Chandra and XMM–Newton detection of large-scale diffuse X-ray emission from the Sombrero galaxy

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ABSTRACT
We present an X-ray study of the massive edge-on Sa galaxy, Sombrero (M 104; NGC 4594), based on XMM–Newton and Chandra observations. A list of 62 XMM–Newton and 175 Chandra discrete X-ray sources is provided, the majority of which are associated with the galaxy. Spectral analysis is carried out for relatively bright individual sources and for an accumulated source spectrum. At energies \( \gtrsim 2 \text{ keV} \), the source-subtracted X-ray emission is distributed similarly as the stellar \( K \)-band light and is primarily due to the residual emission from discrete sources. At lower energies, however, a substantial fraction of the source-subtracted emission arises from diffuse hot gas extending to \( \sim 20 \text{ kpc} \) from the galactic centre. The galactic disc shows little X-ray emission and instead shadows part of the X-ray radiation from the bulge. The observed diffuse X-ray emission from the galaxy shows a steep spectrum that can be characterized by an optically thin thermal plasma with temperatures of \( \sim 0.6–0.7 \text{ keV} \), varying little with radius. The diffuse emission has a total luminosity of \( \sim 3 \times 10^{39} \text{ erg s}^{-1} \) in the 0.2–2 keV energy range. This luminosity is significantly smaller than the prediction by current numerical simulations for galaxies as massive as Sombrero. However, such simulations do not include the effect of quiescent stellar feedback (e.g. ejecta from evolving stars and Type Ia supernovae) against the accretion from intergalactic medium. We argue that the stellar feedback likely plays an essential role in regulating the physical properties of hot gas. Indeed, the observed diffuse X-ray luminosity of Sombrero accounts for at most a few per cent of the expected mechanical energy input from Type Ia supernovae. The inferred gas mass and metal content are also substantially less than those expected from stellar ejecta. We speculate that a galactic bulge wind, powered primarily by Type Ia supernovae, has removed much of the ‘missing’ energy and metal-enriched gas from the region revealed by the X-ray observations.

Key words: galaxies: general – galaxies: individual: Sombrero, NGC 4594 – galaxies: spiral – X-rays: general.

1 INTRODUCTION
Galactic bulges are an important component of early-type spiral galaxies. X-ray studies of the high-energy phenomena and processes in galactic bulges provide a vital insight into our understanding of galaxy formation and evolution. Several facts make Sombrero (Table 1) an ideal target for such a study: (i) this nearby Sa galaxy is massive (circular rotation speed of \( \sim 370 \text{ km s}^{-1} \)) and bulge-dominated, and hence a potential site for probing a large amount of hot gas from intergalactic accretion (e.g. Toft et al. 2002) and/or internal stellar feedback (e.g. Sato & Tawara 1999); (ii) the high inclination of the galaxy (84°) allows for a clean separation between the disc and bulge/halo components; (iii) a well-determined distance (8.9 ± 0.6 Mpc) of the galaxy minimizes the uncertainty in the measurement of X-ray luminosities; (iv) as indicated by its very low specific far-infrared and diffuse radio fluxes (Bajaja et al. 1988), the galaxy shows little indication for recent star formation, minimizing the possibility of heating and/or gas ejection from the galactic disc; (v) the galaxy is isolated and thus uncertainties resulting from galaxy interaction are minimal. Therefore, Sombrero is particularly well suited for an X-ray study of high-energy stellar and interstellar products in a galactic bulge and their relationship to the galactic disc and to the intergalactic environment.

Existing X-ray studies of Sombrero have focused on its discrete X-ray sources. Di Stefano et al. (2003) reported the detection of 122 X-ray sources, based on a Chandra Advanced CCD Imaging Spectrometer, S-array (ACIS-S) observation of the galaxy. In
particular, they classified a population of very soft X-ray sources, which tend to concentrate in the core region of the galactic bulge. Wang (2004) conducted a careful analysis of the luminosity function (LF) of the discrete X-ray sources detected from the same observation by correcting for incompleteness and Eddington bias in the source detection and by removing statistical interlopers in the field. The X-ray behaviour of the central active galactic nucleus (AGN) has been studied by Pellegrini et al. (2003), based on a large sample of discrete X-ray sources detected from the same observation as well as the Chandra data.

We here report a systematic analysis of the XMM–Newton and Chandra observations (Figs 1 and 2), focusing on the study of diffuse X-ray emission in Sombrero. The Chandra data, with superb spatial resolution, are well suited for the study of the galaxy’s inner region where the X-ray source density is high. However, the field of view (FoV) of the Chandra ACIS-S, especially that of the S3 chip (∼8 × 8 arcmin²), does not provide a full coverage of the large-scale X-ray emission of the galaxy (cf. Fig. 3). The XMM–Newton European Photon Imaging Camera (EPIC) observation, on the other hand, has a substantially larger FoV, allowing us to probe the extent of the global diffuse X-ray emission. The combination of the two observations thus provides us with the most comprehensive X-ray view of the galaxy.

2 OBSERVATIONS AND DATA REDUCTION

Our data calibration procedures have been detailed in previous works which dealt with similar Chandra and XMM–Newton observations (e.g. Wang, Chaves & Irwin 2003; Li et al. 2006). Here, we summarize the essential aspects that are specific to the current data.

2.1 Chandra observations

The Chandra ACIS-S observation of Sombrero (Obs. ID. 1586) was taken on 2001 May 31 with an exposure of 18.8 ks. Our work uses the data primarily from the on-axis S3 chip, although part of the adjacent FI chips (S2 and S4) are also included in the source detection. We reprocessed the Chandra data, using CIAO, version 3.2.1 and the latest calibration files. We also removed time intervals with significant background flares, i.e. those with count rates (CRs) >3σ and/or a factor of >1.2 off the mean background level of the observation. This cleaning resulted in an effective exposure of 16.4 ks for subsequent analysis. We created count and exposure maps in the 0.3–0.7, 0.7–1.5, 1.5–3 and 3–7 keV bands. Corresponding background maps were created from the ‘stowed background’ data, which contain only events induced by the instrumental background. A normalization factor of ~1.05 was applied to the exposure of this ‘stowed background’ data in order to match its 10–12 keV CR with that of Obs. 1586.

2.2 XMM–Newton observations

The XMM–Newton EPIC observation of Sombrero (Obs. ID 0084030101) was taken on 2001 December 28, with the thin filter and with a total exposure of 43 ks. We calibrated the data using SAS, version 6.1.0, together with the latest calibration files. In this work, we only use the EPIC-PN (EPIC pn CCDs) data. We found that a large fraction of the observation was strongly contaminated by cosmic-ray-induced flares. To exclude these flares, we removed time intervals with CRs greater than 11 cts s⁻¹ in the 0.2–15 keV band, about a factor of 1.2 above the quiescent background level, and some additional intervals with residual flares found in sub-bands. The remaining exposure is only 10.8 ks for the PN. We then constructed count and exposure maps in the 0.5–1, 1–2, 2–4.5 and 4.5–7.5 keV bands for flat-fielding. We also created corresponding background maps from the ‘filter wheel closed’ (FWC) data, chiefly for instrumental X-ray background subtraction. However, we found that at energies above 5 keV the spectral shape of the instrumental background of Obs. no. 0084030101 is apparently different from that of the FWC data, making a simple normalization inapplicable. Therefore, the FWC data are only used in producing large-scale images. Background adoption for spectral analysis will be further discussed in Section 4.2.

3 DISCRETE X-RAY SOURCES

Fig. 3 shows the overall 0.5–2 keV X-ray intensity image of Sombrero obtained from the PN. The morphology appears more-or-less symmetric, reminiscent of the optical light distribution of Sombrero obtained from the PN.
the galaxy. The X-ray emission likely represents a combined contribution from discrete sources and truly diffuse hot gas. We first detect individual sources and characterize their properties. Then, we try to isolate and study the diffuse X-ray component in Section 4.

3.1 Source detection and astrometry correction

We detect 175 Chandra and 62 XMM–Newton discrete X-ray sources. Tables 2 and 6 summarize the detection results. The source detection is carried out for each observation in the broad (B), soft (S) and hard (H) bands, defined differently for the ACIS-S and PN data, as noted in the tables. Following the procedure detailed in Wang (2004), we use a combination of source detection algorithms: wavelet, sliding-box and maximum likelihood centroid fitting. The map detection and the maximum likelihood analysis are based on data within the 50 per cent PSF energy-encircled radius (EER) for the PN and the 90 per cent EER for the ACIS-S. The accepted sources all have a local false detection probability $P \leq 10^{-6}$. For ease of reference, we will refer to X-ray sources detected in the PN and the ACIS-S with prefixes XP and XA, respectively (e.g. XP-13).

Although the pointing uncertainty of Chandra is on average less than $\sim 1$ arcsec, it is still desirable to quantify and possibly improve the astrometric accuracy of any particular observation. We first use the Two-Micron All-Sky Survey (2MASS) All-Sky Catalogue of Point Sources (Cutri et al. 2003) to find potential near-infrared counterparts for an astrometric calibration. The astrometry of the 2MASS objects is generally much better ($\sim 0.1$ arcsec). We cross-correlate the spatial positions of the objects in the catalogue...
with those of the X-ray sources listed in Tables 2 and 3. For each ACIS-S source, we use a matching radius of twice its position uncertainty, with lower and upper limits of 1 and 2 arcsec. The lower limit is set to account for any systematic errors in the X-ray source positions, whereas the upper limit is to minimize the probability of chance coincidence. Similar calibration is also done for the PN sources outside the ACIS-S FoV (Fig. 2), with lower and upper matching radii of 2 and 4.

The calibration gives five Chandra/2MASS position coincidences. We estimate the required astrometric correction to be 0.4 arcsec to the west and 0.5 arcsec to the north, based on a $\chi^2$ fit to the RA and Dec. offsets of the five matched Chandra/2MASS pairs. The correction is insensitive (with changes $\lesssim 0.1$ arcsec) to the exclusion of any one of the entries in the fit. The correction improves the $\chi^2$/d.o.f. from 21/10 to 4/8. After correcting for the X-ray astrometry, one additional position coincidence (XA-149) is found.

Table 4 presents the matching results, including the position offset of each match, together with the expected position uncertainties quoted from Tables 1 and 2; there is no match with multiple 2MASS objects. The table also includes the $J$, $H$, and $K_s$ magnitudes of the matched 2MASS objects; the 3$\sigma$ limiting sensitivities of the catalogue are 17.1, 16.4 and 15.3 mag in the three bands. We estimate the expected number of chance projections of 2MASS objects within the matching regions to be $\sim 0.2$ for the ACIS-S sources and 0.5 for the PN sources, based on the surface number density of 2MASS objects within annuli of 4–15 arcsec radii around the X-ray sources. Therefore, it is possible that a couple of the matches may just be such chance projections.

The source locations are marked in Figs 1 and 2. Essentially all PN sources within the field of Fig. 2(a) are also detected in the ACIS-S data. All relatively bright ACIS-S sources, except for those in the nuclear region, are detected in the PN data. These consistencies indicate no strong variability of the sources between the two observations. Source confusion is serious for the PN data because of the limited spatial resolution. Some of the PN detections represent combinations of multiple discrete sources, e.g. XP-42 is a combination of XA-148 and 151. This is particularly the case in the nuclear region (Fig. 2c).

We note that the source detection limit is significantly higher in the PN data than in the ACIS-S data. The majority of detected sources are of two populations: sources associated with the galaxy and extragalactic sources mostly being background AGNs. Applying the LF of the AGNs obtained by Moretti et al. (2003), we estimate the number of detected AGNs to be 15.5 (2.3) in the ACIS-S (PN) FoV.

### 3.2 Individual spectra of bright sources

There are eight bright sources in the ACIS-S field as detected with a CR higher than 0.01 cts s$^{-1}$. These are XA-10, 15, 26, 28, 96, 98, 121 and 124 (Table 2). Among them, XA-15 is a foreground star, XA-10 and XA-28 are located outside the S3 chip, X-96 is the nucleus which has been studied by Pellegrini et al. (2003) and X-98 is located within 3 arcsec from the nucleus. We perform spectral fit to individual ACIS-S spectra of the rest three sources, each extracted from a circular region of twice the 90 per cent EER. Corresponding background spectra are extracted from the source-free vicinity of each source. The spectra of XA-26 and XA-121 are fitted by an absorbed power law, whereas the spectrum of XA-124, being very soft, is fitted by an absorbed blackbody. The fit results, summarized in Table 5, are statistically consistent with those obtained by Di Stefano et al. (2003). The spectra and the best-fitting models are shown in Figs 4(a)–(c).

### 3.3 Accumulated source spectrum

We further obtain an accumulated ACIS-S spectrum of the sources to characterize their average spectral property (Fig. 4d). The spectrum is extracted from sources within the $D_{25}$ ellipse; 8.7 $\times$ 3.5 arcmin$^2$, except for the nuclear source and the three bright sources discussed above. The total number of included sources is $\sim 110$. For each source, a circular region of twice the 90 per cent EER is adopted for accumulating the spectrum. A background spectrum is extracted from the rest region of the ellipse. In the PN data, only 10 sources are detected within the $D_{25}$ ellipse and four of them are located within 1.5 arcmin from the galactic centre, where the emission of the nucleus largely affects. Therefore, we do not analyse an accumulated source spectrum from the PN.

We use an absorbed power-law model (PL) to fit the accumulated spectrum, with the absorption being at least that supplied by the Galactic foreground. The model offers an acceptable fit to the spectrum (Table 5), giving a best-fitting photon index of $1.51^{+0.10}_{-0.09}$ and a 0.3–7 keV intrinsic luminosity of $\sim 2.6 \times 10^{40}$ erg s$^{-1}$. All quoted errors in this paper are at the 90 per cent confidence level. The slope of the power law is typical for composite X-ray spectra of low-mass X-ray binaries observed in nearby galaxies (LMXBs; e.g. Irwin, Athey & Bregman 2003). We note that none of the included sources contributes more than 5 per cent of the total counts to the accumulated spectrum. Therefore, the spectrum, along with the fitting model, can be used to characterize the average spectral property of sources.

### 4 THE SOURCE-SUBTRACTED X-RAY EMISSION

Our main interest here is in the diffuse X-ray emission from Sombrero. A first step towards isolating the diffuse emission is to subtract the detected discrete sources from the images. To do so, we exclude regions enclosing twice the 50 per cent (90 per cent) EER around...
each PN (ACIS-S) source with a CR $\leq 0.01$ cts s$^{-1}$. For brighter sources, a factor of $1 + \log(\text{CR} / 0.01)$ is further multiplied to the source-subtraction radius. Our choice of the regions is a compromise between excluding a bulk of the source contribution and preserving a sufficient field for the study of the source-subtracted emission. With the above criteria, about 80 per cent (95 per cent) of photons from individual sources are removed from the PN (ACIS-S) image.

The source-subtracted emission presumably consists of two components: the emission of truly diffuse gas and the collective discrete contributions from the residual emission of detected sources and the emission of undetected sources below our detection limit. In practice, the discrete component can be constrained from its distinct spatial distribution and spectral property. Below, we isolate the two components and characterize the properties of the diffuse emission.

4.1 Spatial properties

4.1.1 Surface intensity profiles

We construct instrumental background-subtracted and exposure-corrected galactocentric radial surface intensity profiles for the source-subtracted emission, in the soft (0.5–1 keV for the PN; 0.3–0.7 keV for the ACIS-S), intermediate (1–2 keV for the PN; 1.5–7.0 keV for the ACIS-S) bands (Fig. 5). While the ACIS-S instrumental background is determined from the ‘stowed background’ data, the instrumental background rates in the PN bands are predicted from the spectral fit to a local PN background spectrum (see Section 4.2). Spatial binning of annuli is adaptively adjusted to achieve a signal-to-noise ratio better than 3, with a minimum step-size of 6 arcsec for the PN and 3 arcsec for the ACIS-S.
the PN profiles, the central 1.5 arcmin is heavily contaminated by the emission from the nucleus. Thus, our analysis for the PN data is restricted to radii beyond 1.5 arcmin. The ACIS-S data, while being capable to probe the central region, are limited by its FoV. Therefore, we restrict our analysis of the ACIS-S profiles within 3.5 arcmin, a maximal radius where complete annuli can be extracted.

It is known that Sombrero has a prominent dust lane (e.g. Knapen et al. 1991; cf. Fig. 3), which may significantly absorb soft X-rays from the galaxy and hence introduce a bias to the bin-averaged intensity. Therefore, when constructing the intensity profiles we exclude a region encompassing the dust lane. We use the digitized sky-survey blue image of the galaxy to map such a region of extinction, in which a pixel is adopted as the region boundary if it is dimmed by a factor being capable to probe the central region, are limited by its FoV.
We then fit the radial distribution of the diffuse component with a subtracting the discrete component from the total intensity profile. The diffuse component is then determined for these two bands by strain the discrete component in the soft and intermediate bands. (Section 3.3). This allows us to use the hard-band intensity to constant intensity (+ \gamma / \alpha + 0.9 \text{arcmin}^{\alpha}). In comparison, the K-band half-light radius is ~1 arcmin (~2.6 kpc; Jarrett et al. 2003). This suggests that the distribution of hot gas is substantially more extended than that of the stellar content.

We also construct vertical intensity profiles of the source-subtracted emission along the galaxy’s minor axis for the ACIS-S 0.3–0.7, 0.7–1.5 and 1.5–7 keV bands (Fig. 6). In general, the intensity decreases rapidly with the offset-distance. We follow the above procedure to decompose the diffuse and discrete components of the vertical profiles. An exponential law, i.e. $I(z) = I_e^{-e^{-z/a_z}}$, is used to fit to the vertical distribution of the diffuse component. The scaleheight $a_z$ is allowed to be different between the south and north sides of the mid-plane. The fit is marginally acceptable, with excess existing at ~2 arcmin from the mid-plane on both sides. Fit results (Table 7) show that in each band there is no significant asymmetry in the intensity distribution with respect to the mid-plane. The best-fitting scaleheight in the soft band (~1/4 arcmin) is less than that in the intermediate band (~1/3 arcmin), indicating that emission is softer in the central region than in the extraplanar region. When the above fit is restricted to a vertical distance >0.5 arcmin, the best-fitting scaleheights for the soft and intermediate bands are nearly identical (~1 arcmin). This is evident that the temperature of hot gas around the disc plane is lower than that in the bulge.

### 4.1.2 Inner region and substructures

We use the ACIS data to probe the diffuse X-ray properties in the inner region of the galaxy. We fill the holes from the source removal with the values interpolated from surrounding bins. Fig. 7 shows ‘diffuse’ X-ray intensity contours, which are substantially less smoothed than presented in Fig. 3. There are considerable substructures in the inner region. Inner contours are extended more to the north than to the south (where strong intensity gradients are

found), indicating a heavier absorption of X-ray emission to the south. This is clearly due to the prominent dust lane that lies at the 10–25 arcsec range to the south of the major axis (Knappen et al. 1991). The intensity contours also become strongly elongated along the galactic disc.

Fig. 7 also presents in grey-scale a continuum-subtracted Hα image of Sombrero, obtained with the 0.9-m telescope at Kitt Peak National Observatory in 1999. The details of observations are presented elsewhere (Hameed & Devereux 2005). Hα emission is distributed, primarily, in an annulus, and individual H II regions can be identified on the ring. There is some Hα emission within the ring, but it is difficult to tell from the image if the emission is diffuse or if it contains H II regions. The Hα ring follows the optical dust lane but is located on its inner side. High extinction possibly obscures ionized emission from the dust lane itself.
which is lower than the average star formation rate (0.9 M⊙/yr) by extinction, is calculated to be 7.5 ± 1.92. The region beyond.

The disc must be absorbing a large fraction of X-ray emission from the X-ray radiation. In contrast, good Hα emission is typically seen in late-type spirals (e.g. Wang et al. 2003; Strickland et al. 2005).

The total Hα flux for Sombrero, uncorrected for internal or external extinction, is calculated to be ~0.8 × 10⁻¹² erg s⁻¹ cm⁻², which translates to a luminosity of ~7.6 × 10⁸ erg s⁻¹. Using Kennicutt’s (1998) formula, we derive a star formation rate of ~0.1 M⊙ yr⁻¹, which is lower than the average star formation rate (0.9 M⊙ yr⁻¹) for early-type spirals (Hameed & Devereux 2005).

Fig. 7 shows that X-ray intensity drops abruptly in the field covered by the front side of the Hα disc, corresponding to the inner region of the cold gas disc of the galaxy. This means that the Hα-emitting region does not contribute appreciable amounts to X-ray radiation. In contrast, good Hα/X-ray correlation is typically seen in late-type spirals (e.g. Wang et al. 2003; Strickland et al. 2004). In fact, the diffuse X-ray intensity in Sombrero is so low in the field covered by the front side of the cool gas disc that the disc must be absorbing a large fraction of X-ray emission from the region beyond.

We probe the azimuthal variation of diffuse emission in the inner region. Fig. 8 shows the azimuthal ACIS-S 0.3–1.5 keV intensity distributions. The distributions deviate from axisymmetry significantly. But the deviations are largely coupled with the orientation of the bulge (0° aligns with the minor axis). When the azimuthal intensity distributions are measured within elliptical annuli with an axis ratio similar to that of the bulge (Fig. 8), the deviations are significantly reduced, with smaller scale fluctuations remaining in certain azimuthal ranges, especially in the inner region. For example, dips present at ~200°–250° and ~330°–350° find their counterparts in Fig. 7. At larger radii, only moderate deviations from axisymmetry can be seen from the azimuthal intensity distributions for the PN data. When an axis ratio of 0.8 is adopted to reflect the geometry of the bulge, most of the deviations vanish and no substantial fluctuations are present. This is evidence that the diffuse emission is nearly axisymmetric at large scale.

Total Hα flux for Sombrero, uncorrected for internal or external extinction, is calculated to be ~0.8 × 10⁻¹² erg s⁻¹ cm⁻², which translates to a luminosity of ~7.6 × 10⁸ erg s⁻¹. Using Kennicutt’s (1998) formula, we derive a star formation rate of ~0.1 M⊙ yr⁻¹, which is lower than the average star formation rate (0.9 M⊙ yr⁻¹) for early-type spirals (Hameed & Devereux 2005).

Table 3. Source Identification.

<table>
<thead>
<tr>
<th>Source</th>
<th>XMMU name</th>
<th>δ (arcsec)</th>
<th>CR (cts ks⁻¹)</th>
<th>HR1</th>
<th>Flag</th>
</tr>
</thead>
<tbody>
<tr>
<td>54</td>
<td>J124016.84–114428.3</td>
<td>5.0</td>
<td>7.53 ± 1.92</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>55</td>
<td>J124024.01–113852.1</td>
<td>4.3</td>
<td>3.71 ± 1.45</td>
<td>–</td>
<td>S</td>
</tr>
<tr>
<td>56</td>
<td>J124024.47–114818.8</td>
<td>5.8</td>
<td>11.04 ± 3.13</td>
<td>–</td>
<td>B</td>
</tr>
<tr>
<td>57</td>
<td>J124025.74–114208.2</td>
<td>3.9</td>
<td>7.39 ± 1.81</td>
<td>–</td>
<td>B</td>
</tr>
<tr>
<td>58</td>
<td>J124027.09–114701.7</td>
<td>4.8</td>
<td>20.44 ± 3.49</td>
<td>–</td>
<td>–0.47 ± 0.16</td>
</tr>
<tr>
<td>59</td>
<td>J124029.34–113643.0</td>
<td>3.6</td>
<td>8.67 ± 1.91</td>
<td>–</td>
<td>B</td>
</tr>
<tr>
<td>60</td>
<td>J124031.31–113156.7</td>
<td>2.8</td>
<td>17.65 ± 2.76</td>
<td>–</td>
<td>0.53 ± 0.17</td>
</tr>
<tr>
<td>61</td>
<td>J124045.40–113918.1</td>
<td>5.4</td>
<td>6.69 ± 2.22</td>
<td>–</td>
<td>S</td>
</tr>
<tr>
<td>62</td>
<td>J124048.10–113703.7</td>
<td>4.2</td>
<td>22.22 ± 3.40</td>
<td>–</td>
<td>0.05 ± 0.17</td>
</tr>
</tbody>
</table>

Notes. The full table is available electronically. The definition of the bands: 0.5–1 (S1), 1–2 (S2), 2–4.5 (H1) and 4.5–7.5 keV (H2). In addition, S = S1+S2, H = H1+H2 and B = S+H. Column (1): generic source number. (2): XMM–Newton X-ray Observatory (unregistered) source name, following the XMM–Newton naming convention and the IAU Recommendation for Nomenclature (http://cdsweb.u-strasbg.fr/iau-spec.html). (3) Position uncertainty (1σ) calculated from the maximum likelihood centroiding. (4) On-axis source broad-band CR – the sum of the exposure-corrected CR in the four bands. (5–6): the hardness ratios defined as $HR = (S_2 - S_1)/S$, listed only for values with uncertainties less than 0.2. (7): The label ‘B’, ‘S’ or ‘H’ mark the band in which a source is detected with the most accurate position that is adopted in Column (3).

Table 4. Spectral fits of discrete sources.

<table>
<thead>
<tr>
<th>Source</th>
<th>$N_H$ (10²² cm⁻²)</th>
<th>Photon indexa</th>
<th>Temperatureb (keV)</th>
<th>$\chi^2$/d.o.f.</th>
<th>$L_X$ (0.3–7 keV) (10³⁹ erg s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>XA-26</td>
<td>8.60⁺₁₁⁻₁₀</td>
<td>2.13⁺₀.₁₆⁻₀.₄₆</td>
<td>–</td>
<td>6.3/7</td>
<td>0.7</td>
</tr>
<tr>
<td>XA-121</td>
<td>8.2⁺₁₂⁻₈.₂</td>
<td>1.87⁻₀.₄₄</td>
<td>–</td>
<td>14.9/12</td>
<td>1.1</td>
</tr>
<tr>
<td>XA-124</td>
<td>3.4⁻₄⁺₃.₄</td>
<td></td>
<td>0.19⁻₀.₀₃</td>
<td>21.1/21</td>
<td>0.9</td>
</tr>
<tr>
<td>Accumulated</td>
<td>10.7⁻₂⁺⁻₂.₁</td>
<td>1.51⁻₀.₀₉⁻₀.₁₀</td>
<td>–</td>
<td>115.2/144</td>
<td>26</td>
</tr>
</tbody>
</table>

Notes.aFor a PL.bFor a black-body emission model.
4.2 Spectral properties of the diffuse X-ray emission

With the above spatial properties in mind, we perform spectral analysis of source-subtracted emission from a series of concentric annuli around the galactic centre. Specifically, spectra are extracted from two annuli with inner-to-outer radii of 30 arcsec to 1–2 arcmin for the ACIS-S data and two annuli of 2–4 and 4–6 arcmin for the PN data. The dust lane region (Section 4.1.1) is excluded from the spectral extraction.

Two factors complicate the background determination in our spectral analysis. First, the sky location of Sombrero is on the edge of the North Polar Spur (NPS), a Galactic soft X-ray-emitting...
I instrumental background is predominant, the local background spectrum of PN, both instrumental and cosmic, by a combination of plausible components. To model the instrumental background, a broken power law plus several Gaussian lines is applied (Nevala, Markewitch & Lumb 2005). The modelling of the cosmic background consists of three components. Two of them are thermal (the APEC model in XSPEC), representing the emission from the Galactic halo (temperature \( \lesssim 0.1 \) keV) and the NPS (temperature \( \sim 0.25 \) keV; Willingale et al. 2003), respectively. The third component is a power law with the photon index fixed at 1.4, representing the unresolved extragalactic X-ray emission (Moretti et al. 2003). Our combined model results in a good fit to the local background spectrum. We note that the decomposition of the local background is not unique, especially at lower energies (\( \lesssim 1 \) keV). We verify our modelling by the fact that the fitted parameters of these commonly used cosmic components are in good agreement with independent measurements (e.g. Moretti et al. 2003; Willingale et al. 2003). The background spectrum in the 0.5–7 keV range, grouped to have a minimum number of 30 counts in each bin, is shown in Fig. 9. The model, scaled according to the corresponding sky areas, is included in the following fit to the PN spectra of source-subtracted emission.

The spectral shape of the ACIS-S instrumental background is rather stable at energies \( \gtrsim 0.5 \) keV.1 Also, as the ACIS-S spectra of source-subtracted emission are extracted within the central 2 arcmin where the surface intensity is peaked, a small uncertainty in the instrumental background subtraction would only cause a minor effect in the analysis. Therefore, we directly subtract a ‘stowed background’ spectrum from the ACIS-S spectra of source-subtracted emission and group them to achieve a signal-to-noise ratio better than 3. The remaining cosmic X-ray background is modelled with the same components as for the PN spectra. We note that an additional factor of 0.43, estimated from the LF obtained by Moretti et al. (2003), is multiplied to the scaling of the extragalactic component in order to account for the lower source detection limit in the ACIS-S data (Wang 2004).

The spectra show a clear line feature at \( \sim 0.9 \) keV (Fig. 10), presumably due to the Fe L-shell complex contributed by the hot gas, while at energies above 1.5 keV the spectra are dominated by the residual emission of discrete sources. We account for the discrete contribution with a PL with a fixed photon index of 1.4, representing the unresolved extragalactic X-ray emission (Moretti et al. 2003). Our combined model results in a good fit to the local background spectrum. We note that the decomposition of the local background is not unique, especially at lower energies (\( \lesssim 1 \) keV). We verify our modelling by the fact that the fitted parameters of these commonly used cosmic components are in good agreement with independent measurements (e.g. Moretti et al. 2003; Willingale et al. 2003). The background spectrum in the 0.5–7 keV range, grouped to have a minimum number of 30 counts in each bin, is shown in Fig. 9. The model, scaled according to the corresponding sky areas, is included in the following fit to the PN spectra of source-subtracted emission.

\footnote{http://cxc.harvard.edu/contrib/maxim/stowed/}

\[ X(R) = I_X(R) + I_e^{-7.67/R_0^{1/4}} + I_b, \]
Table 7. Fits to the vertical intensity profiles.a

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ACIS-S (0.3–0.7 keV)</th>
<th>ACIS-S (0.7–1.5 keV)</th>
<th>ACIS-S (1.5–7 keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2$/d.o.f.</td>
<td>47.2/28</td>
<td>70.4/45</td>
<td>10.5/8</td>
</tr>
<tr>
<td>$I_s(10^{-4}$ cts s$^{-1}$ arcmin$^{-2}$)</td>
<td>160$^{+30}_{-30}$</td>
<td>110$^{+14}_{-14}$</td>
<td>0.22$^{+0.05}_{-0.05}$</td>
</tr>
<tr>
<td>$b_0$ (arcmin)</td>
<td>0.22$^{+0.05}_{-0.05}$</td>
<td>0.31$^{+0.06}_{-0.06}$</td>
<td>0.64$^{+0.08}_{-0.08}$</td>
</tr>
<tr>
<td>$b_0$ (arcmin)</td>
<td>1.0</td>
<td>2.9</td>
<td>2.8</td>
</tr>
<tr>
<td>$b_0$ (10$^{-4}$ cts s$^{-1}$ arcmin$^{-2}$)</td>
<td>11.8</td>
<td>6.7</td>
<td>2.8</td>
</tr>
</tbody>
</table>

Notes. aThe 1.5–7 keV profile is fitted by a normalized $K$-band profile plus a local constant background: $I_K(z) = I_s K(z) + I_b$. For the softer bands, an additional exponential law is applied: $I_X(z) = I_s K(z) + I_{ge} - |z|/z_0 + I_b$. The first and the second values are for the south and north sides, respectively. Same normalization factors and local background rates are applied as for the radial profiles (Table 6).

emission model (APEC) characterizing the emission of hot gas, is used to simultaneously fit the four spectra. Both components are subject to the Galactic foreground absorption. The temperature of the hot gas is allowed to vary, but the abundance is linked among the four spectra. We adopt the abundance standard of Grevesse & Sauval (1998) and set a physically meaningful upper limit of 10 solar for the abundance. The model gives a statistically acceptable fit to all four spectra, with the overall $\chi^2$/d.o.f. = 481.9/511. Fit results (Table 8) suggest that the gas temperature varies little with radius. Interestingly, the metal abundance (≥0.4 solar) is well distinguished from very sub-solar values that were often reported in galactic X-ray studies (e.g. NGC 253; Strickland et al. 2002; NGC 4631, Wang et al. 2001). We suggest that this owes to the proper modelling of the local background, especially at energies below 0.7 keV, where the thermal continuum from the galaxy is highly entangled with the background components. An example of this kind has also been presented by Humphrey & Buote (2006), who find near-solar iron abundances for the hot gas in most of their sample early-type galaxies.

We further use the PROJCT model in XSPEC to fit the spectra for a 2D to 3D deprojection, i.e. the fitting parameters are measured for consecutive spherical shells. The fit is of similar significance, with a $\chi^2$/d.o.f. = 483.2/511. Fit results are listed in Table 9, again indicating a quasi-isothermal hot gas with marginally super-solar abundance in the bulge of Sombrero.

The fitted amount of the PL component in individual spectrum is verified by estimating the contribution of unresolved galactic...
sources. Wang (2004) obtained the LF for the detected galactic sources, mostly LMXBs. Assuming that this LF is also valid for sources below the source detection limit and varies little among the regions of our spectral interest, the contribution of unresolved sources can be taken as the integrated flux from the LF, weighted by the amount of K-band light within individual annulus. We note that the integrated flux of unresolved sources in the PN is ~4 times higher than that in the ACIS-S, due to the higher source detection limit in the PN. The fitted PL fluxes (Table 9) are consistent with the X-ray-to-K-band intensity ratio obtained from the spatial analysis (Table 6), given a CR to flux conversion factor predicted by the PL.

Assuming a filling factor of unity, the mean densities of hot gas are ~6.6, 2.8, 1.2 and 0.79 × 10^{-3} cm^{-3} in the four consecutive shells with increasing radii, derived from the 3D spectral analysis (Table 9). These are shown versus radius in Fig. 11. Also shown is the density profile inferred from the best-fitting de Vaucouleur’s law to the radial intensity distributions (Section 4.1.1; Young 1976),

Table 8. 2D fits to the spectra of source-subtracted emission.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>30 arcsec^{-1} arcm</th>
<th>1–2 arcm</th>
<th>2–4 arcm</th>
<th>4–6 arcm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (keV)</td>
<td>0.62^{+0.09}_{-0.09}</td>
<td>0.59^{+0.07}_{-0.10}</td>
<td>0.63^{+0.07}_{-0.06}</td>
<td>0.78^{+0.13}_{-0.11}</td>
</tr>
<tr>
<td>Abundance (solar)</td>
<td>1.4 (&gt;0.4)</td>
<td>Same</td>
<td>Same</td>
<td>Same</td>
</tr>
<tr>
<td>Photon index</td>
<td>1.51^{b}</td>
<td>Same</td>
<td>Same</td>
<td>Same</td>
</tr>
<tr>
<td>Normalization (APEC; 10^{-5})</td>
<td>2.3^{+0.5}_{-0.5}</td>
<td>3.6^{+0.7}_{-0.7}</td>
<td>3.8^{+0.6}_{-0.6}</td>
<td>2.7^{+0.7}_{-0.8}</td>
</tr>
<tr>
<td>Normalization (PL; 10^{-5})</td>
<td>1.1^{+0.8}_{-0.8}</td>
<td>1.2^{+1.0}_{-0.9}</td>
<td>4.0^{+0.8}_{-0.8}</td>
<td>2.1^{+1.2}_{-1.1}</td>
</tr>
<tr>
<td>f_{0.2–2 keV} (APEC; 10^{-14} erg cm^{-2} s^{-1})</td>
<td>6.2</td>
<td>9.3</td>
<td>9.9</td>
<td>7.2</td>
</tr>
<tr>
<td>f_{0.3–7 keV} (PL; 10^{-14} erg cm^{-2} s^{-1})</td>
<td>7.2</td>
<td>8.0</td>
<td>26.5</td>
<td>14.1</td>
</tr>
</tbody>
</table>

Notes. The spectra extracted from four consecutive annuli are fitted by a combined model of APEC+power law (PL) with the Galactic foreground absorption.

Table 9. 3D fits to the spectra of source-subtracted emission.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>30 arcsec^{-1} arcm</th>
<th>1–2 arcm</th>
<th>2–4 arcm</th>
<th>4–6 arcm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (keV)</td>
<td>0.64^{+0.14}_{-0.20}</td>
<td>0.57^{+0.14}_{-0.16}</td>
<td>0.58^{+0.16}_{-0.25}</td>
<td>0.75^{+0.10}_{-0.11}</td>
</tr>
<tr>
<td>Abundance (solar)</td>
<td>1.7 (&gt;0.4)</td>
<td>Same</td>
<td>Same</td>
<td>Same</td>
</tr>
<tr>
<td>Photon index</td>
<td>1.51^{b}</td>
<td>Same</td>
<td>Same</td>
<td>Same</td>
</tr>
<tr>
<td>Normalization (APEC; 10^{-5})</td>
<td>2.0^{+0.7}_{-0.7}</td>
<td>2.7^{+0.8}_{-0.8}</td>
<td>4.6^{+1.1}_{-1.1}</td>
<td>4.9^{+1.5}_{-1.5}</td>
</tr>
<tr>
<td>Normalization (PL; 10^{-5})</td>
<td>1.1^{+0.8}_{-0.8}</td>
<td>1.2^{+1.0}_{-0.9}</td>
<td>4.0^{+0.9}_{-0.9}</td>
<td>2.2^{+1.2}_{-1.1}</td>
</tr>
<tr>
<td>f_{0.2–2 keV} (APEC; 10^{-14} erg cm^{-2} s^{-1})</td>
<td>6.1</td>
<td>9.3</td>
<td>10.0</td>
<td>7.0</td>
</tr>
<tr>
<td>f_{0.3–7 keV} (PL; 10^{-14} erg cm^{-2} s^{-1})</td>
<td>7.2</td>
<td>8.0</td>
<td>26.2</td>
<td>14.6</td>
</tr>
</tbody>
</table>

Notes. The spectra extracted from four consecutive annuli are fitted by a combined model of PROJCT(APEC)+power law (PL) with the Galactic foreground absorption, where the emission is deprojected and the parameters are measured for consecutive shells.

with the assumption that the temperature of gas is constant along with radius. This profile fairly matches the spectral measurement, indicating consistency between our spatial and spectral analyses.

As shown in Section 4.1.2, deviations from the assumed axisymmetry are present in the diffuse emission, especially in the inner region. Nevertheless, even in the innermost annulus, the deviations would only introduce an uncertainty of 30 per cent in the average intensity, or $\sim 15$ per cent in the measured density. Therefore, the presence of the moderate deviations does not qualitatively affect the determination of the radial profile of hot gas and its implications as we discuss below.

The total mass of hot gas contained in the shells is $\sim 4.6 \times 10^8 M_\odot$ yr$^{-1}$, and the intrinsic 0.2–2 keV luminosity from our spectral extraction region is $\sim 3.1 \times 10^{39}$ erg s$^{-1}$. We note that these values can be approximated as the total mass and luminosity of hot gas in Sombrero, given the steep density distribution (Section 4.1.1). For example, the luminosity within the central 6 arcmin is about 75 per cent of the total for a de Vaucouleur’s distribution with a half-light radius of 2.5 arcmin.

5 DISCUSSION

5.1 The thermal structure of hot gas

We further compare the measured density profile with that predicted from variant thermal structures that may be assumed for the hot gas. One commonly assumed case is that the gas is in hydrostatic equilibrium, i.e. the density profile is simply determined by the gravitational potential and the equation of state for the gas. A second case is that the gas is in the form of a large-scale outflow, i.e. a galactic wind (e.g. Mathews & Baker 1971; Bregman 1980; White & Chevalier 1983), in which the physical structure of the wind predicts. We suggest that this might be the case in Sombrero. A quantitative study of the NEI emission from galactic winds is under investigation.

We now turn to discuss the origin of the hot gas in specific scenarios.

5.2 Accretion from the intergalactic medium?

One scenario that may favour a quasi-hydrostatic gaseous halo comes from a specific prediction of current theories of galaxy formation and evolution: the gas is accreted from the intergalactic medium (IGM) and maintained in the haloes of spiral galaxies. The IGM is supposedly heated to X-ray-emitting temperatures, chiefly due to accretion shocks and gravitational compression (e.g. Toft et al. 2002). Naturally, the X-ray luminosity of gas is a strong function of the gravitational mass of the host galaxy, as characterized by its circular rotation speed ($L_x \propto V_c^2$; Toft et al. 2002).

Surprisingly, there is little direct observational evidence for the presence of such X-ray-emitting haloes even around massive spiral galaxies. Given the high circular rotation speed of Sombrero ($\sim 370$ km s$^{-1}$), it is a good candidate to look for X-ray signals from an accreted gaseous halo around it. Toft et al. (2002, therein fig. 3) predict a 0.2–2 keV X-ray luminosity of $\sim 10^{41}$ erg s$^{-1}$ for galaxies with circular rotation speeds similar to that of Sombrero, about 95 per cent of which coming from within 20 kpc of the disc. However, the observed 0.2–2 keV diffuse X-ray luminosity from Sombrero is only $\sim 3 \times 10^{39}$ erg s$^{-1}$ within the central $\sim 15$ kpc. Therefore, there is a remarkable discrepancy between the amount of observed extraplanar hot gas and that predicted by numerical simulations.

If the hot gas in Sombrero is indeed accreted from the IGM, what may be the cause for this discrepancy? One plausible answer is that the existing simulations have not adequately accounted for the feedback from galaxies, especially the heating due to Type Ia supernovae (SNe). Such stellar feedback tends to provide an effective form of
large-scale distributed heating and thus reduce the cooling of gas in the galactic bulges and haloes. If the feedback is strong enough, the galaxy may even cease further accretion.

5.3 Stellar feedback from Sombrero

Empirically, stars in a galactic bulge continuously deposit energy and mass to the interstellar medium (ISM) at rates of $\sim 6 \times 10^{40} [L_\text{B}/(10^{10} L_{\odot})] \text{ erg s}^{-1}$ and $\sim 0.2 [L_\text{B}/(10^{10} L_{\odot})] M_\odot \text{ yr}^{-1}$ (e.g. Knapp, Gunn & Wynn-Williams 1992; Mannucci et al. 2005), respectively, where $L_\text{B}$ is the blue luminosity of the bulge. Both the stellar mass loss and the Type Ia SN rates are believed to be substantially greater at high redshifts when the bulges are young (e.g. Ciotti et al. 1991). Meanwhile, if the metals contained in the stellar ejecta are uniformly mixed with the ISM, the mean iron abundance of the ISM is expected to be $Z_{\text{Fe}} = Z_{\star,\text{Fe}} + 7.4 (M_{\text{Fe}}/0.7 M_\odot)$, where $M_{\text{Fe}}$ is the iron mass yield per Type Ia SN (e.g. Nomoto, Thielemann & Yokoi 1984) and a solar iron-to-hydrogen ratio in number of $3.16 \times 10^{-5}$ is adopted (Grevesse & Sauval 1998).

Had most of the stellar feedback been retained by the ISM in the galaxy since the onset of Type Ia SNe, it is expected that the observed X-ray luminosity and mass of hot gas be the amount inferred from the above energy and mass input rates. In the case of Sombrero, $L_\text{B} = 3.8 \times 10^{40} L_\odot$, corresponding to an energy input rate of $\sim 2.4 \times 10^{41} \text{ erg s}^{-1}$ and a mass input rate of $\sim 0.8 M_\odot \text{ yr}^{-1}$, or a total mass input of $8 \times 10^{9} M_\odot$ over a period of 10 Gyr. However, our measurement (Section 5.1) shows that the rate of energy released from and the mass contained in the hot gas of Sombrero are nearly 2 orders of magnitude lower than the empirical expectations. Given the prominent Fe L-shell features in the spectra, the fitted metal abundance should be largely weighted by the abundance of iron. Hence, the fitted value is also lower than the empirical expectation, if the iron ejected by the SNe is uniformly distributed into the ISM. It is worth to note that metal abundance can easily be underestimated in the spectral analysis of X-ray CCD data, especially with oversimplified models (e.g. in the case of NGC 1316 as demonstrated by Kim & Fabbiano 2003). Nevertheless, the lack of metals in Sombrero is evident and mostly tied to the small amount of X-ray emission driving the ISM. Overall, there is a ‘missing stellar feedback’ problem in Sombrero.

In fact, this ‘missing stellar feedback’ problem is often met in the so-called low $L_\text{X}/L_\text{B}$ early-type galaxies (typically Sa spirals, S0 and low-mass ellipticals), where the X-ray luminosity, mass and metal content of the hot gas inferred from observations represent only a small fraction of what is expected from the stellar feedback (Irwin, Sarazin & Bregman 2002; O’Sullivan, Ponman & Collins 2003). These discrepancies are a clear indication for Type Ia SN-driven galactic winds (e.g. Irwin et al. 2002; Wang 2005). Globally, winds can continuously transport the bulk of stellar depositions into the IGM, leaving only a small fraction to be revealed within the optical extent of the host galaxy. Locally, our analysis (Section 5.1) for Sombrero indeed shows that the thermal structure of a wind is reasonably consistent with the observation, although more detailed considerations involving NEI processes in the gas are likely needed.

5.4 Feedback from the central AGN

Feedback from AGNs is a potential and sometimes favourable mechanism to affect the accretion of the IGM and the structure of hot gas. This is suggested to be the case in Sombrero (Pellegrini et al. 2003), even though its AGN has only a very sub-Eddington luminosity.

AGN feedback, if present, would disturb the gas distribution in the circumnuclear region. For example, dips seen in the X-ray intensity distributions at certain azimuthal ranges (Figs 7 and 8) might be the result of hot gas removal by the collimated ejecta from the AGN. However, no strong evidence of such collimated ejecta is seen in the radio continuum map of Sombrero (Bajaja et al. 1988). Furthermore, the inclusion of the AGN feedback would only increase the energy discrepancy discussed above. Therefore, although the possibility of AGN feedback cannot be ruled out, we suggest that it plays little role in regulating the large-scale structure of hot gas in Sombrero.

6 SUMMARY

We have conducted a systematic analysis of the XMM–Newton and Chandra X-ray observations of the nearby massive Sa galaxy Sombrero. The main results of our analysis are as follows.

(i) We have detected large-scale diffuse X-ray emission around Sombrero to an extent of $\sim 20$ kpc from the galactic centre, which is substantially more extended than the stellar content.

(ii) While at large scale the distribution of the diffuse X-ray emission tends to be smooth, intensity fluctuations are present in the inner region.

(iii) Our spectral analysis of the diffuse emission reveals a gas temperature of 0.6–0.7 keV, with little spatial variation, while the measured gas density drops with increasing radius, in a way apparent different from the expected density distribution of either an isothermal gas in hydrostatic equilibrium or a galactic wind, assuming CIE emission.

(iv) We have compared our measurements with the predictions of numerical simulations of galaxy formation and found that the observed 0.2–2 keV luminosity ($\sim 3.3 \times 10^{40} \text{ erg s}^{-1}$) is substantially lower than the predicted value.

(v) We have further compared the mass, energy and metal contents of the hot gas with the expected inputs from the stellar feedback in Sombrero. Much of the feedback is found to be missing, as is the case in some other X-ray faint early-type galaxies. A logical solution for this missing stellar feedback problem is the presence of a galactic wind, driven primarily by Type Ia SNe.

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REFERENCES


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