POPULATION OF ACCRETING NEUTRON STARS IN EXTERNAL GALAXIES.

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The X-ray observations of the Milky Way galaxy with non-imaging X-ray satellites (e.g. UHURU, HEAO1) has revealed a number of discrete, point -like bright sources clustered around the Galaxy's center (in the bulge region) and on the plane of the Galaxy (see for example Tanambaum and Tucker, 1984). The brightermost ones have been associated with close accreting binary systems, containing an evolved object (a white dwarf, a neutron star or a black hole) and a companion visible star. For sources with X-ray luminosities $L_x \leq 10^{38}$ erg s^{-1}, the compact object needs to be a neutron star or a black hole.

The bright X-ray sources in the Milky Way are divided into two broad main classes (see the review by van den Heuvel, 1980), depending on the mass of the companion star: massive binaries or Type I sources and low mass systems or Type II sources.

There are several problems in studying X-ray sources in the Milky Way: in most cases it is difficult to assign the proper location of a source in the disk, arms or bulge region, the distances of these objects are poorly known and a large fraction of their emission is absorbed by the intervening material in the galactic plane. Part of these difficulties can be solved by observing these sources in other galaxies. This will improve our knowledge of other systems similar to our own galaxy as well as give us new insights on the properties of the galaxy itself.

The instruments on board the EINSTEIN Observatory (Giacconi et al, 1979) made possible the study of the X-ray emission of normal galaxies, and the nature, distribution and characteristics of the evolved stellar population in other galaxies through its X-ray emission. Since this meeting is focused on the origin and the evolution of neutron stars, I will concentrate on the results regarding X-ray sources in binary systems and disregard all other phenomena that have come out as a result of the study of normal galaxies in X-rays (for details, see Fabbiano and Trinchieri, 1985, 1986; Trinchieri and Fabbiano, 1985; Trinchieri, Fabbiano and Palumbo, 1985; Palumbo et al. 1985; and references therein).

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LOCAL GROUP GALAXIES

The first obvious targets for the EINSTEIN Observatory were the nearby galaxies M31 and the two Magellanic Clouds. The observations were then extended to other galaxies in the Local Group and to even farther away galaxies.

The X-ray images of the nearby galaxies have shown that, as in the case of the Milky Way, the X-ray emission is dominated by point-like, bright individual sources (see M31, van Speybroeck et al, 1979; LMC, Long, Helfand and Grabelsky, 1981; SMC, Seward and Mitchell, 1980, and many others), with X-ray luminosities ranging from $\sim 10^{34}$-10^{36} erg s^{-1} (typical limiting sensitivities for the Magellanic Clouds and M31 respectively) to $<10^{39}$ erg s^{-1} in the EINSTEIN band pass (0.2-4.0 kev). Such high luminosities suggest that in most cases these sources are close accreting binary systems, with a neutron star or a black hole as the compact accreting object.

Massive Binary Systems

A large number of the bright point-like sources detected in these galaxies are found associated with the young Pop I stellar component. Figure 1 (from van Speybroech and Becktold 1980) shows the distribution of the X-ray sources in the M31 galaxy compared to neutral hydrogen emission. Their positional coincidence with regions of star formation would suggest that these sources are binary systems with a young, massive companion. Although secure optical identification of these sources is difficult (see Crampton et al 1984), $\sim$ 13 sources have been associated with blue stars. The average X-ray luminosity of these sources is 2.2×10^{37} erg s^{-1} (van Speybroeck et al, 1979), and if the identifications are correct $L_x/L_{opt} \sim 1$ (Crampton et al 1984), typical of the brightest supergiant OB systems in the Galaxy (Bradt and McClintock, 1983).

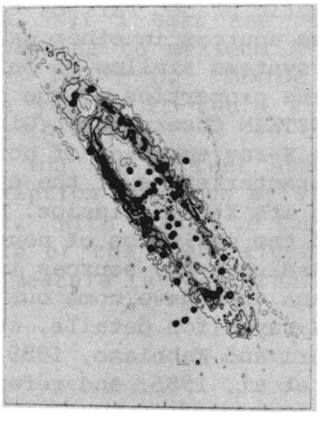

Figure 1: The X-ray sources detected in M31 superposed on the neutral hydrogen emission (from Van Speybroeck and Bechtold, 1980).

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Of the ~ 60 sources detected in the LMC, the largest class of identified objects are Supernova Remnants. About 4 sources (LMC X-1, LMX C-3, LMC X-4, A0538-66) and three other possible candidates have been identified with early type stars in massive binary systems (Cowley et al. 1984). The SMC hosts one of the most luminous non transient X-ray source in the Local Group, SMC X-1, with $L_x > 10^{38}$ erg s^{-1}, identified with a B star system (Webster et al. 1972). A number of sources in M33 are also identified (or candidate) massive binary systems (see Helfand, 1984 and references therein).

Low Mass Binary Systems

In the Galaxy, low mass binary systems are located in the bulge region and in globular clusters. In M31, ~ 20 X-ray sources have been identified with globular clusters. Their average X-ray luminosity is $L_x \sim 5 \times 10^{37}$ erg s^{-1}, higher than for Milky Way globular clusters (van Speybroeck and Bechtold, 1980). However, their optical luminosities seem also to be higher so that the L_x/L_o ratio is comparable (Crampton et al, 1984). No globular cluster sources have been detected in the Magellanic Clouds or in M33 (see Helfand 1984 and references therein).

The bulge region of M31 is seen as a bright extended X-ray source in the lower resolution IPC instrument, and it is resolved in several, bright, point-like sources by the higher resolution HRI. There seem to be two different "bulge" source populations: about 20 sources with average $L_x \sim 4.5 \times 10^{37}$ erg s^{-1} are clustered in an inner region of ~400 pc radius. Outside this inner X-ray bulge but still inside the optical bulge (~ 1 kpc, Morton, Andereck and Bernard, 1977) ~16 more X-ray sources are detected with average $L_x \sim 2 \times 10^{37}$ erg s^{-1} (van Speybroeck and Bechtold, 1980). The integrated spectrum of the bulge region from the IPC data (Fabbiano, Trinchieri and Van Speybroeck, 1986) shows that the X-ray sources in this region have on average a hard (kT>5 kev) spectrum with small low energy cut-off, consistent with typical spectra of low mass binaries in the Galaxy (Jones, 1977).

The detection of "inner" and "outer" bulge sources in M31 is interesting for the problem of the formation of these systems. It is reasonable to assume that all the sources within ~1 Kpc (the optical bulge) are low mass binary systems, given the expected stellar population in the bulge region. However, while formation by capture can be efficient in the high density globular clusters' environments and possibly in the inner bulge region (see van den Heuvel, 1980), it cannot work in the low density regions of the outer bulge. An alternative formation mechanism must be studied. Moreover, the luminosities of the outer bulge sources are indistinguishable from those of the sources in the disk and arms of the galaxy, suggesting perhaps that their nature may be similar. I will come back to this point later.

BEYOND THE LOCAL GROUP

As discussed above, in the very nearby galaxies the X-ray emission is due to the same population responsible for the emission in the Milky

Way. However a larger sample of objects needs to be studied to extend the above results to spiral galaxies in general.

Given the limited sensitivity and resolution of the Einstein instruments, only in the Local Group galaxies can the individual sources be resolved and detected singularly. At larger distances, the X-ray emission appears like an extended source cohextensive with the optical emission with only the very high luminosity end of the galactic X-ray sources detected above it. The total observed X-ray luminosity of normal spiral galaxies (between ~10^{39} erg s^{-1} and ~10^{41} erg s^{-1}) can in most cases be totally accounted for by a collection of galactic-type sources similar to those found in the Milky Way, and their X-ray morphology can be similarly explained (see Fabbiano and Trinchieri, 1985; 1986; and references therein). The spectral signature of their emission also confirms the above result, as will be discussed later in more detail.

Several examples of X-ray maps of spiral galaxies are now available. Figure 2 shows the X-ray map of NGC 253 (HRI data, from Fabbiano and Trinchieri, 1984). It is evident that the X-ray emission is dominated by two main components: a diffuse complex emission from the nuclear, inner disk region and a number of bright sources inside the optical image of the galaxy. At the distance of 3.4 Mpc, their luminosity is $L_X \geqq 10^{38}$ erg s^{-1} (Fabbiano and Trinchieri, 1984).

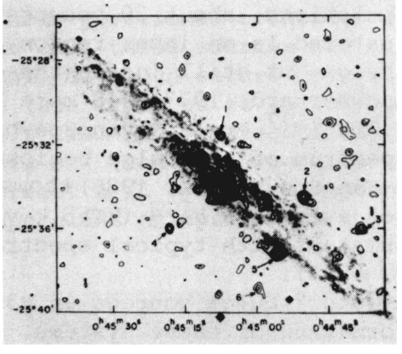
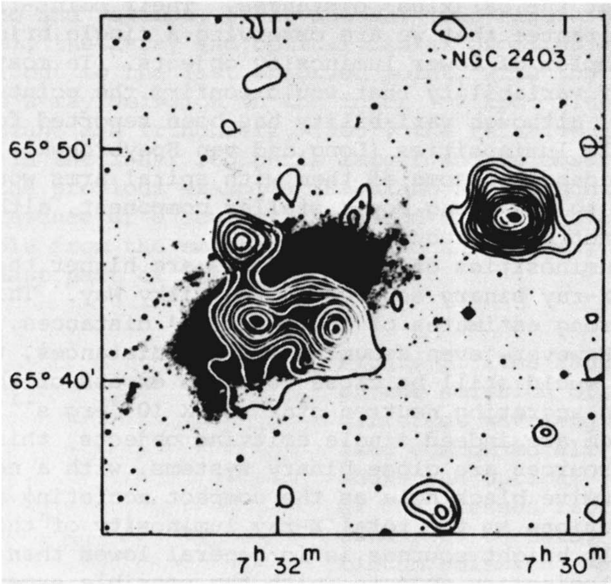


Figure 2: X-ray iso-intensity contours (HRI data) superposed on the optical image of NGC 253 (from Fabbiano and Trinchieri, 1984).

In the X-ray maps of M83, 1 source with luminosity above 10^{38} erg s^{-1} (D=3.5 Mpc) is detected on a spiral arm and two more near the nuclear region (see Figures 3 and 4 in Trinchieri, Fabbiano and Palumbo, 1985) above a low surface brightness emission from the plane. Similarly, in M51 there are 3 bright sources with $L_X \geqq 10^{38}$ erg s^{-1} on the spiral arms (see Figure 2 in Palumbo et al. 1985). Other examples of bright sources are found in M101 (see Long and van Speybroeck, 1983; McCammon and Sanders, 1984), IC 342, NGC 2403, NGC 4631 and NGC 6946 (Figure 3, see also Fabbiano and Trinchieri, 1986). Most of these sources have no obvious optical counterpart, although in most cases they are located on the spiral arms and are close to HII regions or radio sources (see Palumbo et al, 1985; Fabbiano and Trinchieri, 1986).

What is the nature of these bright sources in spiral galaxies? The



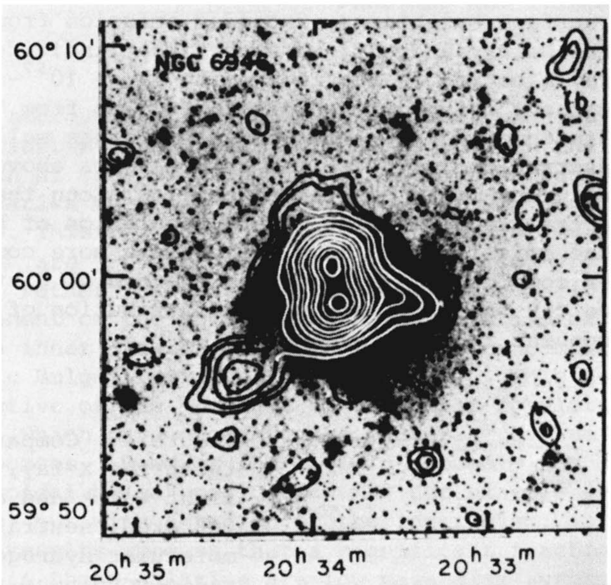


Figure 3: Iso-intensity IPC contours superimposed on the optical plates of NGC 2403 and NGC 6946. The SE source on the spiral arm of NGC 6946 is the supernova SN 1980k (from Fabbiano and Trinchieri, 1986).

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quality of the available X-ray data does not allow us to make a detailed study of the nature of these sources. Their X-ray luminosity exceeds ~ 10^{38} erg s^{-1}, at the galaxies' distances. Their point-like appearance does not guarantee that we are observing a single bright object rather than a complex of lower luminosity objects. In most cases there is no evidence of variability that would confirm the point-like nature of these sources, although variability has been reported for sources in M101 of comparable luminosities (Long and van Speybroeck, 1983). The positional coincidence of some of them with spiral arms would suggest that they belong to the young Pop I stellar component, although projection effects cannot be excluded.

The X-ray luminosities of these sources are higher than typical luminosities of X-ray binary sources in the Milky Way. This could be due in part to wrong estimates of the galaxies' distances, uncertain by large factors. However, even assuming smaller distances, the luminosity of these sources would still be close to or in excess of the Eddington luminosity for an accreting neutron star (~2×10^{38}erg s^{-1}). Since at least some of them are indeed single emitting objects, this would suggest that these sources are close binary systems, with a neutron star or possibly a massive black hole as the compact accreting object.

The contributions to the total X-ray luminosity of these galaxies from the extremely bright sources is in general lower than the contribution of lower luminosity objects, with the possible exception of NGC 253 and of the LMC (Fabbiano and Trinchieri, 1986). This component is seen as a low surface brightness, extended emission from the plane. By analogy with the Galaxy and M31, we expect that individual sources, in particular X-ray binaries in the luminosity range 10^{37}-10^{38} erg s^{-1}, dominate this component. Support to this comes also from the spectral signature of the integrated X-ray emission, on average well represented by a thermal bremsstrahlung with typical temperatures above 2 kev and no intrinsic low energy cut-off above the absorption along the line of sight. These spectra are consistent with a population of binary systems dominating the emission (SNR have typically a more complex spectrum with a softer component). By studying the radial distribution of this component, we can therefore study the distribution of the X-ray binary source component in other galaxies.

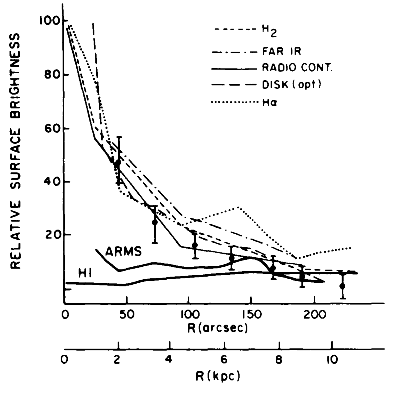

Figure 4: Comparison between the X-ray, Hα, blue light (disk and arms), far-infrared, neutral hydrogen, molecular hydrogen and 21 cm radio continuum surface brightness profiles in M51. X-ray points for R<2kpc are off scale. All curves are arbitrarily normalized.

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The spatial distribution of the X-ray emission is remarkably similar to the optical one. In the two best studied cases, M83 (see Trinchieri, Fabbiano and Palumbo, 1985) and M51 (see Figure 4 , from Palumbo et al., 1985), the X-ray and optical radial profiles are consistent with each other out to the last observed point, with the exception of a relative excess X-ray emission in the inner ~ 2 kpc. In NGC 6946 (Figure 5, from Fabbiano and Trinchieri, 1986), the relative increase in the X-ray emission in the inner region is larger and is observed on a larger scale than in the previous examples (Fabbiano and Trinchieri, 1986); however, the presence of a source associated with the starbust nucleus, indistinguishable from the emission from the inner disk, could be responsible for at least part of this phenomenon.

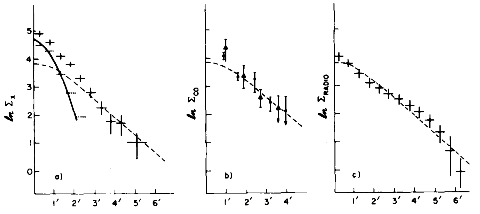

Figure 5: The radial distribution of the emission of NGC 6946 at different wavelengths. The dashed line common to all three figures shows the optical (B-band) profile: a) The crosses represent the X-ray data; b) CO data; c) radio continuum emission. All data are at the same resolution of ~ 1' (from Fabbiano and Trinchieri, 1986).

The X-ray sources are distributed like the exponential disk, rather than the much flatter distribution of the light from the arms or of the neutral hydrogen HI (see M51, Figure 4), although a contribution from the massive binaries associated with the spiral arm population is allowed by the data. This result suggests that the majority of the X-ray binary systems are related to the older (~ 10^9 yr) Population I disk component, rather than to the extremely young (~ 10^7 yr) Population I stellar component of the spiral arms. The relative excess X-ray emission in the inner disk is observed in a region comparable in extent to the "Galactic Bulge" region of the Milky Way. This X-ray excess could be indicative of the presence of a similar population of low mass binary sources, which have on average a higher X-ray luminosity than more massive sources. However these would probably not be associated with the "spheroidal bulge" region (in M83 for example it extends only for $r < 500$ pc) but with a region of the inner disk.

The above results suggest that a significant fraction of the X-ray binary sources in these galaxies are low mass disk systems. This is certainly a new result that has bearing upon the theories for the formation and evolution of low mass binary systems in our own galaxy as well, since the Milky Way is morphologically similar to the above galaxies (Hodge, [1983] classifies it a Sbc or Sc galaxy). A substantial fraction of low mass binary sources could therefore originate from the evolution of disk systems (Fabbiano and Trinchieri, 1985; Fabbiano, 1985).

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STATISTICAL RESULTS

In order to analyze a larger number of normal galaxies, we can study the average properties of a representative sample and compare the integrated luminosities of the sample objects at different wavelengths. The results are shown in Figure 6 and can be summarized as follows (see Fabbiano and Trinchieri, 1985, for details):

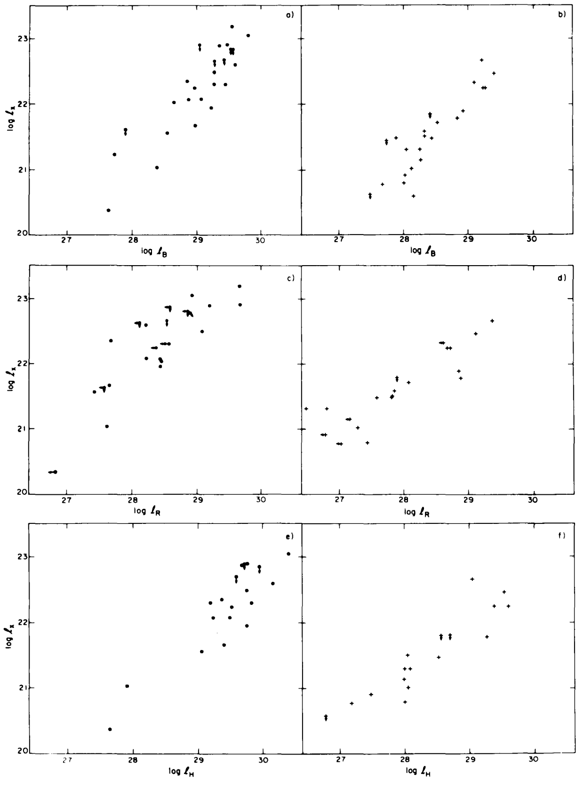

Figure 6: Plot of the total X-ray luminosity (ℓ_X) versus the optical (ℓ_B), radio continuum (ℓ_R) and near infrared (ℓ_H) luminosities for a sample of normal spiral and irregular galaxies (from Fabbiano and Trinchieri, 1985).

- There is a very tight, linear correlation between the X-ray and the optical (blue band) luminosity of spirals of all morphological types. The X-ray luminosity also correlates with the near-IR luminosity (H band). The slope of the correlation is ~0.7. However, this latter correlation is likely to be the result of stronger links between X-ray and B emission and B and H emission.

The number of X-ray sources scales linearly with the stellar population dominating the B-band light. This is a further indication of a strong association between the X-ray sources and the relatively young disk population, rather than with the galaxy mass and the old stellar component dominating in the near infrared.

- The X-ray and radio continuum emission are well correlated, with a dependence of the kind $\ell_X \propto \ell_R^{\sim 0.5-0.6}$. This correlation is statistically more significant than any of the correlations between radio continuum luminosity and optical or near-infrared luminosities or B-H colour.

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The close link between the X-ray and the radio emission is a new and rather puzzling result. The radio emission in spiral galaxies is the result of the interaction between the Cosmic Ray relativistic electrons and the galactic Magnetic Field (see for example the review by Ekers, 1980). If the X-ray emission is dominated by the contribution from low mass binary systems, the above result points to a close link between low mass binary sources and cosmic ray production (see Fabbiano and Trinchieri, 1985, for a more detailed discussion).

BINARY SYSTEMS IN EARLY TYPE GALAXIES

So far the discussion has focused on the binary systems in spiral galaxies. What do we know about this population in elliptical galaxies? Extended X-ray emission has been detected in many elliptical galaxies, but individual sources have not been seen (except possibly in M32, van Speybroeck and Bechtold, 1980). However, since elliptical galaxies and spiral bulges are similar in their properties, stellar population and colours, we can use the observations of M31 to derive an estimate of the expected X-ray binary population in early type galaxies, and compare the results with the observations (the details of how this estimate has been derived are in Trinchieri and Fabbiano, 1985). Figure 7 shows the results of this comparison: the line labelled L_{dscr} indicates the expected integrated X-ray luminosity due to binary systems as a function of the optical luminosity.

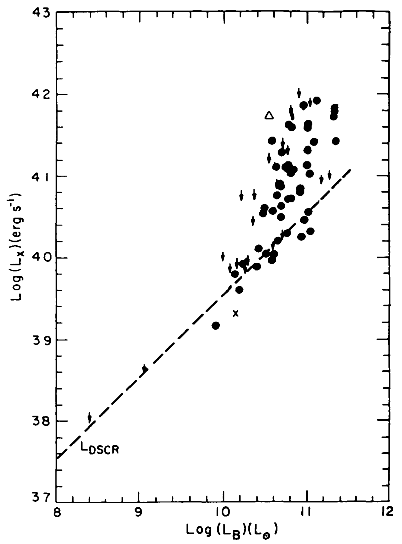

Figure 7: Plot of the total X-ray luminosity ℓ_X versus the optical (ℓ_B) luminosity for a sample of normal elliptical and SO galaxies (from Canizares, Fabbiano and Trinchieri, 1986).

It is clear that for the brightermost objects, the X-ray luminosities are well above the expected contribution from discrete sources. For these objects, the X-ray emission is due to the thermal emission from hot (~ 1 Kev) gas (see Forman, Jones and Tucker, 1985; Trinchieri and Fabbiano, 1985; Trinchieri, Fabbiano and Canizares, 1986; and references therein). However, for the low luminosity objects, the

X-ray emission could indeed be dominated by the integrated contribution of X-ray binary systems. Unfortunately, with the available data it is not possible to investigate further whether the discrete source component is indeed dominant in the low luminosity objects. More definitive conclusions will have to wait for new X-ray data from the planned future missions, such as the German X-ray satellite ROSAT and the AXAF project.

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DISCUSSION

E. van den Heuvel: Your results on M51 are extremely important. The fact that the X-ray source distribution scales with the stellar luminosity (which is dominated by the intermediate-age stellar population) indicates, as you point out, that the low-mass X-ray binaries dominate the X-ray luminosity also at larger distances from the center. This is very important for our understanding of the formation of millisecond binary radio pulsars in the outer regions of spiral galaxies like our own.

G. Trinchieri: Of course I agree. I should also point out that we are analyzing more data on a few other spiral galaxies in the hopes of providing theoreticians with more convincing examples of the above results.