DIFFUSE THERMAL EMISSION FROM VERY HOT GAS IN STAR-BURST GALAXIES: SPATIAL RESULTS

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ABSTRACT

New \textit{BeppoSAX} observations of the nearby prototypical starburst galaxies NGC 253 and M82 are presented. A companion paper (Cappi et al. 1998) shows that the hard (2-10 keV) spectrum of both galaxies, extracted from the source central regions, is best described by a thermal emission model with $kT \sim 6$–9 keV and abundances $\sim 0.1$–0.3 solar. The spatial analysis yields clear evidence that this emission is extended in NGC 253, and possibly also in M82. This quite clearly rules out a LLAGN as the main responsible for their hard X-ray emission. Significant contribution from point-sources (i.e. X-ray binaries (XRBs) and Supernovae Remnants (SNRs)) cannot be excluded; neither can we at present reliably estimate the level of Compton emission. However, we argue that such contributions shouldn’t affect our main conclusion, i.e., that the \textit{BeppoSAX} results show, altogether, compelling evidence for the existence of a very hot, metal-poor interstellar plasma in both galaxies.

PREVIOUS SPATIAL RESULTS

Evidence for complex galactic-scale outflows driven by starburst activity has been gathered in recent years based, primarily, on optical and soft ($\sim 0.1$–3 keV) X-ray observations (Fabbiano 1989 and ref. therein). These have sometimes been called “superbubbles” or “superwinds”, the latter referring to those manifestations where the extended hot gas emitting optical emission lines and soft X-rays was apparently ejected into the intergalactic medium (IGM). Because of the extinction of the optical emission (often almost completely reprocessed into IR emission), X-ray data provided the most direct view of the hot wind material. In general, spectroscopic studies confirmed or, at least, were consistent with thermal emission from a hot plasma, most likely shock-heated by supernovae (e.g. Dahlem, Weaver & Heckman 1998). The detailed physical characteristics of the gas (in particular its metal abundance), however, have remained unclear because the analysis in the soft X-ray band is complicated by the unknown line-of-sight extinction, the large uncertainties in theoretical models used (in particular around the Fe L-shell energy band), and the presence of multiple temperatures (typically with $kT$ between 0.2–3 keV).
At higher energies, the images available to date have been essentially limited to the ASCA observations of the two brightest starburst galaxies (SBGs), NGC 253 and M 82 (but see recent studies on star-forming dwarf galaxies by Della Ceca et al. 1996, 1997). ASCA resolved the 2–10 keV emission of NGC 253 (Ptak et al. 1997) but not from M 82 (Tsuru et al. 1997). However, the ASCA data did not allow adequate spatial analysis. From the ASCA spectral analysis, the hard components of both sources are well described by either a thermal model (kT \sim 6–9 keV), or a power-law model (\Gamma \sim 1.8–2.0). The absence in the data of a significant Fe-K line emission has, however, always been puzzling and has induced several authors to propose alternative explanations to the thermal emission, i.e. the presence of a low-luminosity active galactic nucleus (LLAGN) (Ptak et al. 1997, Tsuru et al. 1997), or non-thermal emission from Compton scattering of relativistic electrons by the intense FIR radiation field (Rephaeli et al. 1991, Moran & Lehnert 1997).

In a companion paper (Cappi et al. 1998), we have presented the BeppoSAX spectral results that clearly show the first evidence of Fe-K line emission (at \sim 6.7 keV) and high-energy rollover expected in the case of thermal emission for both NGC 253 and M 82 (see Persic et al. 1998 for more details on the results for NGC 253). Here we present preliminary results obtained from the spatial analysis which support the thermal origin of the hard component in NGC 253 and, to a lesser extent, in M 82.

**BEPPOSAX IMAGES OF NGC 253 AND M 82**

BeppoSAX observed NGC 253 on Nov.29–Dec.2, 1996 and M 82 on Dec.06–07, 1997 with the LECS, MECS and PDS detectors operating between 0.1–4 keV, 1.3–10 keV and 13–60 keV, respectively (see Table 1). The spectral results have demonstrated that two thermal components (kT \sim 0.1–0.3 keV and kT \sim 6–9 keV) are required to fit the spectra of both sources (Cappi et al. 1998, Persic et al. 1998), and that the hard thermal component needs to be absorbed in order not to over-produce the continuum at E < \sim 1 keV. Therefore, the present analysis will focus on the spatial properties in only the 3–10 keV energy range, where the contribution of the soft component is marginal. Here we present preliminary results obtained from only the MECS instruments.

| Source | Inst. | Exposure Ksec | Count-rate 10^-2 cts/s |
|--------|-------|---------------|------------------------|
| NGC 253 | LECS | 55 | 3.9 |
| | MECS | 113 | 9.2 |
| PDS(13-100 keV) | | 51 | 7 (~ 2.5\sigma detection) |
| M 82 | LECS | 29 | 19 |
| | MECS | 85 | 35 |
| PDS(13-25 keV) | | 30 | 8 (~ 6\sigma detection) |

Figure 1 shows the MECS 3–10 keV images of both galaxies superimposed on Digital Sky Survey images. The left panel clearly shows that the hard X-ray emission of NGC 253 is extended and elongated along its major axis. No point sources embedded in the extended emission are detected, but given the limited resolution they cannot be ruled out; note that there is an indication for a “cone” of X-ray emission that extends toward the southwest direction. Another interesting feature is the apparent extended emission perpendicular to the major axis in the northwest and southeast, in a way similar to the ROSAT PSPC and HRI results (Dahlem, Weaver & Heckman 1998). As a matter of fact, such emission could be the signature of a very hot gas ejected out of the galaxy, into the IGM. Further analysis work is in progress to determine the detailed characteristics (e.g. flux, temperature vs. distance) of this extended component. The right panel suggests the presence of a more symmetric X-ray halo in M 82, though with some excess emission oriented along the optical minor axis in the northwest direction.

The radial profiles of the 3–5 keV, 7–10 keV and 6–7 keV emission from NGC 253 and M 82 are shown in
**Fig.1:** *BeppoSAX* MECS 3–10 keV image of NGC 253 (left) and M82 (right), superimposed on DSS images. The displayed FOV are \( \sim 38' \times 33' \) for NGC 253 and \( \sim 25' \times 25' \) for M82. The circle on the top-right of each source represents the MECS 50% Half Power Radii averaged over all energies (radius \( \sim 1.3' \)). The apparent shift between the centroid of the X-ray contours and of the DSS image of M82 is within the systematics (of \( \sim 1' \)) in the absolute position determination of *BeppoSAX*.

Figure 2 together with the instrumental PSF energy-weighted over the source spectra. The new and most convincing result of the present analysis is that the hard X-ray emission in NGC 253 extends to \( \sim 8' \). There is also evidence that M82 extends to \( \sim 5' \), however the effect is in this case only marginal. In NGC 253, the extension is also evident if one considers the FeK line flux only (i.e. in the 6–7 keV band).

**ON THE ORIGIN OF THE HARD SPECTRAL COMPONENT**

The origin of the hard extended component is puzzling. It could be due to either a collection of point sources which contribute to the 3-10 keV emission (e.g., XRBs, SNRs), or a truly diffuse emission due to Compton scattering of IR-optical photons from relativistic e\(^-\). Alternatively, it could be a very hot (\( \sim 6–10 \times 10^7 \) K) ISM phase the cause of the hard extended component. *Individually*, each of these components, except for the hot ISM phase hypothesis, seems unlikely to dominate the 3-10 keV of these galaxies. The average spectrum of an ensemble of SNRs would probably be too soft (\( kT \leq 4 \) keV), and Compton emission would predict a spectrum with a power-law shape at odds with what shown in the companion paper (Cappi et al. 1998). An accurate study by Dahlem, Weaver & Heckman (1998) based on spatially resolved ROSAT PSPC spectra of NGC 253 and M82, has shown that the 0.1-2 keV flux of NGC 253/M82 can be divided into emission from the source disk+core (53%/82%), the halo (25%/11%) and point sources (22%/7%). Extrapolating the average spectrum of the ROSAT point sources of NGC 253 and M82 to higher energies, we obtain a 3-10 keV flux of \( \sim 1.4 \times 10^{-12} \) erg cm\(^{-2}\)s\(^{-1}\) and \( 5 \times 10^{-14} \) erg cm\(^{-2}\)s\(^{-1}\), respectively. This is negligible in the case of M82 (\( F_{3-10\,\text{keV}} \sim 2.3 \times 10^{-11} \) erg cm\(^{-2}\)s\(^{-1}\)), and less than 40% of the flux of NGC 253 (\( F_{3-10\,\text{keV}} \sim 3.6 \times 10^{-12} \) erg cm\(^{-2}\)s\(^{-1}\)). In conclusion, alternatives to the hot ISM phase could hardly produce, by themselves, all the hard X-ray emission detected in both galaxies. Therefore the interpretation according to which most of the hard X-ray emission is produced in a hot ISM plasma seems to be favored.

However, as mentioned above for NGC 253, XRBs (and possibly Compton emission, Rephaeli et al. 1991) certainly contribute to the hard X-ray emission. Thus we estimated how their contribution would modify our conclusions on the measurements of temperature and abundance of the hard component. To do so, we added an extra hard component (an absorbed power-law) to the best-fit spectra shown in Cappi et al. (1998) to mimic the extra contribution from XRBs and/or Compton emission and/or emission from a LLAGN. For several values of \( N_H \) (from \( 10^{22} \) to \( 10^{24} \) cm\(^{-2}\)) and \( \Gamma \) (from 1 to 2), we found no improvement of the fit and upper-limits of (at most) 20% and 10% of the observed 3-10 keV flux of NGC 253 and M82, respectively.
Fig. 2: Radial profiles (data points) of the sources' emission between 3–5 keV (upper panels), 7–10 keV (middle panels) and 6–7 keV (lower panels) as compared to the PSF for an on-axis point source (solid line) calculated over the corresponding energy range weighting the different energies with the sources' spectra. Extended emission is clearly detected (for all energy bands) in NGC 253 and marginally in M82.

In NGC 253, forcing the power-law contribution to be about 40% of the total 3-10 keV flux, the thermal component softens from $kT \sim 6$ keV to $\sim 4.8$ keV and the abundances increase from $\sim 0.25$ to $\sim 0.34$ solar. In M82, forcing a power-law contribution of 50% of the total 3-10 keV flux, the thermal component softens from $kT \sim 8$ keV to $\sim 6$ keV, and the abundances increase from $\sim 0.08$ to $\sim 0.25$ solar, but the fit becomes worse by $\Delta \chi^2 = 11$ (mainly because of the clear cutoff obtained from the PDS data). However, it should be pointed out that the average spectrum of XRBs may not be well described by a single absorbed power-law but might require the addition of an FeK line emission (most XRBs are known to emit strong FeK lines at 6.4 and/or 6.7 keV). In such case, abundance differences would become even lower.

It should be noted also that in the case of M82, some short-term ($\sim$ hrs) variability (with $\sim 30\%$ amplitude) was detected in the 3–10 keV light curve of M82, possibly indicating a contribution from XRBs to the hard X-ray flux. Given the lack of strong point-sources in the ROSAT PSPC observations of M82 reported by Dahlem, Weaver & Heckman (1998), these could either be highly-variable (as suggested by Ptak et al. 1997), or be strongly absorbed in order to show up at $E > \sim 3$ keV. However, our timing analysis indicates a dispersion of the light curve around its mean value of only $(15\pm 4)\%$. Therefore, as shown above, such a contribution should not have strong effects on our spectral results.

The overall results presented here are thus consistent with a major contribution in the 3-10 keV band from a hot and diffuse thermal plasma. A significant contribution from other emission mechanisms (point-source population and/or Compton emission) cannot be excluded based on the present data but even with the extreme hypothesis of a $\sim 30\%$ contribution between 3-10 keV, best-fit temperatures and abundances derived from the hard component would become only slightly lower and higher than reported. In any case, the present results clearly rule out the possibility that a LLAGN makes the bulk of the hard X-ray emission in these two SBGs.

The above is consistent with our preliminary results obtained from a spatially-resolved spectral analysis of the MECS data of NGC 253 (Cappi et al., in prep.) which clearly shows that the temperature of the hard
component decreases with increasing distance from the core (from $kT \sim 6$ keV in the core to $kT \sim 4$ keV in the disk). This suggests either a thermal contribution from point-source populations in the core and in the disk (but both with thermal average spectra) or thermal emission from a hot ISM gas.

If due to hot gas, the observed temperatures ($T_{\text{obs}} \sim 6.5/9.7 \times 10^7$ K for NGC253/M82) are much higher than the “escape temperature” ($T_{\text{esc}} \sim 2/1 \times 10^6$ K for NGC253/M82; Wang et al. 1995) of the gas in these galaxies, so the gas should easily escape from the galaxies. As pointed out by Heckman (1997), this could consequently be very important for understanding galactic evolution and the chemical enrichment of IC and IG gas.

Finally, it is interesting to note the analogy of our results with those on clusters of galaxies obtained about 25 years ago. Indeed, the Perseus, Virgo and Coma clusters were known to be X-ray sources but the origin of their 2–10 keV emission was at first unclear. Several hypotheses were proposed: e.g., a collection of AGNs or AGNs-related (point) sources (Kellog et al. 1972), Compton scattering of microwave background photons by electrons emitting the diffuse radio halos (Forman et al. 1972) or a hypothetical intracluster medium (Gott and Gunn 1971). But it was only after the first observational evidence with *UHURU* that cluster 2–10 keV emission was shown to be extended (Forman et al. 1972, Kellog et al. 1975) and by the detection by *Ariel* − 5 (Mitchell 1976) and *OSO*-8 (Serlemitsos et al. 1977) of an iron emission line at 6.7 keV that the origin of their hard X-ray emission was attributed to a hot, evolved, and diffuse intracluster gas. Does history repeat itself?

CONCLUSIONS

The main conclusion from the above results is that the *BeppoSAX* observations of the two prototypical SBGs NGC 253 and M82 have revealed for the first time evidence of a *very hot and diffused thermal plasma* which is mainly responsible for their hard (2–10 keV) emission. This discovery is likely to have important implications on the AGN/starburst connection and on our understanding of the chemical enrichment of the IG medium and on the formation and evolution of galaxies.

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