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XMM-Newton Observations of Starburst Galaxies

M. Ehle[1] and M. Dahlem[2]

[1] XMM-Newton Science Operations Centre, European Space Agency, Villafranca del Castillo, P.O. Box 50727, 28080 Madrid, Spain

[2] Australia Telescope National Facility, Paul Wild Observatory, Locked Bag 194, Narrabri NSW 2390, Australia

Abstract. We report on the results of *XMM-Newton* observations of nearby starburst galaxies that form part of a multi-wavelength study of all phases of the extraplanar interstellar medium (ISM) in external galaxies. This study is conducted in order to assess the importance of halos as repositories of a metal-enriched medium and their significance in terms of galactic chemical evolution and possible metal enrichment of the intergalactic medium (IGM). Here we shortly summarize our findings based on *XMM-Newton* observations of NGC 1511 and NGC 1808 and present preliminary results for NGC 4666 and NGC 3628.

Key words. X-rays: galaxies – Galaxies: individual: NGC 1511, NGC 1808, NGC 4666, NGC 3628 – Galaxies: ISM, halos, starburst

1. Introduction

The high sensitivity of *XMM-Newton* enables us to conduct observations of fainter targets than before and to obtain a much more detailed picture of those known already. Increased sensitivity leads to significant progress in investigations of low surface-brightness emitters, such as for example hot gaseous halos around actively star-forming spiral galaxies.

We have selected nearby edge-on oriented starburst galaxies to perform a multi-wavelength (radio-continuum, HI, optical and X-ray) study of all phases of extraplanar 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 its gravitational potential, is another parameter affecting the evolution of galactic halos. One main goal of this project is the determination of the energy budget in the halos (magnetic field, thermal and radiation energy densities).

XMM-Newton X-ray observations presented here (performed as Guaranteed Time Proposals of the Project Scientist) are used to detect previously unknown extended halo emission due to hot gas and to investigate the metallicity of the hot gas via X-ray spectroscopy. An earlier report on the status of our ongoing work was given by Ehle et al. (2004).

Send offprint requests to: M. Ehle, e-mail: mehle@xmm.vilspa.esa.es

2. Previous Results

2.1. NGC 1511: the quest for hot gas in the halo

The starburst galaxy NGC 1511 was studied as part of our project and results presented at the EPIC consortium meeting have recently been published (Dahlem et al. 2003). *XMM-Newton* revealed for the first time the presence of a diffuse hot gaseous phase partly extending out of the disk plane. Extra-planar emission due to cosmic rays and magnetic fields was also 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 integral 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 10^{40} erg s^{-1} X-ray source) showed a complex emission composition: a best-fitting model was found with two thermal components and a power law contributing 12% (0.19 keV), 11% (0.59 keV) and 77% (powerl) to the total flux, respectively. The corresponding total X-ray luminosity (L_X = 1.11 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).

2.2. NGC 1808: combined starburst/AGN activity

XMM-Newton data of NGC 1808 (detailed analysis by Jiménez Bailón et al. (2003) and in prep.) shed new light on the unclear (starburst and/or AGN) nuclear activity of this galaxy, which is well known for its high level of star forming activity: the EPIC-pn spectrum shows the presence of two thermal components plus an additional hard X-ray power law tail and favours the physical scenario of a co-existence of a starburst and an obscured AGN, as previously suggested by Awaki et al. (1996) based on ASCA observations. The AGN dominates the hard X-ray spectrum while the soft emission (below 1 keV) is dominated by an extended starburst, corroborating previous ASCA and ROSAT results. Both EPIC-pn and RGS data provide for the first time reliable detections of a number of X-ray emission lines similar in wavelength and relative intensity ratios to the ones found for the prototypical starburst galaxy M82 (Read & Stevens 2002).

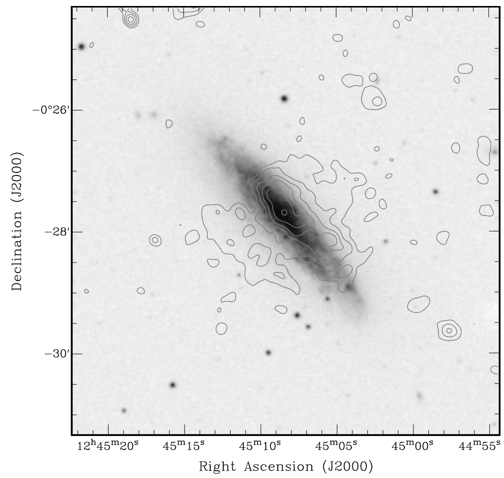

Fig. 1. *XMM-Newton* combined pn-MOS image of NGC 4666 in the 0.2 - 0.5 keV energy band overlaid on a DSS image. The data was slightly smoothed with a non-adaptive Gaussian to a spatial resolution of 10.4″.

3. Preliminary Results

3.1. NGC 4666: a "superwind" galaxy

The high far-infrared flux ratio of f_{60}/f_{100} = 0.45 for NGC 4666 makes this galaxy a good candidate to search for halo emission in different wavebands. In fact, evidence for a starburst driven galactic superwind in NGC 4666 - based on optical emission line imagery, radio continuum maps, and soft X-ray ROSAT images - was already given in Dahlem et al. (1997).

New *XMM-Newton* observations of NGC 4666 show for the first time that extended soft X-ray emission exists on both sides of the galactic disk, originating from a huge, structured hot gas halo (Fig. 1 and 2).

The complex EPIC-pn spectrum of the diffuse disk emission can be fitted by a com-

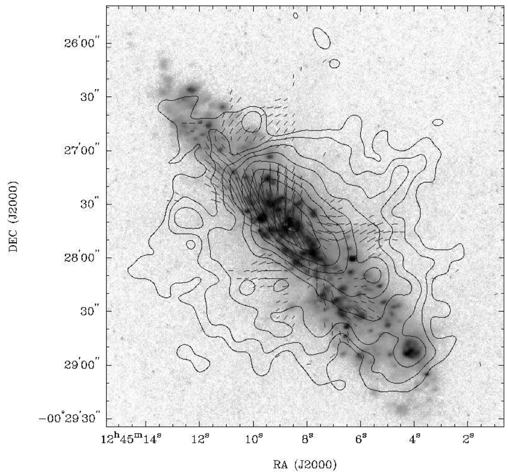

Fig. 2. *XMM-Newton* combined pn-MOS image of NGC 4666 in the 0.5 - 0.9 keV energy band overlaid on the Hα+N[II] optical narrow band image from Lehnert (1992). In the halo the most extended optical emission line filaments, which form an "X"-shaped structure (cf. the plates in Lehnert & Heckman 1996), reach out to distances above the plane of up to ~ 7.5 kpc. Vectors mark the orientation of the magnetic field observed at 4.89 GHz with the VLA, their lengths are proportional to the polarized intensity.

bination 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 halo emission does not need a second MEKAL component but is fitted reasonably well with a 0.22 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 the soft 0.3-0.9 keV band (contributing 75% and 82% to the 'diffuse' disk and halo emission, respectively).

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.

3.2. NGC 3628: outflow and a strange luminous source

NGC 3628 is a peculiar galaxy known to be an interacting member in the Leo Triplet. Earlier X-ray observations with the Einstein (Fabbiano et al. 1990) and ROSAT satellites (Dahlem et al. 1996) 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. 3) are able to detect the extraplanar diffuse emission with much higher significance: the EPIC image clearly separates the southern collimated spurlike halo emission from nearby (most possibly background) point sources and calls the proposed link between this X-ray filament and QSOs (Arp et al. 2002) to question. A detailed comparison of the diffuse ex-

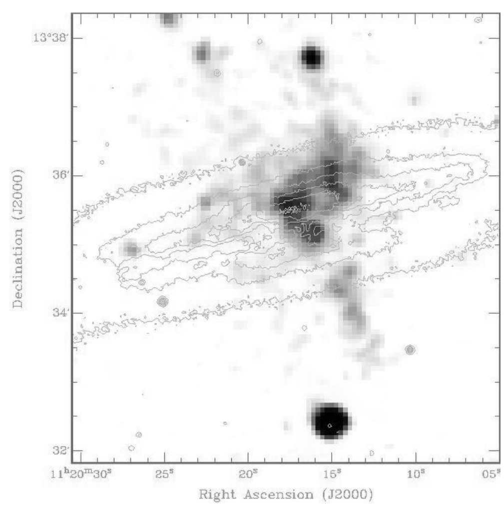

Fig. 3. *XMM-Newton* EPIC greyscale image of NGC 3628 in the 0.3 - 2.0 keV band. Contours mark the distribution of the optical light and are based on a DSS image.

traplanar X-ray emission with Hα filaments (a plume extending about 130″ to the SW in position angle ~ 210° and faint more widespread filamentary extraplanar structures to the north - see Hα map published in Fabbiano et al. 1990) is ongoing (Ehle et al. in prep).

XMM-Newton, however, is not only sensitive to the extended extraplanar emission but also to the nuclear emission region (Fig. 4).

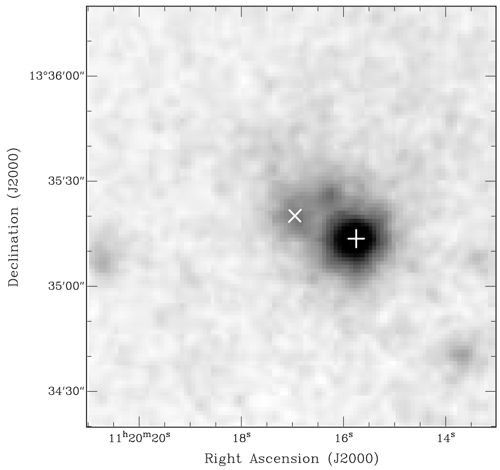

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Fig. 4. Central 2′ square *XMM-Newton* EPIC greyscale image of the nuclear region of NGC 3628 in the 0.3 - 8.0 keV band (same spatial and energy selection as the *Chandra* image by Strickland et al. (2001), their Fig. 1). The '×' marks the position of the 365 MHz radio continuum peak (Douglas et al. 1996), presumed to be the nucleus of the galaxy, and the '+' that of the IXO.

We confirm the result obtained from *Chandra* data (Strickland et al. 2001) which showed a very luminous point source located offset from the nucleus of NGC 3628. This source (possibly a member of the enigmatic class of intermediate-luminosity X-ray objects (IXOs)) is most probably the reason for the strong variability of the integrated nuclear emission noted by Dahlem et al. (1995). A preliminary fit to the pn spectrum of this source is in good agreement with the *Chandra* results.

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