Nuclear and global X-ray properties of LINER galaxies: *Chandra* and *BeppoSAX* results for Sombrero and NGC 4736

S. Pellegrini¹, G. Fabbiano², F. Fiore³, G. Trinchieri⁴, A. Antonelli³

¹ Università di Bologna, Dipartimento di Astronomia, via Ranzani 1, I-40127 Bologna, Italy
e-mail: pellegrini@bo.astro.it

² Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
e-mail: pepi@head-cfa.harvard.edu

³ Osservatorio Astronomico di Roma, via Frascati 33, I-00044 Monteporzio Catone, Italy
e-mail: fiore@quasar.mporzio.astro.it, angelo@coma.mporzio.astro.it

⁴ Osservatorio Astronomico di Brera, via Brera 28, I-20121 Milan, Italy
e-mail: ginevra@brera.mi.astro.it

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**Abstract.** We report on the 0.1–100 keV *BeppoSAX* observations of two nearby LINER galaxies, Sombrero and NGC 4736. *Chandra* ACIS-S observations supplement this broad-beam spectral study with a high resolution look into the nuclear region, and show a dominating central point source in Sombrero and a complex X-ray binary dominated/starburst region in NGC 4736. A compact non-thermal radio source, present in the nucleus of both galaxies, coincides with the central source in Sombrero, while in NGC 4736 its X-ray counterpart is a much fainter point source, not the brightest of the central region. On the basis of these and other results, we conclude that the LINER activity is linked to the presence of a low luminosity AGN in Sombrero and to a recent starburst in NGC 4736, and that *Chandra*'s spectroscopic capabilities coupled to high resolution imaging are essential to establish the origin of the nuclear activity.

**Key words.** Galaxies: spiral – Galaxies: individual: NGC 4594, NGC 4736 – Galaxies: active – Galaxies: nuclei – X-rays: galaxies

1. **Introduction**

Optical spectroscopic surveys showed that low ionization nuclear emission line regions (LINERs, Heckman 1980) are very common among ellipticals and early type spirals (Ho et al. 1997). It is also currently believed that most galactic spheroids host supermassive black holes, based on *Hubble Space Telescope* (*HST*) stellar or ionized gas spectroscopy coupled to dynamical modeling (e.g., Richstone et al. 1998). So, it has become natural to ask whether AGN activity stops at Seyfert galaxies or extends down to lower luminosities, including LINERs. The answer to this question has important consequences for the history of accretion in the Universe (e.g., Haiman & Menou 2000). The LINER emission, though, need not be powered by AGN-like activity: collisional ionization by shocks and/or photoionization by the UV radiation from hot, young stars were also suggested as possible mechanisms (Terlevich et al. 1992, Alonso-Herrero et al. 2000). Observational support for this interpretation, in some cases, comes from optical and ultraviolet *HST* observations (e.g., Maoz et al. 1995) and from infrared studies (Larkin et al. 1998).

An important way of discriminating between different emission mechanisms is to observe LINERs in hard X-rays, where the AGN presence is easily identifiable, even when it is obscured by intervening matter (e.g., the LINER NGC 6240 turned out to be an obscured, high luminosity AGN from hard X-ray observations; Vignati et al. 1999). For this reason we observed Sombrero (NGC 4594) and NGC 4736 with *BeppoSAX* over 0.1–100 keV, as they are early type spirals hosting two of the closest examples of LINER activity (Table 1). Thanks to their proximity, they are excellent targets to explore the questions raised above and have been subject to thorough studies at various wavelengths, including high angular resolution observations with *HST*, the *ROSAT* HRI and the VLA.

However, a *BeppoSAX* study is severely limited by the available angular resolution, as are all the reports so far on the hard X-ray properties of LINERs based on spectra from a few arcminute beams. These show power laws that could equally come from an active nucleus or the collective emission of X-ray binaries [see the reviews by Fabbiano...]

Send offprint requests to: S. Pellegrini
(1996) and Serlemitsos, Ptak & Yaccoob (1996); and Ptak et al. (1999)]. When the analysis of the BeppoSAX data was complete, the Chandra observations of our target galaxies became available in the public archive, providing us with the unique opportunity to supplement our study with a very high resolution look into the nuclear regions. We therefore added the analysis of these data to our work. The Chandra observation of Sombrero was reported as part of a snapshot survey of faint nearby AGNs (Ho et al. 2001); we considered more in detail those data here. After submission of this paper, a preprint appeared on the astroarchive discussing in detail the overall Chandra observation of NGC 4736 (Eracleous et al. 2001); our analysis is limited to the centermost region only.

1.1. Properties of the target galaxies

At the nucleus of Sombrero, identified as a LINER (Heckman 1980), high resolution HST spectroscopy confirmed the presence of a central dark object of $10^8 M_\odot$ and also revealed a faint broad H$\alpha$ component with full width at zero intensity of $\approx 5200$ km s$^{-1}$ (Kormendy et al. 1996). This nucleus hosts a compact and variable radio continuum source (Thean et al. 2000) and is a pointlike source in an HST image at 3400Å (Crane et al. 1993).

In the X-ray, a ROSAT HRI image showed a pointlike central source, clumpy emission associated with the disk and diffuse or not resolved emission from the bulge (Fabbiano & Juda 1997, hereafter FJ). How much of this diffuse emission comes from a hot medium and how much from the integrated emission of evolved stellar sources could not be established. ROSAT PSPC spectra of the central circles of 1' and 2' radius indicate a steeper photon index (from $\Gamma = 1.76^{+0.44}_{-0.36}$ to $\Gamma = 1.84^{+0.43}_{-0.28}$) for the larger aperture, which FJ interpreted as an indication that the extended HRI emission is relatively soft. Nicholson et al. (1998) obtain $\Gamma = 1.63 \pm 0.05$ and a column density $N_H = 5.3 \times 10^{20}$ cm$^{-2}$ from the combined ASCA and ROSAT spectra; allowing for contamination by soft emission, the column density to the power law is $2.9 \times 10^{21}$ cm$^{-2}$. Ptak et al. (1999), from combined ASCA and ROSAT data, find thermal emission with very low abundance (< 0.1Z$_\odot$) coupled to a power law of $\Gamma = 1.97^{+0.33}_{-0.29}$ absorbed by an excess $N_H < 1.7 \times 10^{22}$cm$^{-2}$ over the Galactic value. Recently, Ho et al. (2001) report the first results from an arcsecond resolution snapshot survey of nearby galaxies performed by Chandra. In their morphological classification into four classes of the X-ray images obtained, Sombrero belongs to the class of objects with a “dominant nuclear source”.

NGC 4736, a LINER2 galaxy (Ho et al. 1997), shows various pieces of evidence suggesting star formation that took place in its recent past. Balmer absorption lines and strong C$^\prime$O absorption indicate a nuclear starburst that occurred $\sim 1$ Gyr ago (Wong & Blitz 2000). A bright optical ring is prominent in HI (Mulder & van Driel 1993), molecular gas (Gerin, Casoli & Combes 1991) and H$\alpha$ (Pogge 1989). A younger stellar population is also revealed by 6cm radio continuum observations of compact HII regions associated with hot, young stars and young supernova remnants (Turner & Ho 1994) and by near-infrared spectra (Larkin et al. 1998). The nuclear region hosts a compact non-thermal radio continuum source (Turner & Ho 1994) and a bright UV point source revealed by HST (Maoz et al. 1995).

A ROSAT PSPC pointing showed within the central few kpc a compact source plus an extended distribution of hot gas ($kT \sim 0.3$ keV) contributing 30–35% of the total observed 0.1–2 keV flux (Cui, Feldkhun & Braun 1997). ROSAT HRI data showed 12 discrete sources superimposed on the optical disk and ring regions, likely X-ray binaries (hereafter XRBs), supernova remnants or recent supernovae; the brightest source was by far the galactic “nucleus” (Roberts, Warwick & Ohashi 1999, hereafter R99). The combined PSPC and ASCA spectrum (R99) is composed of a hard continuum, equally well modeled with a power law (with $\Gamma \sim 1.7$) or bremsstrahlung emission (with $kT \sim 8$ keV). The soft thermal emission was modeled with a two-temperature plasma (of $kT = 0.1$ and 0.6 keV) and solar abundance. A Fe K$\alpha$ line may also be present at 6.81$^{+0.13}_{-0.28}$ keV.

2. Spatial analysis

2.1. BeppoSAX observations

Sombrero and NGC 4736 were observed with the Low Energy Concentrator Spectrometer (LECS, Parmar et al. 1997), the Medium Energy Concentrator Spectrometer (MECS, Boella et al. 1997) and the Phoswich Detector system (PDS). The latter is a collimated instrument, operating in rocking mode, that covers the 13–300 keV energy band. It has a triangular response with FWHM of $\sim 13$ (Frontera et al. 1997). Its data were reduced using the variable risetime threshold technique to reject particle background (Fiore, Guainazzi & Grandi 1999). The journal of these observations is given in Table 2.

BeppoSAX was pointed to the optical centers of the galaxies, on which the X-ray emission is peaked (Fig. 1) within the accuracy with which positions are given by the satellite (Boella et al. 1997). In the MECS image of Sombrero there is a prominent source at RA=12 39 45.2, Dec=−11 38 49.6; we identify it with a bright 9.7 mag G0 star (HD 110086). The absence of this source in the harder 4.5–10 keV image indicates its soft nature and supports its identification. We determined the spatial extent of the galactic emission using the MECS data from azimuthally averaged brightness profiles in concentric annuli centered on the X-ray centroids. The background profile in the same detector region was estimated from event files.

1 The PSF of the MECS includes 80% of photons of energies $\geq 1.5$ keV within a radius of 27 (Boella et al. 1997). The LECS PSF is broader than this below 1 keV and similar above 2 keV.
Table 1. General galaxy properties

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Type</th>
<th>RA (J2000)</th>
<th>Dec (J2000)</th>
<th>d</th>
<th>$B_0^a$</th>
<th>$\log L_B$</th>
<th>$N_{H,gal}^d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sombrero</td>
<td>Sa</td>
<td>12°39'59.4&quot;</td>
<td>-11°37'23&quot;</td>
<td>9.4</td>
<td>8.38</td>
<td>10.79</td>
<td>3.5×10^{20}</td>
</tr>
<tr>
<td>NGC 4736</td>
<td>Sab</td>
<td>12°50'53.6&quot;</td>
<td>+41°07'10&quot;</td>
<td>5.9</td>
<td>8.75</td>
<td>10.23</td>
<td>1.4×10^{20}</td>
</tr>
</tbody>
</table>

$^a$ from de Vaucouleurs et al. (1991). $B_0^a$ is the total B magnitude, corrected for extinction.
$^b$ distance from Ajhar et al. (1997) for Sombrero and Schöniger & Sofue (1994) for NGC 4736.
$^c$ total B-band luminosity, derived using the indicated distance and $B_0^a$.
$^d$ Galactic neutral hydrogen column density from Stark et al. (1992).

Table 2. BeppoSAX observation Log

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Date</th>
<th>Exposure time $^a$ (ks)</th>
<th>Count Rate $^b$ (10^{-2} ct/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LECS</td>
<td>MECS</td>
<td>PDS</td>
</tr>
<tr>
<td></td>
<td>0.1–4 keV</td>
<td>1.7–10 keV</td>
<td>13–30 keV</td>
</tr>
<tr>
<td>Sombrero</td>
<td>2000 Jun 29</td>
<td>23.635</td>
<td>72.087</td>
</tr>
<tr>
<td>NGC 4736</td>
<td>2000 Dec 29</td>
<td>24.356</td>
<td>76.182</td>
</tr>
</tbody>
</table>

$^a$ On-source net exposure time. The LECS exposure time is considerably shorter than the MECS one, because the LECS can operate only when the spacecraft is not illuminated by the Sun.
$^b$ Background subtracted count rates, with photon counting statistics errors, from extraction radii of 6' for Sombrero [with the bright G0 star (Sect. 2.1) removed] and 4' for NGC 4736.

Fig. 1. The MECS image of Sombrero (left) and NGC 4736 (right) in the 2–10 keV band, smoothed with a gaussian of σ = 24". Contour levels represent the 8, 10, 15, 20, 30, 50, 70, 90 and 95% of the peak intensity (left), and 6, 8, 10, 12, 15, 20, 25, 30, 40, 50, 70 and 95% of it (right). The contours are overlaid on the DSS image of the Space Telescope Science Institute.

accumulated on different pointings of empty fields$^2$. Figs. 2 and 3 show that the source emission becomes comparable to the background level at radii of ~5–6' for Sombrero and ~3–4' for NGC 4736. The hard emission is clearly

$^2$ These files are those released in Nov. 1998 for the MECS and Dec. 1999 for the LECS. A comparison of the background emission estimated from the field of the galaxies (in a region far from sources) with that estimated from the blank fields (in the same region, in detector coordinates) shows that the two estimates agree within 5% for the MECS and 1% for the LECS.
Fig. 2. The MECS 2–10 and 4.5–10 keV radial profiles of the total (squares) and background (solid line) emission from Sombrero. Also shown is the PSF profile of 2 (dashed line) and 5 keV (dotted line) photons. A circular region of 32° radius centered on the G0 star was omitted.

Fig. 3. The MECS 2–10 and 4.5–10 keV profiles of the total (squares) and background (solid line) emission from NGC 4736. Dashed and dotted lines represent the 2 and 5 keV PSF profiles.

extended in Sombrero relative to the instrumental PSF, while a less significant excess is seen in NGC 4736 above 4 keV. In order to reassure ourselves that the angular extension is not produced by the presence of the star in Sombrero, we derived radial profiles in four azimuthal sectors positioned along the north-south and east-west axes. The same conclusions as before are drawn.

The background-subtracted PDS count rate toward the Sombrero galaxy is \((4.32 \pm 1.35) \times 10^{-2}\) counts s\(^{-1}\) in the 13–30 keV band. This corresponds to a \(\gtrsim 3\sigma\) detection. We have checked for any possible contaminants in a region of 2 degrees radius around Sombrero using the ASCA SIS and GIS and HEAO – 1 Source Catalogs; we found no catalogued and bright hard X-ray sources. Of course it is possible that both faint unknown hard X-ray sources and small systematic errors in the background subtraction (Guainazzi & Matteuzzi 1997) contribute to the observed PDS count rate. For this reason we consider this detection tentative. It must be confirmed by hard X-ray imaging observations. NGC 4736 was not detected by the PDS instrument; the net 13–30 keV count rate is \((1.8 \pm 1.3) \times 10^{-2}\) counts s\(^{-1}\).

### 2.2. Chandra observations

The journal of the Chandra ACIS-S observations (Weisskopf, O’Dell & van Speybroeck 1996) is given in Table 3. We used Level 2 reprocessed archived event files produced at the Chandra X-ray Center (CXC). The 0.3–7 keV images of the central region of the pointed fields are shown in Figs. 4 and 5, where the data were adaptively smoothed with the CXC CIAO tool csmooth. The