that many of them will be found inside the main luminous body of the galaxy. In our view these are the ultraluminous X-ray sources that are beginning to be found in comparatively close by galaxies.

One piece of evidence which tends to bear this out is associated with M 82. In this galaxy a number of QSOs have been found very close to the main body. M 82 is the nearest active galaxy (D = 3.63 Mpc). We have recently discovered many X-ray QSOs in addition to those which were discovered earlier in this system (Burbidge et al. 2002). Most of the QSOs lie within $10'$ or less of the center of M 82 and they are quite faint $\sim18^{\rm m}$–$20^{\rm m}$. This means that they have absolute magnitudes in the range $-7.4 < M < -9.4$. The configuration of the QSOs about M 82 strongly suggests that they are associated with it. We therefore believe that the X-ray sources found in the main body of M 82 by Kaaret et al. (2001) and Makishima et al. (2000) are also QSOs in the process of ejection. If M 82 was observed at the distance of Arp 220, all of the QSOs which we have found to be associated with it would be much too faint, and much too close to the main body of the galaxy to be detectable. However, they will contribute significantly to its X-ray luminosity.

Obviously, the test of this general hypothesis is to detect a QSO in the main body of a galaxy and show that it has a large redshift. Has this already been achieved?

In the next section we discuss this and other evidence.

3. Observational evidence bearing on this hypothesis

(a) Spectral properties - As far as the spectral properties are concerned, Foschini et al. (2002a) give ULX photon indices from 1.1 to about 2.3, with an average of about 1.9. This close to the canonical value for broad line, unabsorbed AGN according to Piconcelli et al. (2002).

(b) Luminosity function of ULX's - Finoguenov & Jones (2002) state that there is a break in the log$N$–log$S$ curve at about 2.4×10^{39} erg s^{-1}, close to the Eddington luminosity seen in star forming galaxies.

(c) Emission nebulae - Pakull & Mirioni (2002) have found some ULX's surrounded by low redshift emission line nebulae which are presumably being excited by central sources. In some cases blue objects have been detected. These might be high redshift QSOs which are exciting low redshift gas but no spectra have been obtained.

(d) Probability arguments - All of the galaxies in or near which ULX sources have been found cover very small areas in the sky ($\sim$2–4 arcmin^2). This means that the probability that a genuine background QSO accidentally lies along the line of sight to the galaxy will be very small. For a density of X-ray QSOs of 10/sq. deg and an average area of 4 sq. min per galaxy we would only expect to find about 4 background QSO in every 100 galaxies. thus it is very unlikely that the comparatively large numbers of such sources which are now beeing found are likely to be background QSOs.

(e) The source in NGC 5204 - Roberts et al. (2001) have recently found an optical counterpart to an X-ray source in NGC 5204 which they call NGC 5204 X-1. At the distance of NGC 5204, it has an X-ray luminosity of 5.2×10^{39} erg s^{-1}. It has a blue continuum with $m_v = 19.7$. At the distance of NGC 5204 $M_v = -8.7$. Roberts et al. point out that the spectrum is featureless in all wavelengths, point like, and it shows long term X-ray variability. Thus they originally suggested that it might be a background BL Lac object. We suggest that it is a genuine BL object within the body of NGC 5204 in the process of being ejected from it.

(f) The source in NGC 4698 - Foschini et al. (2002b) have reported that they have found what they call a background BL Lac object with $z = 0.43$ in NGC 4698 ($z = 0.0033$). This clearly can be interpreted as evidence for a local QSO with an intrinsic redshift of 0.43 being ejected from NGC 4698. The object has an X-ray luminosity of 3×10^{39} ergs s^{-1}.

4. Conclusion

There is circumstantial evidence suggesting that some of the recently discovered ultraluminous X-ray sources in the bodies of comparatively nearby galaxies are local QSOs and BL Lac objects being ejected from those galaxies.

This evidence simply comes from the fact that many comparatively nearby galaxies in different stages of activity are surrounded by "local" QSOs which are physically associated with them. The obvious conclusion is that these QSOs were created in the nuclei of the galaxies, and have been ejected from them. The speeds of ejection are apparently $\leq 0.1c$. Thus, such QSOs will take $\geq 10^6$ years to escape from the main body of a galaxy. Consequently we would expect to find some of them inside the galaxy, moving outward.
Tests of this hypothesis are:

- 1. To obtain optical spectra of such objects and show that they have large redshifts. This may have already been accomplished in the case of the QSOs in NGC 1073, 3628, 4151 and 4698.
- 2. To attempt to detect proper motions of such sources. For sources in M 82, a speed of $0.1c$ across the line of sight, which may be high, corresponds to a proper motion of about 2 milli-arcsecond per year.
- 3. Show that the X-ray emitting properties of these objects are similar to those of the QSOs in general.

Of course, this explanation does not exclude the possibility that some of these sources are indeed accreting objects containing black holes with $M = 10^3 - 10^4\ M_\odot$. Such sources will have the normal properties of accreting objects, and will be distinguishable from local QSOs because they will not have large redshifts or comparatively large proper motions. But in general we predict that the higher luminosity objects will turn out to be QSOs.

In all of the cases where there is circumstantial evidence that QSOs are being ejected from an active galaxy the parent galaxy is a spiral or irregular system. In the case of NGC 4697 which is an elliptical galaxy, many luminous X-ray sources have also been detected outside the nucleus (Sarazin et al. 2001). The luminosities range from 5×10^{37} erg s^{-1} to 2.5×10^{39} erg s^{-1} and Sarazin et al. have suggested that these arise in accreting systems containing black holes with $M = 10^3 - 10^4\ M_\odot$. We consider that this is probably correct.

In our opinion the universe is sufficiently complex for both types of beasts to exist in it. The distinction between them is that the active variable objects will have intrinsic redshifts and will only be found in galaxies with active nuclei or star-forming activity, while the accreting massive black hole systems will largely be thermal emitters and will tend to be found in ellipticals.

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