XMM-Newton Observations of Extra-planar Gas in Nearby Starburst Galaxies

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Abstract.

We report on first results\(^1\) of XMM-Newton observations of nearby starburst galaxies that form part of a multi-wavelength study of gaseous halos around late-type spiral galaxies and their dependence on the level of star formation activity in the underlying disks.

XMM-Newton, with its extraordinary sensitivity for faint extended X-ray emission, is used to derive spatial and spectral properties of the very hot extra-planar/halo gas. For example, spectral models can be tested and hot gas properties like density, mass and energy can be estimated. Comparing the distribution of the halo X-ray emission with optical filaments and/or observed magnetic field structures uncovers interesting correlations on which work just has started.

Our study aims - in general - at assessing the importance of galactic halos as repositories of a metal-enriched hot medium and their significance in terms of galactic chemical evolution and possible metal enrichment of the intergalactic medium.

1. Introduction

We have selected nearby edge-on oriented starburst galaxies to perform a multi-wavelength (X-ray, radio-continuum, HI and optical) study of all phases of extra-planar gas to investigate the dependence of galactic halo properties on the energy input rate due to star formation (SF) in the underlying galactic disk. Special care must be taken to separate halos created by a sufficiently high energy input and extra-planar emission which is caused by galactic interactions or nuclear activity. The galaxy’s size, i.e. the depth of the gravitational potential, is another parameter affecting the evolution of galactic halos. One of the main goals of this project is the determination of the energy budget in the halos (magnetic field, thermal and radiation energy densities).

XMM-Newton [Jansen et al. (2001)] X-ray observations presented here are used to detect previously unknown extended halo emission due to hot gas and/or to re-visit galaxies with known (from earlier X-ray missions) extra-planar X-ray emission features but now with a hitherto unreached sensitivity that can only be provided by deep XMM-Newton observations. Such observations also allow us to investigate with unprecedented signal-to-noise the characteristics (temperature, metallicity, energy density) of the hot gas via X-ray spectroscopy.

\(^1\)This work is based on observations obtained with XMM-Newton, an ESA science mission with instruments and contributions directly funded by ESA Member States and the USA (NASA).
2. Observations

This paper is based on XMM-Newton observations of the starburst galaxies NGC 1511, NGC 4666 and NGC 3628 carried out as part of the Guaranteed Time proposal 011098 in July 2000, June 2002 and November 2000, respectively. The X-ray data have been cleaned for periods of high radiation background and images and spectra were generated with the Science Analysis System (SAS) software package (in its version 5.4.1, except for NGC 1511 that was processed with 5.3.3). We also made use of the EPIC background blank field files and tools provided by A. Read (Read & Ponman 2003).

3. Results

3.1. NGC 1511

The starburst SAApec:HII type galaxy NGC 1511 was studied as part of our project and X-ray results presented at this meeting have been published in Dahlem et al. (2003). XMM-Newton EPIC (Strüder et al. (2001); Turner et al. (2001)) revealed for the first time the presence of a diffuse hot gaseous phase in NGC 1511 partly extending out of the disk plane. Extra-planar emission due to cosmic rays and magnetic fields was earlier seen in radio continuum emission (Dahlem et al. 2001) and is suggestive of a common origin for the outflow of these components of the ISM. The X-ray spectral analysis of the integrated 0.2-12 keV emission (excluding a strong point source about 30'' north of the centre, which - if associated with NGC 1511 - might be an ultra-luminous $L_X = 1.18 \times 10^{40}$ erg s$^{-1}$ X-ray source) showed a complex emission composition: one (although not the only possible) best-fitting model was found consisting of two thermal components and a power law contributing 12% (0.19 keV), 11% (0.59 keV) and 77% (powerlaw) to the total flux, respectively. The finding that a spectral model with a single temperature gas component is not sufficient to describe the emission, points toward the fact that the X-ray emitting gas contains several phases. The best-fit model corresponding total X-ray luminosity ($L_X = 1.11 \times 10^{40}$ erg s$^{-1}$) leads to a far-infrared-to-X-ray luminosity ratio for NGC 1511 which is typical for starburst galaxies (Heckman et al. (1990); Read & Ponman (2001)).

The Optical Monitor (OM, Mason et al. (2001)) on board XMM-Newton was used to observe NGC 1511 in the UV during the X-ray observations and obtained images showing that this galaxy is heavily disturbed (as it also can be seen in Hα (Lehnert & Heckman (1995)) and in the near infra-red). Strong evidence for tidal interactions has only recently been obtained through HI observations (Dahlem et al., 2005), unfortunately rendering NGC 1511 unsuitable as target galaxy to study the dependence of its gaseous halo’s properties on the distribution and level of SF in the underlying disk.
3.2. NGC 4666

Based on multi-wavelength (optical, radio continuum and ROSAT X-ray observations), we ‘classified’ NGC 4666 as a ‘superwind’ Sc galaxy (Dahlem et al. 1997) harboring an extra-planar outflow cone emanating from a central SF region of \( \sim 3.2 \) kpc in radius, and having an opening angle of \( 30^\circ \pm 10^\circ \). The outflow could be traced up to \( \sim 7.5 \) kpc above the disk plane by optical emission line filaments.

The ROSAT X-ray observations (Dahlem et al. 1998, see Fig. 1, left panel) indicated the presence of soft extended X-ray emission outside of the disk on the north-western (closer to us) side of NGC 4666. Our XMM-Newton EPIC observation, in contrast, show for the first time that such soft X-ray emission exists on both sides of the galactic disk, originating from a huge, structured hot gas halo (Fig. 1, right panel, and Fig. 2).

Figure 1. Soft X-ray image of NGC 4666 obtained with ROSAT PSPC at 0.25 keV (left panel; from Dahlem et al. 1998) and with XMM-Newton EPIC (right panel) from combined pn-MOS data in the 0.2 - 0.5 keV energy band, overlaid on a DSS image. The XMM-Newton data was slightly smoothed with a non-adaptive Gaussian to a spatial resolution of 10\(^{\prime}\)4.

The diffuse emission detected by EPIC-pn is strong enough to allow us to perform a spectral analysis in several areas in the galactic disk and halo: the complex spectrum of the diffuse disk emission (Fig. 3 top) can be fitted by a combination of an internally absorbed MEKAL (0.54 keV) and power law component plus another MEKAL model (0.18 keV) all affected by Galactic foreground absorption. The lower halo emission (Fig. 3 middle) shows a similar spectral behavior as the disk spectrum. The spectrum of the upper halo emission (Fig. 3 bottom), however, does not need a second MEKAL component but is fitted reasonably well also with a single 0.23 keV thermal plasma. Most of the total flux above 0.9 keV originates from the power-law type emission (presumably due to unresolved point-like sources), whereas the thermal plasma clearly dominates in
Figure 2. XMM-Newton combined pn-MOS image of NGC 4666 in the 0.5 - 0.9 keV energy band overlaid on the Hα+N[II] optical narrow band image from Lehnert (1992). In the halo the most extended optical emission line filaments form an “X”-shaped structure (cf. the plates in Lehnert & Heckman (1996)). Vectors mark the orientation of the magnetic field observed at 4.89 GHz with the VLA, their lengths are proportional to the polarized intensity.

If the diffuse X-ray emission in the soft energy band is assumed to be due to hot gas, it is possible to calculate the gas density $n_e$ and its mass $m_{\text{gas}}$. To this end we used the model of thermal cooling and ionization equilibrium of Nulsen et al. (1984) where $L_{\text{X}}(\text{soft}) \simeq \Lambda(T)n_e^2V\eta$. The unknown filling factor $\eta$ allows for some clumpiness of the gas. If we fit all the spectra extracted from the three areas with a single-temperature MEKAL model, the unabsorbed flux in the 0.3 - 12 keV and corresponding luminosity (adopting $D = 26.3$ Mpc) are given in Tab. II. For the gas temperatures of the hot gas, Raymond et al. (1976) give a cooling coefficient $\Lambda(T)$ of $\sim 10^{-22}$ erg cm$^3$ s$^{-1}$. Assuming an ellipsoid for the disk and the outflow cone geometry (see above) for the emitting halo volume $V$, and typical volume filling factors of 0.1 - 0.8, we derive gas densities and masses listed in Tab. II.

Such estimated gas densities together with the fitted temperature allow us to compare the energy density of the hot gas with e.g. that of the magnetic field (magnetic field strengths were derived from radio continuum observations as 14.4 $\mu$G in the disk and 7.1 $\mu$G in the halo (see Dahlem et al. (1997)). Whereas in general the ratio between the thermal and magnetic energy densities is $< 1$.
Figure 3. XMM-Newton EPIC-pn spectrum of the disk (top), lower halo (middle) and upper halo (bottom) region of NGC 4666. The spectral models are described in the text. In the lower panels, residuals between the spectral model and the data are shown.

Table 1. Parameters of the diffuse X-ray emission components of NGC 4666

| Region   | $T$ [keV] | $f_{X,0.3-12}^{mekal,unabs}$ $10^{-14}$ erg/cm$^2$/s | $L_X$ $10^{39}$ erg/s | $n_e$ $10^{-3}$cm$^{-3}$ | $m_{Gas}$ $10^7 M_{sun}$ | $U_{th}/U_{mag}$ |
|----------|-----------|------------------------------------------------------|----------------------|------------------------|---------------------|------------------|
| disk     | 0.29 ± 0.01 | 7.21                                                  | 5.97                  | 1.0 - 2.9              | 2.5 - 7            | 0.1 - 0.2        |
| lower halo | 0.35 ± 0.03 | 2.77                                                  | 2.29                  | 2.5 - 7.1              | 0.5 - 1            | 0.7 - 2.0        |
| upper halo | 0.23 ± 0.01 | 4.40                                                  | 3.64                  | 1.2 - 3.3              | 1 - 4              | 0.2 - 0.6        |
| total halo | 0.27 ± 0.01 | 7.38                                                  | 6.11                  | 1.4 - 4.0              | 2 - 5              | 0.3 - 0.9        |
(see Tab. 1), and hence the magnetic field important for the dynamics of the hot gas (‘channeling’ the outflow), in the lower halo the relatively high thermal energy density is supportive of the idea that in this region the gas outflow might easily take place, even against a disk-parallel magnetic field configuration.

A detailed analysis of the halo emission and a possible correlation with Hα and radio polarization filaments (as started in Dahlem et al. 1997), see also Fig. 2 will be addressed in an upcoming paper by Ehle et al.; there we also plan to present a self-consistent dynamical and thermal spectral model (Breitschwerdt & Schmutzler 1999, Breitschwerdt 2003) which does no longer depend on the usual assumption of collisional ionization equilibrium (CIE).

We note that the same XMM-Newton observations have been discussed by Persic et al. (2004) comparing the disk-emission with spatially unresolving BeppoSAX data. The authors discuss their findings with respect to the discovery of starburst plus AGN activity both contributing to the X-ray emission of NGC 4666: the SF activity was found to be extended over most of the disk and associated with diffuse thermal emission, whereas the quite small low-luminosity type-2 AGN contribution (revealed by prominent Kα line emission from “cold” iron at 6.40 keV) was detected from the nuclear region.

In NGC 4666, Walter et al. (2004) failed to detect conclusive evidence for the existence of HI gas in its halo. However, seen in their HI maps are prominent tidal arms probably generated by interactions with the galaxy NGC 4668 and previously undetected dwarf companions. The high SF rate responsible for the superwind of NGC 4666 hence might be triggered by gravitational interaction.

3.3. NGC 3628

NGC 3628 is a peculiar Sbc galaxy known to be an interacting member in the Leo Triplet (Arp 317, assumed distance $D = 10$ Mpc). Earlier X-ray observations with Einstein (Fabbiano et al. 1990) and ROSAT (Dahlem et al. 1996), see Fig. 4 left panel) showed evidence for a collimated outflow along the minor axis from a starburst nucleus in NGC 3628 and led to the detection of an extended soft X-ray halo.

Our XMM-Newton observations (Fig. 4 right panel) are able to detect the extraplanar diffuse emission with much higher significance: the EPIC image clearly separates the southern collimated spur-like halo emission from nearby (most possibly background) point sources (see Fig. 5 left panel) and calls the proposed link between this X-ray filament and QSOs (Arp et al. 2002) to question.

A detailed comparison of the diffuse extraplanar X-ray emission with for example the Hα filaments (a plume extending about 130″ to the SW in position angle $\sim 210^\circ$ and faint more widespread filamentary extraplanar structures to the north - see Hα map from Fabbiano et al. 1990 or Rossa & Dettmar 2003) and Fig. 5 right panel) is ongoing.

4. Discussion

In the framework of our multi-wavelength project to investigate gaseous halos around late-type spiral galaxies and their dependence on the level of star-formation activity in the underlying disks (cf. M. Dahlem (this volume)) we
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Figure 4. X-ray image of NGC 3628 obtained with ROSAT PSPC at 0.75 keV (left panel; from Dahlem et al. (1996)) and with XMM-Newton EPIC (right panel) from combined pn-MOS data in the 0.3 - 2.0 keV energy band shown as greyscale image with overlaid contours of a DSS image. Whereas the ROSAT image has a spatial resolution of 48′′, the XMM-Newton data was slightly smoothed with a non-adaptive Gaussian to 10′′. The ‘box’ painted on top of the ROSAT map roughly marks the area of the displayed EPIC image.

Figure 5. XMM-Newton EPIC 0.5-0.9 keV contour map of NGC 3628 over plotted on a VLT-FORS2 image (left, see ESO Messenger, March 2002) and (only showing a single low intensity contour) on the Hα greyscale image (from Rossa & Dettmar (2003)). The ‘box’ in the left panel roughly marks the spatial extent of the Chandra image by Strickland et al. (2001), their Fig. 1).

showed in this paper X-ray results from three of our sample galaxies. The presented observations demonstrate that only with the advent of high sensitivity observatories (like XMM-Newton), it is becoming possible to detect and study in detail the hot halo gas component of the interstellar medium.

Our original sample selection criterion (based on far infra-red colors, see Dahlem et al. (2001) and references therein), that showed to be a good tool to
select candidates for the search for radio halos, is likely to also work in the X-ray regime. In all three XMM-Newton targets we find extra-planar X-ray emission which is bright enough to allow us detailed spectral investigations and also to test model assumptions (i.e. collisional ionization equilibrium versus radiative cooling with the dynamics in full non-equilibrium).

We note the co-existence of extra-planar soft X-ray emission above the most actively star forming regions in the galactic disk and the co-existence of such features with Hα filaments as well as vertical magnetic field structures (in case of NGC 4666).

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