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Chandra observations of nearby galaxies

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Abstract. We present the first results from observations of nearby galaxies with the *Chandra* X-ray observatory. We observed the prototypical star-forming galaxies M82 and the Antennae as well as two examples of composite starburst/AGN galaxies: NGC1808 and NGC6240. The observations of the first two were carried out with the ACIS-I and ACIS-S detectors respectively, whereas for the composite objects we used the HRC camera.

The first important result from these observations is that we witness a large number of discrete sources producing more than half of the hard X-ray emission in the star-forming galaxies. A significant number of these sources have luminosities ranging between $10^{38} - 10^{41}$erg/s, much larger than the Eddington luminosity of an $1M\odot$ neutron star. This means that if they are associated with X-ray binaries they must have a black hole with mass in the 10-1000$M\odot$ range. Indeed, as we find in the case of M82 most of these sources are variable which makes them candidates for this class of exotic objects. The rest of the hard X-ray emission is diffuse, most probably produced by thermal gas and unresolved sources.

In the case of the starburst/AGN composite galaxies we find that extended emission associated with circumnuclear star-formation has significant contribution to the total 0.1-10.0keV X-ray emission (up to 80%).

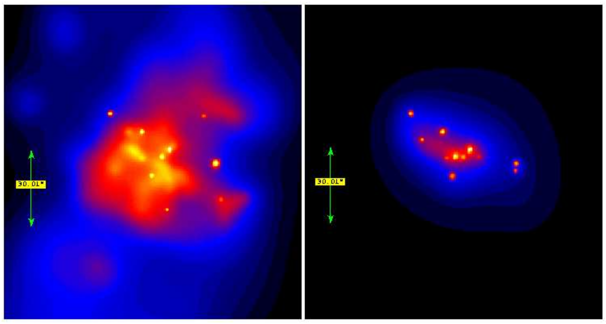

Fig. 1. An adaptivelly smoothed soft (0.5-2.5keV; left) and hard (2.5-10.0kev; right) ACIS-I image of M82. In this and all following images North is up and East is left.

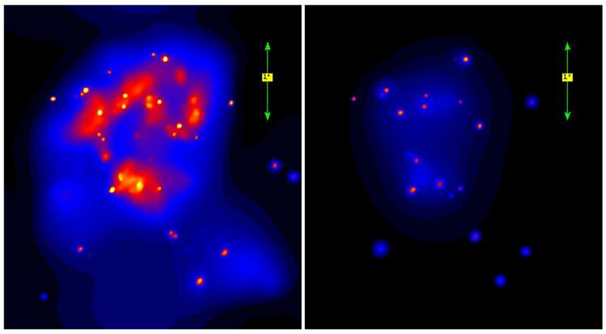

Fig. 2. An adaptivelly smoothed soft (0.1-2.5keV; left) and hard (2.5-10.0kev; right) ACIS-S image of the Antennae.

1. Introduction

X-ray imaging observations of galaxies over the past 10 years with the *Einstein*, ROSAT, ASCA and Beppo-SAX observatories, showed that the X-ray emission of star-forming/normal galaxies is very complex. It arises from at least two different components: discrete sources associated with supernova remnants (SNRs) and X-ray binaries and diffuse gas often in the form of a superwind (eg. Fabbiano 1989; Read *et al* , 1997; Ptak *et al* , 1999). However, the relatively poor spatial resolution of these missions hampered any attempt to quantify the contribution of each component and study their properties in detail. *Chandra* is revolutioning the field by providing X-ray images over a wide energy band, with an unprecedented spatial resolution. Here we present the first results from observations of two well studied star-forming galaxies (M82 and the Antennae) and two composite starburst/AGN galaxies (NGC1808 and NGC6240).

2. The star-forming galaxies: M82 and The Antennae

M82, the prototypical star-forming galaxy, is observed with ACIS-I for 15ks, as part of the *Chandra* GTO program. Previous observations with *Einstein* and ROSAT showed that the bulk of the soft X-ray emission is in the form of a galactic scale superwind (eg. Watson *et al* , 1984; Fabbiano 1988; Read *et al* 1997). ASCA and SAX showed that the hard X-rays are not as extended but a fraction of them may originate by thermal gas as well. Moreover, these observations showed that the hard X-ray emission is variable in timescales of a few months (Ptak & Griffiths 1998; Matsumoto & Tsuru 1998; Persic *et al* , 1999).

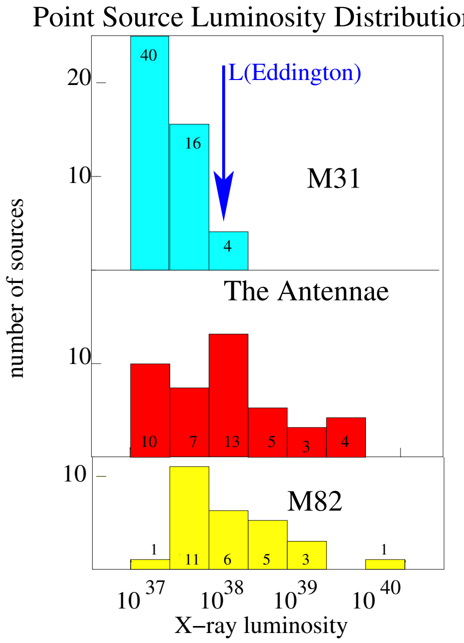

Fig. 3. The luminosity distribution of the discrete sources in M82 and the Antennae compared with that of M31. The Eddington luminosity for accretion onto an 1M⊙ compact object is indicated.

The Antennae are the prototypical example of merging galaxies. They were observed with ACIS-S for 75ks as part of the *Chandra* GTO program as well. Previous observations with *Einstein* and ROSAT showed that their soft X-ray emission is extended and mostly associated with the bodies of the merging galaxies (Fabbiano & Trinchieri 1983; Read *et al* , 1995; Fabbiano *et al* , 1997). ASCA observations showed that there is a significant extended hard component well fit either by a power-law or a thermal plasma model (Sansom *et al* , 1996).

Both the soft and the hard X-ray emission in M82 and the Antennae, as observed with *Chandra* ACIS, are clearly extended (figs 1,2). However, the most striking result is the very large number of individual sources found.

These sources account for 10% of the soft (0.3-2.5keV) and 50% of the hard (2.5-10keV) X-ray emission in M82. In the case of the Antennae, their contribution is 35% and 80% of the total emission in the soft and hard band respectively. The luminosity of the discrete sources ranges from $\sim 10^{37} - 10^{41}$erg/s with a significant number of them being above 10^{38} erg/s, in contrast to what we see in normal galaxies like M31 (fig 3). Some of the individual sources of M82 show variability up to a factor of 7 on timescales of a few months (fig 4), suggesting that they are associated

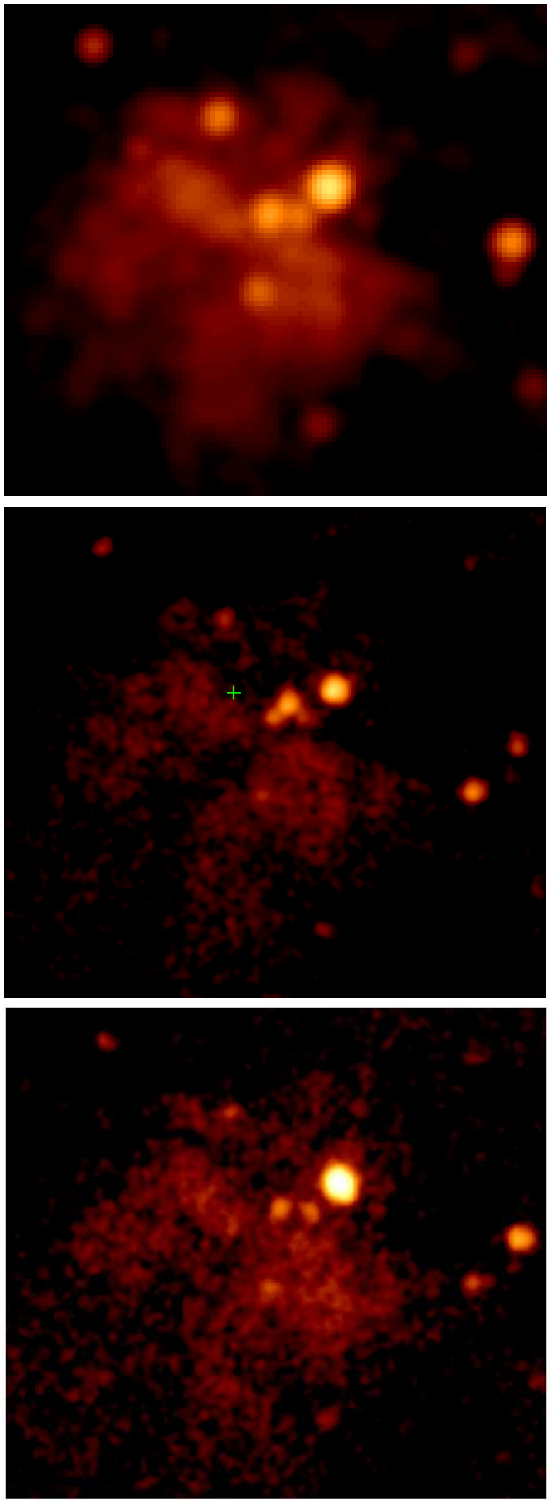

Fig. 4. The central (0.9″ x 0.9″) region of M82 as observed in September 1999 (left), October 1999 (middle) and January 2000 (right). The three images are on the same spatial scale. The two first images share the same color-map, whereas in the third one the color-map is stretched in order to show the fainter sources. The cross in the second image marks the dynamical center of the galaxy.

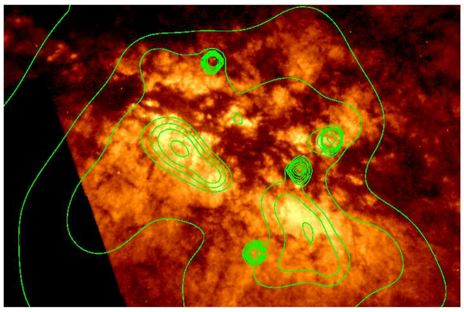

Fig. 5. An Hα HST WFPC2 observation of the nuclear region of M82 with overlaid soft X-ray contours.

with X-ray binaries (Zezas *et al* 2000, in preparation). A surprising result is that only 4 out of 16 X-ray sources detected in the central 0.5×1.0kpc of M82 are coincident with radio sources (fig 7), suggesting that there are SNRs at different evolutionary stages. A similar discrepancy is found between the radio and FeII sources (Alonso-Herrero - private communication). In the case of the Antennae we observe a larger number of ultra-luminous sources but at this point we cannot securely classify them as X-ray binaries as we lack variability information although the spectra of most of them are similar to the spectra of galactic black-hole binaries (Fabbiano *et al* , 2000; Zezas *et al* in preparation).

The luminosity of these sources exceeds by a factor of 10-100 the Eddington luminosity for accretion onto an 1M$\odot$ neutron star. This means that if they are associated with X-ray binaries they are candidates for intermediate mass black-holes X-ray binaries with compact objects in the mass range 10-1000M$\odot$. Although a few such candidates were found in the past (eg. Fabbiano 1989; Marston *et al* , 1995; Fabbiano *et al* , 1997; Zezas *et al* , 1999; Matsumoto *et al* , 1999; Ptak *et al* 1999; Makishima *et al* 2000) it is with *Chandra* that we can detect them in such large numbers and we can study their properties in detail. An alternative to the intermediate mass black hole scenario, is that these sources are beamed and therefore their actual luminosity in much lower. However, the large number of ultraluminous sources observed, make this possibility unlikely.

The diffuse emission of M82 and the Antennae is mainly soft and extended. Several regions with enhanced emission are associated with star-clusters and gas-bubbles found in Hα maps (figs 5,6). Also the general outline of the X-ray emission follows the optical emission very well. In the case of M82 whereas the soft X-ray emission follows very well the Hα emission, the hard X-rays trace the Paα emission better (fig 7). This could be due to an obscuration effect. The origin of the hard X-ray emission is still uncertain, but the good spatial correlation with the Paα emission and the previous detection of an Fe-K line (Ptak etal, 1999, Persic etal, 1999) favors a thermal gas

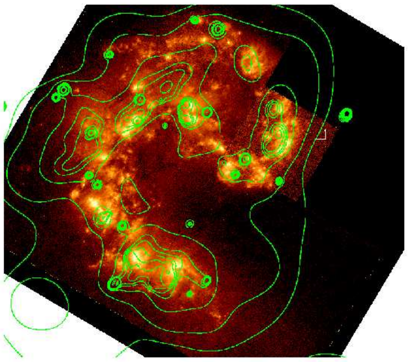

Fig. 6. An Hα HST WFPC2 observation of the Antennae with overlaid soft X-ray contours.

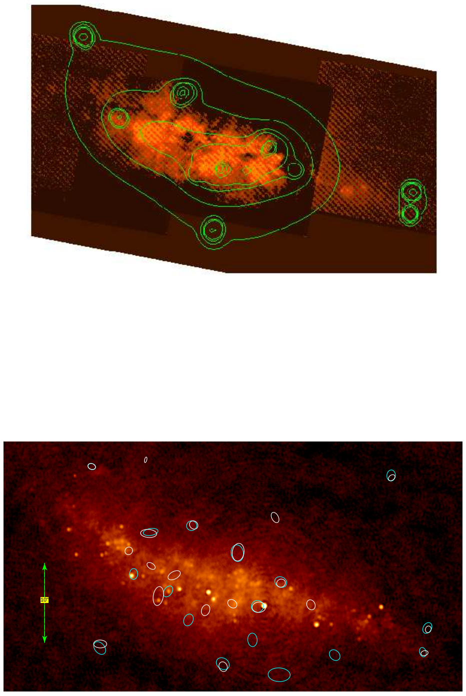

Fig. 7. An HST NICMOS Paα observation of M82 with hard X-ray contours overlaid (top). A MERLIN radio image of M82 with the soft (1-2.5keV) X-ray sources marked as white ellipses and the ultra-soft sources (0.5-2.5keV) marked as blue ellipses (bottom). The ellipse size indicates the positional uncertainty of the X-ray sources.

origin although some contribution from inverse Compton scattering is not ruled out.

3. The Composite galaxies : NGC1808 and NGC6240

Observations of the starburst/AGN composite galaxies NGC1808 and NGC6240 with the HRC, as part of the *Chandra* GTO program, show a similar picture. In the case of NGC1808 (fig 8a) which is the closer of the two, a point-like source with a luminosity of 1.2×10^{39} erg/s is coincident with the nucleus. Two other sources produce 10% of the total emission and are coincident with HII regions in the circumnuclear starburst. These sources which have a luminosity of 1.1×10^{39} erg/s, are embedded in diffuse emission most probably due to unresolved sources and gas heated by the numerous supernovae in the starforming region. In contrast, the X-ray emission of NGC6240 (fig 8b) is mainly diffuse and no prominent sources are resolved. In the nuclear region we only detect some diffuse emission with a luminosity of 2.4×10^{41} erg/s (10% of the total emission). The absence of a strong nuclear source is consistent with ASCA and BeppoSAX result which showed that it hosts a highly highly obscured AGN (Iwasawa & Comastri, 1998; Vignati *et al* , 1999). From the comparison between Hα and the X-ray images, is clear that there is a striking similarity in the morphology of the emission in the two bands. The most interesting feature is the arc at the north-west of the nucleus with a luminosity of 1.7×10^{41} erg/s which is most probably associated with shock heated gas associated with an outflow.

4. Summary

We have presented the results of a study of two starforming galaxies (M82 and the Antennae) and two composite starburst/AGN galaxies (NGC1808 and NGC6240) with the *Chandra* observatory. In all cases the X-ray emission is clearly extended and for the most nearby objects resolved down to individual sources. A significant number of these sources have much higher X-ray luminosities than sources found in normal galaxies. If these sources are X-ray binaries their compact objects must have masses $\sim 10-100M\odot$, and some indeed show significant variability on timescales of a few months clearly suggesting that they are X-ray binaries. In the case of NGC1808 and NGC6240 the overall X-ray emission is not dominated by the AGN present in these objects but by a diffuse component spatially coincident with HII regions, most probably associated with circumnuclear star-formation.

5. Acknowledgments

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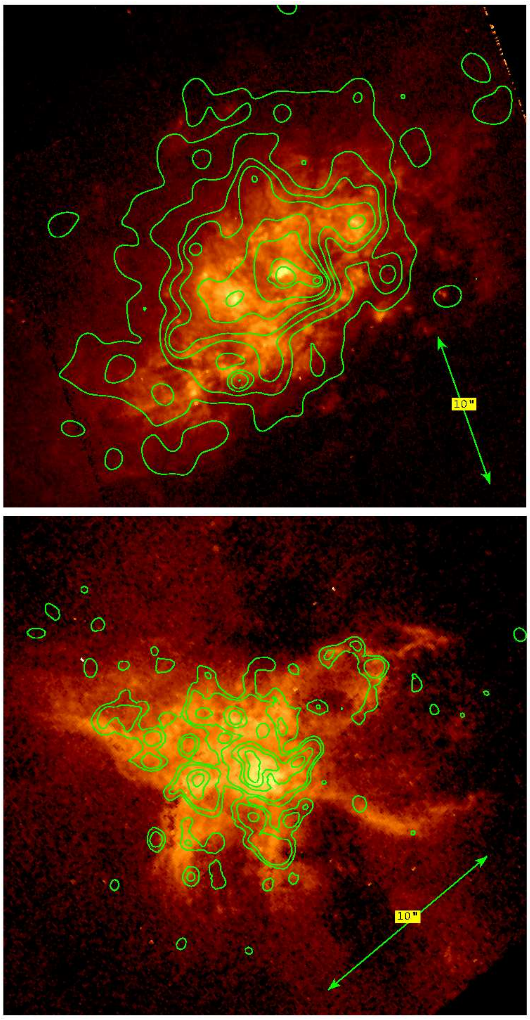

Fig. 8. HST WFPC2 Hα images of NGC1808 (top) and NGC6240 (bottom) with overlaid *Chandra* HRC contours.

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