ABSTRACT

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abundances are under debate.

By treating all available imaging and spectroscopy data from *ASCA* and *ROSAT* (both HRI and PSPC) in a self-consistent manner, Dahlem et al. (1998; hereafter Paper I) and Weaver et al. (2008; hereafter Paper II) were able to reconcile the apparent discrepancies based on a mini-survey of 5 nearby edge-on starburst galaxies.

The results from Paper I and Paper II suggest that the combined *ASCA* and *ROSAT* PSPC integral spectra of NGC 253 and M 82 can be fit with comparable values of $\chi^2$ by different combinations of spectral components, which means that there is an ambiguity in the choice of the best-fitting spectral model. By cross-checking the spectral results with *ROSAT* PSPC and HRI imaging data, a spectral composition of (at least) two thermal plasmas, with temperatures in the ranges 0.1–0.4 keV and 0.6–0.8 keV, respectively, plus a hard power law component turns out to be the only model combination that can explain all observational data of all galaxies in the sample simultaneously (Paper II).

This is in contrast with the recent findings by Cappi et al. (1999; hereafter C99), based on *BeppoSAX* data of NGC 253 and M 82. These authors claim that there is “compelling evidence for the presence of an extended hot thermal gas” of several keV temperature in these two galaxies. The purpose of the current letter is to investigate this apparent discrepancy between their results and ours by re-analyzing the *BeppoSAX* observations of NGC 253 and M 82, taking into account earlier results based on *ROSAT* and *ASCA* observations.

2. Observations and data reduction

All parameters of the *BeppoSAX* observations of M 82 and NGC 253 are as described by C99. The data were reduced in the standard fashion, using SAXDAS 2.0. LECS and MECS data were extracted for joint spectral fitting from a circular region centered on the position of the sources, using radii of 4'. Background subtraction was performed using standard files (Parmar, Oosterbroek, & Orr 1999 ***check***).

Spectral fitting was performed using XSPEC in the following way. We first used the input model preferred by C99 to ensure that we can reproduce their results. Then we tried the model used by us for the analysis of the joint *ASCA* + *ROSAT* PSPC spectrum (Paper I and Paper II).

In the following we will list and discuss our results for both NGC 253 and M 82. However, since we used the same data extraction, reduction, and spectral fitting technique for both galaxies, only one (NGC 253) will be presented in figures.

3. Results and discussion

3.1. NGC 253

We could reproduce the results by C99 within the uncertainties, using a spectral model with 2 Mekal plasma components (2M; see their Fig. 4). The fit to the *BeppoSAX* data of NGC 253 following the model preferred by us, with a Mekal and a power law (M+P) component, is displayed in Fig. 1. This is evidently also an acceptable fit. The goodness of fit for our preferred model (Paper II) is $\chi^2 = 261.9$ for 265 d.o.f. ($\chi^2/\nu = 0.99$), while that for the 2 Mekal (hereafter “2M”) model favored by C99 is $\chi^2 = 282.5$ for 268 degrees of freedom (d.o.f.) and thus $\chi^2/\nu = 1.05$. The M+P model fits the data better than the 2M model at the highest and lowest energies of the passband. The results of the two spectral fits to the *BeppoSAX* data of NGC 253 are tabulated in Table 1. All uncertainties are given at the 90% confidence level for one interesting parameter; note that these only apply under the assumption that the choice of model components represents the different contributing emission mechanisms correctly.

The softest thermal emission component found in the *ROSAT* data is not required. When including a thermal plasma of 0.26 keV energy, $\chi^2$ is improved, but not significantly. Therefore it was left out in the fits to the *BeppoSAX* data.

The hard part of the X-ray spectrum can be fit with a power law that is compatible with those of Galactic X-ray binaries (XRBs) and can thus be explained naturally as the continuum emission from HMXRBs (Paper II). The integral spectrum of all the point sources from the *ROSAT* PSPC observations is consistent with this interpretation, as is the contribution of this spectral component to the total X-ray flux (Paper I). There is no reason why all compact sources should emit a thermal spectrum.

The claim that there is a hot thermal gas at a few keV energy (C99) hinges only on the assump-
tion that this is the only mechanism that could explain the observed Fe line around 6.7 keV. However, supernova remnants (SNRs) and XRBs, including high-mass XRBs (HMXRBs), can produce both fluorescent and thermal Fe line emission, i.e., at 6.4 keV and 6.7 keV, respectively (e.g., Nagase 1989; White, Nagase, & Parmar 1995; Liedahl et al. 1999), while C99 assume that all line emission is of thermal origin. Thus, the observed Fe line might well be a superposition of emission from hot gas and from X-ray binaries. The fitted equivalent width of the Fe line (Table 1) is in agreement with this interpretation. It, too, might be a composition of a (broad) thermal component and a (narrow) XRB contribution. However, a composite line fit cannot be performed based on the current data, because the line is only marginally resolved.

The above finding that different models can fit the data equally well proves that the “optimal” fit is model-dependent, as already stated in Paper II. Therefore, there is no reason to reject the M+P model. Moreover, it is, as argued in Paper II, the physically most plausible model choice.

Taking into account the ROSAT imaging results, which indicate clearly that there is a considerable number of unresolved compact sources in the central part of the disk of NGC 253 (Paper I), the most likely identification of those sources—based on their spectral properties and soft X-ray luminosities, $L_X$—is that they constitute a population of HMXRBs (Paper I). Thus, part of the emission distribution seen by BeppoSAX is not truly “diffuse”, but smeared out by its broad point-spread function.

These point sources detected by ROSAT contribute about 50% of the flux from the central disk (Paper I and Paper II). Thus, they are very significant contributors to the measured total flux, especially in the hard part of the X-ray spectrum.

On the other hand, the spectral model preferred by C99 does not take into account the presence of HMXRBs and their spectral signature. Given the luminosities of emission mechanisms tracing the presence of high-mass stars in galaxies like NGC 253 and M 82, especially far-infrared radiation, a large number of HMXRBs must be expected to be present in them.

It is still unclear how the previously detected X-ray emitting thermal plasma (with temperatures in the range of a few tenths of a keV) is heated, especially in the galaxy halos, up to several kpc away from the disk planes of the starbursts. The presence of another, extremely hot medium of several keV energy contributing of order 2/3 of the total 2–10 keV flux, as suggested by C99, would further exacerbate the problem of energy supply.

When taking into account the trade-off between metallicities and absorbing H I column densities in fitting the softest part of X-ray spectra (which cannot be resolved by BeppoSAX data only, but requires the low-energy response of ROSAT), extreme subsolar metallicities, $Z$, are not required to obtain a good fit (Paper II). This $N_H$ vs. $Z$ dichotomy is another, independent ambiguity in the minimum $\chi^2$ space of the spectral fits. Low metallicities in starburst galaxies, i.e., the galaxies with the highest star formation rates in the local Universe, would be hard to understand because of the proven presence of large numbers of massive stars, which are the most prolific producers of metals.

3.2. M 82

The same ambiguities are present in fits to the BeppoSAX data of M 82. We could fit almost equally well the model by C99 and ours from Paper I and Paper II. Just as for NGC 253, the M+P model fits the data points at the very highest energies slightly better than a 2M model. The goodness of fit is $517.4/446$ d.o.f. = 1.16 (2M model) and $466.9/442$ d.o.f. = 1.06 (M+P model), respectively. Note that, just as for the combined ROSAT + ASCA data, the BeppoSAX data require another, soft thermal component to be added to the M+P model.

With the M+P spectral model composition, we obtain almost equally good fits with two very different metallicities. In one case, $Z = 17Z_\odot$ (constrained to be $> 2.2$ at the 90% confidence level), in the other $Z = 0.13Z_\odot$. In the high-metallicity case the flux at $\sim$ 1 keV is modeled primarily as Ne and Fe-L line emission, while in the low-metallicity case it is modeled as a peak in the thermal distribution. The energy resolution of the LECS of $\sim$ 200 eV (FWHM) at 1 keV is insufficient to discriminate between the two options. Note that these two fits do not yet take into account the additional information obtained with ASCA and ROSAT requiring an additional soft thermal com-
ponent (Paper I and Paper II).

There is less evidence from ROSAT imaging for the existence of large numbers of compact sources in M 82. Instead, there appears to be a spatially extended, hard spectral component. Part of this might be truly diffuse, in which case the most likely interpretation is that of a very hot gaseous component, as suggested by C99. Only recently the Chandra image by Griffiths et al. (2000) showed that there is indeed a population of compact sources in M 82, surrounded by diffuse emission. The compact sources in the central part of M 82 could not be resolved by ROSAT, because they are too close to each other. The most likely identification is again that they are HMXRBs (Griffiths et al. 2000). Individual HMXRBs could also explain the observed X-ray variability in the hard part of the spectrum, while there is no evidence in the Chandra data for the presence of an AGN (Ptak & Griffiths 1999, Matsumoto & Tsuru 1999, Gruber & Rephaeli 1999, C99).

The measured position and equivalent width of the Fe line in M 82 of 6.63 ± 0.21 keV and 60 ± 40 eV, respectively, leaves open whether the line emission comes from either binaries or diffuse hot gas or a superposition of both. In both M 82 the width of the Fe line near 6.6 keV is unresolved. Thus, except for the (poorly constrained) position of the line centroid, no further information on the relative contribution of thermal or fluorescent line emission can be made based on the existing data. Both model compositions tested above fit the data (statistically) so well that no useful constraint can currently be derived on the possible contribution of both a hot thermal plasma and HMXRBs to the 2–10 keV flux of M 82, when fitted simultaneously.

4. Summary

There are several ambiguities in the fits to complex X-ray spectra of starburst galaxies, such as NGC 253 and M 82. The “best-fitting” model is not necessarily unique, because the spectral models required to explain all observations are more complex than can be fit unambiguously to one single dataset. In such cases statements that a fit is good at a certain significance level can be misleading, because they only apply if the correct spectral model composition was chosen. There are also intrinsic degeneracies, i.e., trade-offs of different fit parameters against each other (e.g., $N_H$ vs. $Z$).

This study makes it clear how important it is to consider all available information, including in particular X-ray imaging results of extended sources, when interpreting their integral spectral properties. The new generation of X-ray satellites, Chandra, XMM, and Astro-E, will resolve much of this ambiguity because of their high spectral resolution, combined with high sensitivity and good imaging capabilities over wide bandpasses, rendering possible spatially resolved spectroscopy of individual (classes of) sources within nearby galaxies.

REFERENCES


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### Table 1

Comparison of fit results to *BeppoSAX* data of NGC 253

<table>
<thead>
<tr>
<th>Source $^1$</th>
<th>Model $^2$</th>
<th>$kT_m^3$ (keV)</th>
<th>$N_{H,m}$ $(10^{22}$ cm$^{-2}$)</th>
<th>$Z_m$ $(Z_\odot)$</th>
<th>$kT_h/\Gamma$ (keV/...$^4$)</th>
<th>$N_{H,h}$ $(10^{22}$ cm$^{-2}$)</th>
<th>$Z_h$ $(Z_\odot)$</th>
<th>$\chi^2/\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C99</td>
<td>2M</td>
<td>0.65$^{+0.09}_{-0.07}$</td>
<td>0.33$^{+0.22}_{-0.07}$</td>
<td>0.25$^{+0.06}_{-0.09}$</td>
<td>5.90$^{+0.3}_{-0.4}$</td>
<td>0.33$^{+0.22}_{-0.07}$</td>
<td>0.25$^{+0.09}_{-0.09}$</td>
<td>1.05</td>
</tr>
<tr>
<td>Paper II</td>
<td>M+P</td>
<td>0.75 $\pm$ 0.06</td>
<td>0.013(7)</td>
<td>0.16 $\pm$ 0.02</td>
<td>2.22 $\pm$ 0.04$^4$</td>
<td>1.11 $\pm$ 0.11</td>
<td>$\ldots$</td>
<td>0.99</td>
</tr>
</tbody>
</table>

$^1$C99 = Cappi et al. (1999); Paper II = Weaver et al. (2000)

$^2$M = Mekal + Mekal; M+P = Mekal + Power Law

$^3$Subscript $m$ for “medium” energy thermal component (Paper II), subscript $h$ denotes the alleged “hot” thermal component (C99)

$^4$Fe K$\alpha$ line fitted independently at 6.62 $\pm$ 0.07 keV, with an equivalent width of $EW = 480 \pm 110$ eV

$^f$Parameter fixed

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**Fig. 1.** — Fit of the model by Weaver et al. (2000) to the *BeppoSAX* observations of NGC 253; the model fit to the data (left) and the unfolded spectrum (right) are displayed.