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Diffuse X-ray Emission from Galaxies

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Abstract. I review here the current ideas regarding the origin, evolution, and physical nature of hot diffuse gas in normal, starburst, interacting and merging galaxies, using recent X-ray observations with XMM-Newton and Chandra. Many types of diffuse X-ray structures, including winds, bubbles, halos, chimneys and fountains, can be formed in galaxies, and can enrich the intergalactic medium with mass, energy and metals. This has profound implications as regards galactic formation and evolution, and the enrichment and evolution of galaxy groups and clusters.

Keywords. ISM: general, ISM: jets and outflows, galaxies: general, galaxies: interactions, galaxies: ISM, galaxies: starburst, X-rays: galaxies, X-rays: ISM.

1. Introduction

Spiral galaxies undergoing moderate to high (starburst) levels of star-formation can become complex, multi-phased objects, and the diffuse thermal emission from 10^6–10^8 K gas is a very important probe of the conditions within the halos of these star-forming galaxies. If the star-formation is of a high enough level, then the most dramatic of diffuse X-ray emission structures can be formed − superwinds.

In the standard model for galactic superwinds driven by multiple ($\sim 10^6$) supernovae, the merged, metal-enriched SN ejecta are expected to have a central starburst temperature of $\sim 10^8$ K (and are hence a source of faint hard thermal X-rays). The warm neutral and ionized gas in superwinds is seen to have velocities of between 200−1000 km s^{-1} (Heckman *et al.* 2000), and this material is believed to be embedded within or at the boundaries of a hot metal-enriched, wind fluid, with an even higher velocity (Strickland & Stevens 2000). Various processes, such as strong shocks ($T \sim 3.5 \times 10^6 [v_{Shock}/500\,\mathrm{km\,s^{-1}}]^2$) or thermal conduction at interfaces between the warm gas and the hot wind fluid, are able to create soft ($E < 2$ keV) thermal X-ray emission.

Diffuse thermal X-ray emission from galaxies is a mixture of continuum (bremsstrahlung and recombination) and line emission. For low-temperature thermal plasmas, the net emission is dominated by line emission for $Z > Z_{\odot}$. Because newly-synthesized metals are believed to enter the hot phases of the ISM, X-ray observations are critical in seeing the processes of galactic chemical evolution and IGM enrichment at work.

In the following sections, I shall review the recent Chandra and XMM-Newton X-ray observations of the diffuse gas in normal, starburst, and interacting/merging galaxies, i.e. attaining higher and higher levels of star-formation activity.

2. Normal Galaxies

Normal spiral galaxies, like our own, typically exhibit only low levels of diffuse emission. Typically, the emission can be described using two very soft low-metallicity thermal plasmas. Only in the most star-forming normal galaxies is diffuse emission seen to rise significantly above the galactic plane, in the form of hot coronae − very few significant

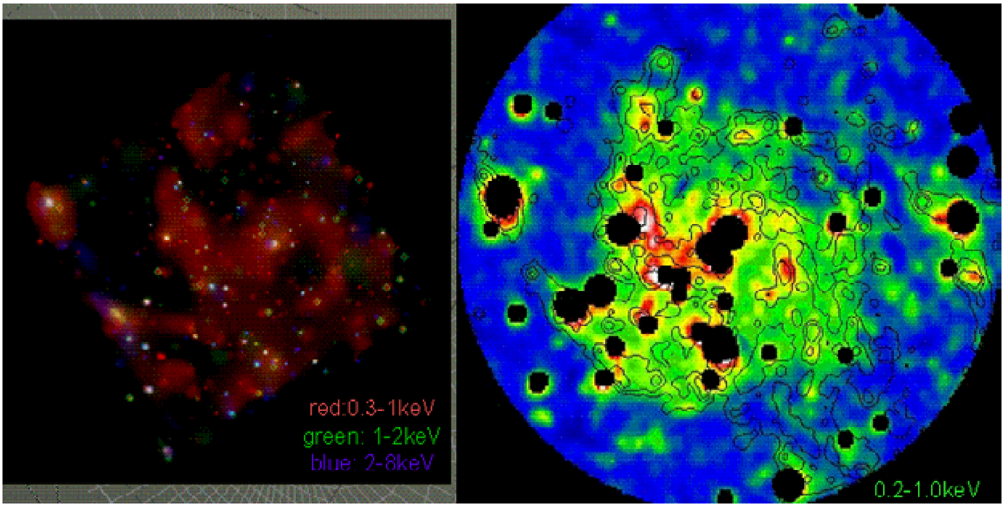

Figure 1. Diffuse X-rays from M101: (left) Chandra: Red 0.3−1 keV, green 1−2 keV, blue 2−8 keV (di Stefano & Kong 2004) (right) XMM-Newton: 0.2−1 keV with contours of GALEX UV emission (Warwick *et al.* 2005).

outflows, winds or superwinds are seen, and there is very little mass, energy or metal losses from these systems via hot diffuse gas.

Our nearest large neighbour, M31, is seen by XMM-Newton to have what appears to be genuinely diffuse gas only at the very centre of the galaxy (Shirey *et al.* 2001). Chandra is able to resolve out some of this emission into discrete sources (Garcia *et al.* 2001), but a small amount of genuine diffuse hot gas remains. Much more diffuse emission is seen in the more active normal galaxies. M101 for instance shows a lot of diffuse emission associated with the star-forming regions in its spiral arms (see Fig. 1). The correlation between the diffuse X-ray emission and the spiral arms is rather striking.

It is worth stressing at this point that the spectral analysis of soft diffuse X-ray features that cover a significant portion of any X-ray detector is prone to difficulties, in that it is essential that the background must be modelled as correctly as possible. There are many methods to do this, and some may be better than others, depending on the instrument, the type of data, the source, and the science attempted, to name but a few factors. Essentially though the problem is that extracted spectra contain vignetted photon background and non-vignetted particle background. Hence the source (diffuse) spectrum will have a rather different photon-to-particle background mix than the actual extracted background spectrum (taken from a very different part of the X-ray detector, away from the diffuse emission source). A way to correct for this is to use pure particle spectra, extracted from regions of the detector out of the field of view, and use the areas of the various extraction regions, as performed on the M101 EPIC data in Warwick *et al.* (2005). Here, using such a method, the spectral parameters for M101's diffuse emission are seen to be identical to those obtained by Chandra (Kuntz *et al.* 2003). The emission is described by two very soft low-metallicity thermal plasmas ($kT = 0.2$ & 0.65 keV), and such a result is typical of many normal galaxies (e.g. NGC300, Carpano *et al.* 2005).

3. Starburst Galaxies

Though there is a continuous distribution in galaxy star-formation activity, starburst galaxies are here defined using the widely-used IRAS $60\mu m$ to $100\mu m$ flux ratio

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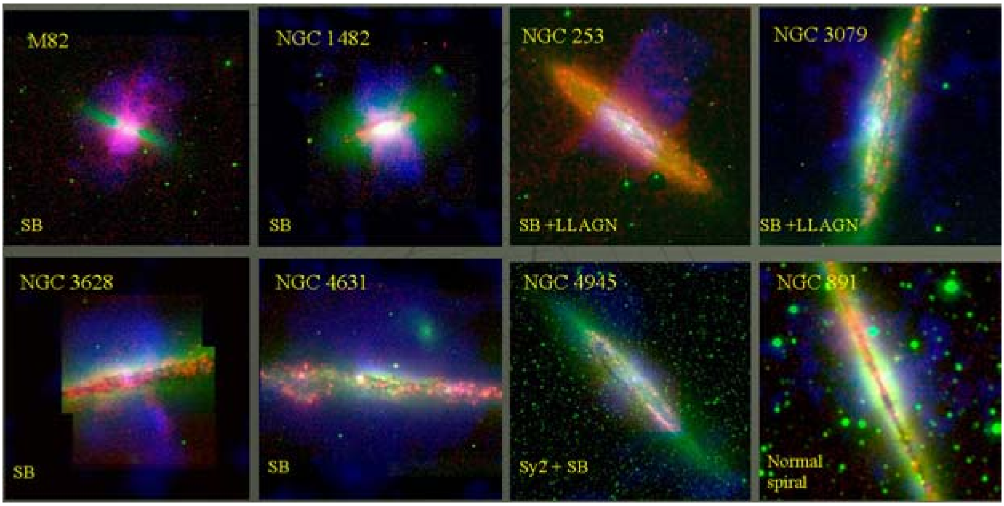

Figure 2. 8 Galaxies from a Chandra survey of superwinds (Strickland *et al.* 2004a,b): Green – optical R-band (stars), red – optical Hα emission (gas at T$\sim 10^4$ K), blue – Chandra 0.3$-$2 keV X-ray emission (gas at T$\sim 5 \times 10^6$ K), heavily smoothed.

$f_{60}/f_{100} > 0.4$. These more active, star-forming galaxies exhibit greater levels of diffuse emission than normal galaxies. The gas is hotter and exists not only in the form of coronae and halos, but also as outflows – superwinds. Consequently starburst galaxies can lose significant amounts of mass, energy and metals to the IGM.

A superwind starts in the nucleus of a galaxy some $\sim$40 Myr after a strong star-forming episode, when the high-pressure, high-temperature gas of some $\sim 10^6$ merged SN ejecta expands, and breaks out along the poles of the galaxy into the halo at $v \sim 1000$'s of km s^{-1}. On the way it entrains and accelerates cool dense, ambient gas from the galactic disk and halo, and it is this shocked gas that is believed to give rise to the soft X-rays, and the optical Hα emission. Possibly the wind fluid and the entrained gas is then able to escape the galaxy halo into the IGM. Superwinds are very important as regards galactic evolution and chemical evolution, mass-loss from galaxies, the metal enrichment of the IGM in clusters of galaxies (this is perhaps very important at high redshift from small galaxies) and energy injection into galaxy clusters.

Because of their small mass, dwarf galaxies are more susceptible to 'blow-outs' of the ISM, such as superwinds. Having said this however, it is not just the galaxy mass that comes into play here – the disk and halo parameters are poorly known and could play a very fundamental role (Strickland *et al.* 2004b). X-ray observations of dwarf galaxies (e.g. NGC1569; Martin *et al.* 2002) show low-temperature (0.3 keV), enhanced O/Fe abundance (2$-$4 times solar) outflows, carrying nearly all the metals ejected by the starburst. Most of the X-ray emitting material is thought to be entrained ISM.

Extra-planar soft diffuse thermal emission is seen in many starburst galaxies (Strickland *et al.* 2004a,b), as can be seen in Fig. 2. Thought to be *the* prototypical starburst galaxy, M82 has been observed several times in X-rays. It is close (D=3.6 Mpc), very IR bright and its starburst is triggered by the interaction with its neighbour, M81. Its superwind is visible in Hα and in X-rays (Stevens *et al.* 2003), extending some $\sim$14 kpc out of the plane of the galaxy. Various features are seen in the XMM-Newton view of the superwind, including a Hα 'cap' at the edge of the wind (thought to be an interaction of the superwind with an ionized cloud), an X-ray bridge connecting to this, and bright and dark lanes within the wind. The central region of the wind is hot, fitted with

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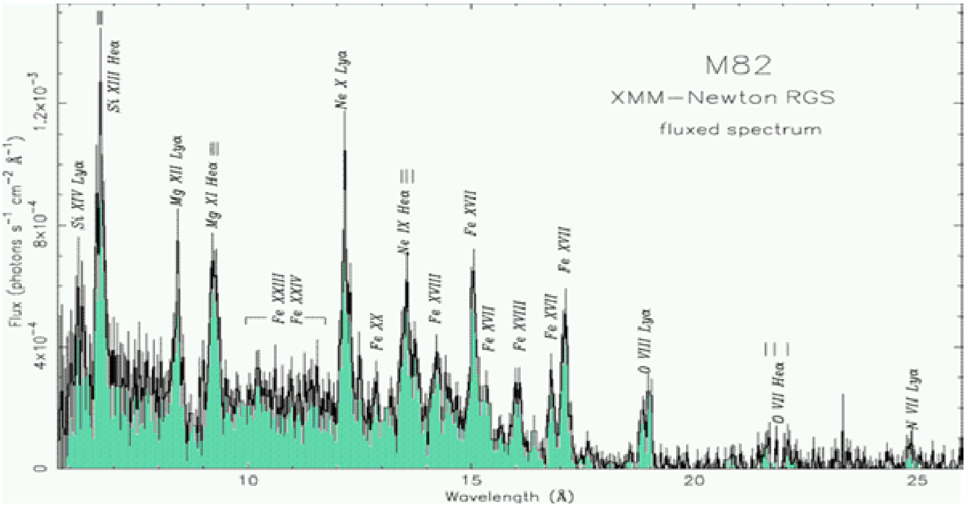

Figure 3. The fluxed RGS spectrum (RGS 1 & 2, order 1) of the M82 starburst. Bright emission lines (both hydrogen-like and helium-like triples) are indicated (Read & Stevens 2002).

a two-temperature (0.54 & 0.9 keV) model, while further out, the wind is cooler (0.37 & 0.54 keV). Furthermore there appears to be a HI hole associated with the superwind breakout, and an excess of HI associated with the dark lanes in the superwind (Stevens *et al.* 2003).

The XMM-Newton RGS observation of the M82 starburst (Read & Stevens 2002) yields the deepest high-resolution X-ray spectrum of a starburst galaxy (Fig. 3). Here, line broadening is seen due to the extended nature of the starburst wind. A complex array of lines is seen, including Lyman α emission from low-Z elements (N, O, Ne, Mg, Si), plus helium-like ions and the Fe-L series. The OVII line triplet can be resolved and is seen to be consistent with hot gas in collisional ionization equilibrium. A differential emission measure model fit to the data results in gas over a range of temperatures (0.2−1.6 keV).

M82 is also the galaxy in which we believe we have seen the first direct evidence of hard diffuse X-ray emission from a starburst galaxy. Old claims of diffuse hard X-rays from galaxies have now been proved to be incorrect, the emission just being due to unresolved point sources. New Chandra observations however show a few starbursts with possible genuine diffuse hard X-ray emission in the nuclear starburst region; M82, NGC 253, NGC 2146 (Strickland *et al.* 2003). Likely causes of this emission could be fluorescence or scattered AGN light from a LLAGN, or non-thermal (e.g. inverse Compton) or thermal (merged SN ejecta − the superwind) emission from the starburst. As M82 has no LLAGN, the first meaningful detection of diffuse hard (2−8 keV) emission in this starburst, using the damaged ACIS-I (Griffiths *et al.* 2000), may be the first direct detection of the wind fluid itself.

In their Chandra survey of superwinds, Strickland *et al.* (2004a,b) analysed many edge-on starburst and normal galaxies, including M82, NGC1482, NGC253, NGC3628, NGC3079, NGC4945, NGC4631, NGC891 and NGC6503. They found extended extraplanar emission in 80% of their sample, and the X-ray surface brightness is seen to be best fit with an exponential of scale height ∼2–4 kpc. Further, it is seen that the extent of the diffuse X-ray emission scales with the size of the host galaxy. The Chandra spectra are best fit using two-temperature models with enhanced α-to-iron abundance ratios. The diffuse X-ray luminosity is proportional to the mechanical energy input from the stellar component, but the mass and energy estimates are strongly dependent on the (poorly

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constrained) X-ray filling factor (the fraction of the volume that is occupied by emitting gas). There is also evidence of a threshold in star-formation rate per unit surface area, before blow-out from the disk can occur, and evidence of nuclear processed material being swept out of these galaxies, and the entrained ISM being driven out as well.

As regards soft X-ray emission from superwinds, the current synopsis is that genuine spatial structure is seen in the X-ray, on scales similar to the structure in Hα. The best interpretation is that the X-rays are due to limb-brightening on small and large scales: There are kpc-scale nuclear outflow cones observed, where the soft X-rays and Hα are correlated on 10−20 pc scales, and there is 10 kpc-scale extraplanar emission, where there is correlation on $\sim$1 kpc scales. Furthermore the soft X-rays and the Hα are well correlated in flux. The high alpha-element/iron abundance ratios indicate that the X-ray emitting material is either metal-enriched or dusty. It is now thought (Strickland *et al.* 2004a,b) that a superwind is not a volume-filling wind of the kind modelled by Suchkov *et al.* (1996). The majority of the emission must come from relatively low filling factor (0.01−0.3) material. This low volume filling factor indicates that the visible X-rays are not representative of the full energy and volume of the wind. The soft X-ray emission arises in fact from the interaction of the wind with the galaxy ISM (disk and halo), and possible physical origins include: high-velocity shocks in clouds, or ambient disk or halo gas along the wind walls; conductively-evaporated layers around the clouds or walls; stand-off (reverse) shocks in the wind, i.e. compressed, enriched wind-fluid.

4. Interacting and Merging Galaxies

Interacting and merging galaxies, due to their rapidly changing environments, can reach very large star-formation rates, and very powerful starbursts and starburst-driven superwinds are observed. These galaxies can attain levels of diffuse emission greater even than in the classic starburst galaxies. Very large outflows and extensions are seen − both superwinds and possibly other more exotic structures − and it appears that very significant mass, energy and metal losses may be occurring.

The Mice, for instance, are a pair of spiral galaxies at an early stage of merging. Chandra observations (Read 2003) show starburst-driven galactic winds, similar to, though not yet of the size of the M82 wind, outflowing along the minor axes of both galaxies. That such a phenomenon can occur in such a rapidly evolving and turbulent system is surprising, and this is first time that the very beginning of starburst-driven hot gaseous outflow in a full-blown disk-disk merger has been seen. Other interacting galaxies show more peculiar phenomena. NGC520 for instance (Read 2005), shows what appears to be a starburst-driven galactic wind outflowing perpendicularly to only one of the nuclei − nothing is seen emanating from the second nucleus. This is thought due to the fact that NGC520 is believed to be the result of an encounter between a gas-rich and a gas-poor disk.

It is when the interacting galaxies come close to merging that very violent starbursts take place, and very large and unusual diffuse emission structures are seen. In the Antennae, one of the closest and best known very active merging pairs, a long 411 ks Chandra observation (Fabbiano *et al.* 2004) has revealed the presence of both extensive hot diffuse X-ray emission associated with the galactic disks, and what appears to be large (10 kpc) off-galaxy diffuse loops to the south (see Fig. 4). The diffuse emission within the galactic disks is seen to vary very considerably from region to region − some diffuse emission regions are best described by low-temperature, sub-solar abundance plasmas, while others require higher abundances, or additional strong power-law components, or very high abundances indeed. Results consistent with ASCA (where $\sim$0.2 solar abundances were

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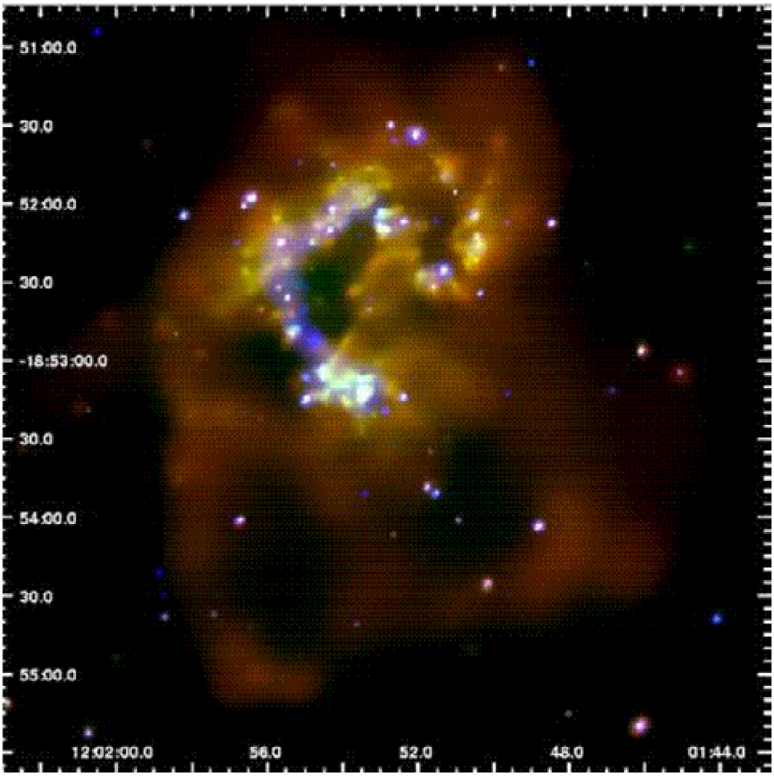

Figure 4. Chandra diffuse X-ray emission from the Antennae merging galaxy pair (Fabbiano *et al.* 2004): red 0.3−0.65 keV, green 0.65−1.5 keV, blue 1.5−6 keV. Two large loop/bubbles are seen to the south, lying outside of the optical disks and the HI tails.

found; Sansom *et al.* 1996) can be obtained if the entire integrated emission is fitted. Such apparent low abundances had been a common and puzzling feature of starburst X-ray spectra. In the Antennae at least, and by extension, perhaps in other starbursts as well, this is evidently a spatial resolution problem, and strong and variable line emission exists within different regions of the hot ISM, even after thorough point-source subtraction.

The large 10 kpc diffuse loops visible to the south of the Antennae are especially interesting. Not due to an artifact of any adaptive smoothing techniques, they lie outside of the optical disks and outside of the huge HI tidal tails, and resemble giant loops or bubbles. A radial profile of the soft band emission shows that there is significant hot gas extending even beyond these X-ray loop/bubbles. While this very extended gas is seen to be at ∼0.2 keV, the loops/bubbles are seen to be at ∼0.3–0.35 keV (both inside of, and in the rim of, each bubble). Can they be starburst-blown bubbles? Each bubble appears to have $L_X \sim 5 \times 10^{39}$ erg s^{-1} and contains $\sim 10^8\,\mathrm{M}_\odot$ of gas. The cooling time of the gas (∼1 Gyr) is some ten times longer than the merger timescale, and the thermal energy contained within each bubble is around 1.5×10^{56} erg, equivalent to ∼15,000 supernovae. As the supernova rate is $\sim 0.3\,\mathrm{yr}^{-1}$, then there is certainly plenty of energy that is potentially available to power these bubbles. However, since the two bubbles are of the same size, they might seem to require two simultaneous events. Furthermore, the entropy ($\propto T/n_{\mathrm{e}}^{2/3}$) of the gas into which the bubbles are expanding appears to be *higher* than that in the bubble rims. This does not sit well with the idea that the emission at

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the bubble rims is due to shocks sweeping out into the surrounding halo gas (Ponman *et al.* 2005).

As a final thought regarding merging galaxies, it is very intriguing that similar bubble features are seen in Arp220 (McDowell *et al.* 2003), an extremely bright, active merging galaxy pair, whose nuclei are the point of colliding (i.e. at an evolutionary stage slightly later than the Antennae). It may even be that two double-bubbles are seen in diffuse X-rays within this system, and that therefore something rather unexpected may be occurring in merging galaxies. The evolution of the diffuse X-ray emission in merging galaxies is investigated more fully in Brassington *et al.* (2005).

5. Final Remarks

The best examples of normal galaxies, of dwarf and disk starbursts, and of interacting and merging galaxies have now been observed with XMM-Newton and Chandra, and we are steadily building up larger and large samples of each of these galaxy types. Although not discussed in this review, the same is also true of elliptical galaxies, of which there are now many examples. In order to study the diffuse emission correctly in external galaxies, it certainly seems the case that detailed studies can still only be performed on the closest, brightest objects. High spatial resolution is needed to disentangle the point sources from the diffuse emission in galaxies. Of great importance also, especially considering the relatively low temperature (0.3−1.0 keV) of diffuse gas in galaxies, is to model and subtract the background as correctly as possible, and complex methods can be necessary to do this. Though we have gained many insights into the feedback processes from these X-ray observations, uncertainties do remain. It may have been that Astro-E2 would have been helpful for some of the bright starbursts − indeed, it would have perhaps been able to probe the velocities of the X-ray emitting gas, were it not for the XRS failure. Though a dark age may loom, in that XEUS et al. are perhaps still a long way off, their time is getting closer, and both Chandra and XMM-Newton have performed splendidly so far, and hopefully, will do for years to come.

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Discussion

Ward: What is the mass of the hot gas in the superwinds of M82 and NGC253, and what is the ratio of this to the HI?

Read: For M82, the EPIC observations yield values of 1.5 and $1.7 \times 10^7 \eta^{1/2}\,\mathrm{M}_\odot$ for the hot gas mass in the nuclear and inner wind regions respectively. Approximate estimates of the hot gas masses in the entire X-ray superwinds range from 2.5 (NGC253) to 5.5 (M82) $\times\, 10^8 \eta^{1/2}\,\mathrm{M}_\odot$. This is ~10% of the HI mass.

Völk: Regarding outflow velocities from starburst galaxies, your problem with the soft X-ray gas not being representative might be resolved by comparing the synchrotron morphology with wind models to obtain the flow velocity. For NGC253, this gives ~900 km s^{-1} (see arXiv:astro-ph/0509248). Do you agree?

Read: Certainly, it is believed from theory and simulations that the flow velocity of the hot wind fluid is somewhere close to this value, or possibly higher. As synchrotron halos have now been discovered in a number of starburst galaxies (e.g. NGC253, NGC4631), this new insight on starburst winds is very much worth pursuing further.

Courvoisier: How do your results bear on the question of the emission of the iron that is observed in the intracluster gas?

Read: Results so far suggest that, for the outflowing or off-galaxy components of the diffuse emission, the metallicity appears to be very low (~0.2 solar). We may however be seeing a similar effect to that discussed in the context of the brighter central diffuse regions of the Antennae, whereby, only when we have sufficient spatial resolution and effective area are we able to detect high-metallicity regions within these low surface brightness diffuse emission features.

Meurs: The harder part of the X-ray emission from galaxies is often being used as a rather safe indicator of the SFR, since the diffuse emission is not expected to influence the results very much. You mentioned a few cases of diffuse emission extending into the hard X-ray region. Could this affect such SFR estimates?

Read: Not really, as, even in the very few galaxies where hard diffuse emission is perhaps detected, the hard X-ray emission is still very much dominated by the point source (compact object) population (XRBs LLAGN etc.).

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