DIFFUSE X-RAY EMISSION FROM THE SPIRAL GALAXY NGC 2403 DISCOVERED WITH CHANDRA

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ABSTRACT

We have detected diffuse soft X-ray emission (0.4–1 keV) from the disk of the spiral galaxy NGC 2403 with Chandra. This diffuse emission [with a total luminosity of $2.1 \times 10^{38}$ ergs s$^{-1}$ and a gas temperature of $(2-8) \times 10^{6}$ K] is well separated from the numerous bright point sources. NGC 2403 is a luminous spiral galaxy with a high rate of star formation. Recent H I observations have revealed an extended H I halo with anomalous velocities and a general inflow toward the central regions of the galaxy. This result and the present detection of a diffuse, hot X-ray–emitting gas point to a very active disk-halo connection and galactic fountain types of phenomena.

Subject headings: galaxies: individual (NGC 2403) — galaxies: ISM — galaxies: kinematics and dynamics — galaxies: structure

On-line material: color figures

1. INTRODUCTION

Before the launch of Chandra, the study of diffuse X-ray emission from normal (nonstarburst) spiral galaxies was seriously impeded by lack of spatial resolution (Fabbiano 1989). The point sources could not be well separated from the diffuse thermal gas. The detection of diffuse emission from the disk of spiral galaxies was therefore possible only for some nearby objects (e.g., M33, Long et al. 1996; M101, Snowden & Pietsch 1995; M51, Ehle, Pietsch, & Beck 1995). Coronal (halo) emission was observed in some nearby edge-on spiral galaxies like NGC 891 (Bregman & Houck 1997) and NGC 4631 (Wang et al. 1995, 2001). Also, the diffuse component of the hot thermal plasma in the Milky Way has been studied extensively (e.g., Kaneda et al. 1997; Valinia et al. 1998).

Here, we present Chandra observations of the spiral galaxy NGC 2403 that made it possible to unambiguously separate discrete sources from diffuse emission. This galaxy is a nearby Sc spiral, morphologically similar to M33, viewed at an inclination angle of $\sim 60^\circ$. It is well isolated on the sky and shows no signs of recent interactions. H I observations (Fraternali et al. 2002) have revealed a kinematically anomalous component of neutral gas. The H I position-velocity (p-v) diagram along the major axis of this galaxy (Fig. 1) shows systematic asymmetries in the form of wings in the line profiles at lower velocities with respect to the rotation curve (white squares). In the central part of the galaxy, such wings extend up to 150 km s$^{-1}$ from the rotation curve. This kinematical pattern is different from that expected for a thin cold disk of H I (see the model in the right panel of Fig. 1). This anomalous gas was previously unknown. It has not been detected before, mainly because of a lack of sensitivity of the observations.

A detailed analysis of the H I data of NGC 2403 has shown that the wings of H I are produced by gas (the "anomalous gas") located above the plane of the galaxy and rotating $\sim 20-50$ km s$^{-1}$ more slowly than the gas in the disk. A similar slower rotation of the "halo" gas had already been observed in the edge-on galaxy NGC 891 (Swaters, Sancisi, & Van der Hulst 1997). The anomalous gas in NGC 2403 extends out to $\sim 15$ kpc from the center of the galaxy and has a total mass of about $3 \times 10^8 M_\odot$ ($\sim 1/10$ of the total H I mass). The study of its velocity field has also revealed a probable large-scale radial inflow ($10-20$ km s$^{-1}$) toward the center of the galaxy (Fraternali et al. 2001).

A possible interpretation is that of a galactic fountain (Shapiro & Field 1976; Bregman 1980), and the observed neutral gas may be the result of cooling of ionized gas blown up from the disk into the halo. The discovery of hot X-ray–emitting gas from the disk of NGC 2403, reported here, supports this picture. The anomalous H I may be related to the hot X-ray gas.

2. OBSERVATIONS

NGC 2403 was observed with Chandra in 2001 April for a total time of 36 ks. The galaxy was centered on the ACIS-S3 CCD with a $Y$ offset of about $l'$ from the nominal pointing of the chip to better fit in the $\sim 8' \times 8'$ field. The S3 chip (back-illuminated) was chosen because of the higher sensitivity in the soft X-ray band. The on-axis Chandra spatial resolution is $\sim 1''$, corresponding to 15 pc at NGC 2403 (we adopted the distance of 3.18 Mpc from Madore & Friedman 1991). The orientation of the telescope was chosen in such a way that the diagonal of the chip was parallel to the major axis of the galaxy. The data were reduced and analyzed with the packages CIAO (version 2.1) and XSPEC (version
11.0.1). We removed high background time by excluding events exceeding $\pm 3\sigma$ the mean chip count rate. The resulting exposure time of the observation was 34.9 ks. The energy range was restricted to 0.4–10 keV.

Figure 2 shows the optical Digitized Sky Survey (DSS) and Chandra images of NGC 2403. In the soft (0.4–1 keV) X-ray image (top right panel), an adaptive smoothing was applied to the original data after the background subtraction. The background was subtracted using deep blank field data sets with the same focal plane temperature. The background was subtracted using deep blank field data sets with the same focal plane temperature as NGC 2403 observations (–120°C). The bottom panels of Figure 2 show two 5″ smoothed S3 images in the soft (left, 0.4–1 keV) and hard (right, 1–10 keV) bands without background subtraction. These images show numerous discrete X-ray sources located in the bright part of the stellar disk of NGC 2403. The adaptively smoothed image also shows the presence of diffuse emission in the soft X-ray band.

2.1. Discrete Sources

Discrete X-ray sources were detected in NGC 2403 using CIAO wavdetect on the full-resolution S3 image. We used a threshold of $10^{-6}$ ($4.7\sigma$ level, or less than 0.25 false detections per chip). We looked for sources of different sizes, from 1″ to 16″, to detect both point and extended sources, and in different energy bands to detect both soft and hard sources. A total of 41 sources were found in the field of the S3 CCD. Assuming a standard ($kT \sim 5$ keV) spectrum, the faintest source has an X-ray flux of $\approx 10^{-15}$ ergs cm$^{-2}$ s$^{-1}$ or a luminosity of $\approx 10^{30}$ ergs s$^{-1}$ at the distance of NGC 2403.

Some of these sources are probably background sources unrelated to NGC 2403. On the basis of the ROSAT log $N$– log $S$ (Hasinger et al. 1998) at the above flux limit and considering the shadowing by the galaxy [with a typical H i column density of $(0.5–1) \times 10^{21}$ cm$^{-2}$], we estimate about 5–10 background sources in our S3 chip.

The majority of the detected sources are unresolved and show emission in the hard band. Those for which a spectral analysis was possible show binary-type spectra. Three sources are extremely bright, with observed fluxes (0.4–10 keV) of $4.3 \times 10^{-13}$, $6.2 \times 10^{-13}$, and $1.1 \times 10^{-12}$ ergs s$^{-1}$ cm$^{-2}$. If they belong to the galaxy, their luminosities are $5.2 \times 10^{38}$, $7.1 \times 10^{38}$, and $1.3 \times 10^{39}$ ergs s$^{-1}$ (see also Kotoku et al. 2000). These sources have luminosities and spectra typical of the class of the ultraluminous X-ray sources found in several nearby galaxies (King et al. 2001). Most of the X-ray sources of NGC 2403 are inside the stellar disk, tracing the spiral pattern of the galaxy. This suggests a relation with the stellar Population I as found for other late-type spiral galaxies (e.g., M33; Long et al. 1996). Three sources coincide with bright H ii regions and are clearly resolved in the Chandra images (Fig. 2).

3. Diffuse Emission

Point sources (except the three H ii regions) were removed from the full-resolution Chandra data of NGC 2403 by masking elliptical areas around each source. Each elliptical area found by wavdetect (3 $\sigma$ of the PSF) was visually inspected in order to enlarge, if necessary, the masking area. Pixels inside the ellipses were filled by local background values (Poisson method in dmfilth). Figure 3 (left) shows the exposure-corrected X-ray Chandra image in the soft band (0.4–1 keV) after the subtraction of the point sources (H ii regions excluded) and smoothed to a resolution of 15″. The contribution to the diffuse emission from sources under the detection limit can be estimated from the luminosity function. We obtained the luminosity function from the log $N$– log $S$ calculated for the 38 point sources and assumed a standard spectrum for X-ray binary with $\Gamma = 1.6$ (Tennant et al. 2001). The best power-law fit for luminosities above $2 \times 10^{36}$ ergs s$^{-1}$ is $N(> L) = 38.04 L^{-0.61}$, where $N(> L)$ is the number of the sources above a given luminosity limit and $L_{36}$ is the luminosity in units of $10^{36}$ ergs s$^{-1}$. From this function, we estimate the contribution of sources under the detection limit to be lower than about 5%.
Fig. 2.—Optical DSS (top left panel) and X-ray S3 Chandra images of NGC 2403 (all on the same scale). The X-ray image in the top right panel is the result of an adaptive smoothing in the soft energy band (0.4–1 keV) after the background subtraction. The bottom panels show two 5” smoothed S3 images in the soft (left, 0.4–1 keV) and hard (right, 1–10 keV) bands. [See the electronic edition of the Journal for a color version of this figure.]

Fig. 3.—Diffuse X-ray emission (0.4–1 keV) after the subtraction of point sources (left panel) and Hα image of NGC 2403 (right panel). The two images are on the same scale. The resolution of the X-ray image is 15″. The X-ray gray scale ranges from about 3 to 40 in units of rms noise above the background (1σ is 6.8 × 10^{-7} counts s^{-1} arcsec^{-2}). Note the great similarity between the distribution of hot and ionized gas. The brighter Hα regions have X-ray counterparts, and the hot gas seems to roughly follow the spiral arms of the galaxy. [See the electronic edition of the Journal for a color version of this figure.]
Therefore, the X-ray emission in Figure 3 is most likely produced by truly hot interstellar gas. The right panel of Figure 3 shows, for comparison, an Hα line image of NGC 2403 taken from the archive of the CFHT Telescope. The distributions of Hα and X-ray emission are very similar, and the main features agree in position very well. The hot gas seems to follow the spiral structure, suggesting that most of this emission comes from the disk of NGC 2403 and is related to star formation (e.g., see Trümper et al. 1991). The emission from the halo, which is expected to be uniform, is not dominant here.

The spectrum of the diffuse emission was extracted with the software packages calcrmf and calcart provided by A. Vikhlinin. The response matrices were determined from the FITS embedded function response file FP-120 for the operating temperature of −120°C. The spectrum was obtained from an elliptical region of diameter 8′ with the same position angle (P.A. = 124°) as the disk of NGC 2403. In order to perform a spectral analysis, a careful estimate of the background is needed. We extracted two background spectra: the first was extracted from the same elliptical region as that of the galaxy on the blank field data; the second was obtained from an elliptical region (about 4′ diameter) in the top left corner of our S3 chip. The two backgrounds are similar in the soft (0.4–1 keV) band (1.0 × 10−7 and 1.2 × 10−7 counts s−1 pixel−1 for the first and the second, respectively) while above 1 keV, the background of our S3 field is higher (by a factor of 2) than the one of the blank field. This difference is not caused by background variations within the chip. We tested this by extracting backgrounds from different regions across the blank field chip and finding no significant variations. The contamination of our S3 background by the galaxy is also excluded because the differences show up in the spectral region (1–2 keV), in which the galactic emission is much weaker. Besides, we also extracted a third background from an elliptical region on the S1 chip (back illuminated) and found it very similar to the S3 one. Therefore, there is probably a slightly intrinsic difference between the background during our observations and that on the blank field above 1 keV. This could be caused by a local anisotropy in the pointing direction or by a different instrumental noise. In the following spectral analysis, we preferred to use the background obtained from our S3 chip.

Figure 4 shows the spectrum of the X-ray emission of NGC 2403 after the subtraction of point sources in the band 0.4–2 keV. A fit with a MEKAL thermal plasma model (Mewe, Lemen, & Van den Oord 1986) with one component gives a temperature of $kT \approx 0.25 \pm 0.1$ keV ($T \approx 2.9 \times 10^6$ K) with a $\chi^2 = 1.72$. Better one-component fits ($\chi^2 = 1.5$) are obtained with a 0.1 solar abundance or an underabundance of alpha elements ($O, Mg, Si, Ca$) of about 0.3 solar. A significantly better fit ($\chi^2 = 1$), solid line in Figure 4, is obtained with two components at temperatures $kT_1 \approx 0.18 \pm 0.03$ keV ($T \approx 2.1 \times 10^6$ K) and $kT_2 \approx 0.73 \pm 0.07$ keV ($T \approx 8.4 \times 10^6$ K) and absorption column density fixed to the galactic value of $4.1 \times 10^{20}$ cm−2. Given the poor statistics, the metal abundances are substantially unconstrained, giving acceptable results for values from 0.1 to 1 solar (see also Dahlem et al. 2000). In the fit in Figure 4 the abundances are fixed to 0.3 solar. The

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1 Information on these software packages can be found at http://asc.harvard.edu/cont-soft/software/calcrmf.1.08.html.

2 Information on the ACIS background can be found at http://cxc.harvard.edu/contrib/maxim/bg/index.html#spec.
halo) for NGC 2403 (Fraternali et al. 2002), we get an escape velocity of 300–350 km s\(^{-1}\) in the central 4 kpc. The thermal velocity of the hot gas is likely to be between the adiabatic velocity of the hot gas \((v_{\text{ad}})\) and the post-shock speed \((v_{\text{sh}})\). We take the temperature \(kT\) of the one-component MEKAL fit \(kT \approx 0.25\) keV \((T \approx 2.9 \times 10^6\) K\). If we obtain a thermal velocity for the hot gas \((n_{\text{He}}/n_{\text{H}}) = 0.1\) of 170–300 km s\(^{-1}\), lower than the escape velocity. Similar values have been found for other galaxies (e.g., NGC 4631: Wang et al. 1995; Milky Way: Kaneda et al. 1997). The above estimates show that at least part of the X-ray–emitting gas found in NGC 2403 is likely to be bound to the galaxy. One implication of this result is that this hot gas does not substantially contribute to the enrichment of the surrounding intergalactic medium. Furthermore, if this gas can temporarily escape from the disk into the halo region, it will necessarily fall down onto the disk. According to a “galactic fountain”–type of process, the hot gas escaping from the disk is expected to cool quickly because of adiabatic expansion, and in the final phase it could become observable as neutral gas at anomalous velocities. The anomalous H\(_{\text{I}}\) shown in the p-v diagram of Figure 1 is likely to represent such a final phase of the galactic fountain, whereas the hot X-ray–emitting gas would pertain to the initial phase of it.

From the above X-ray luminosity and temperature, we estimate an electron density and a mass of the hot gas of \(0.15 \times 10^{-3} h^{-1/2} f^{-1/2} \text{cm}^{-3}\) and \(6.0 \times 10^4 h^{1/2} f^{-1/2} M_{\odot}\), where \(h\) is the scale height of the disk in kpc and \(f\) is the filling factor. The cooling rate of the hot gas can be estimated with the formula \(M_{\text{cool}} \approx M_X/\tau_{\text{cool}} = 2 \mu_{\text{H}} L_X/3 kT\) (Nulsen, Stewart, & Fabian 1984), which for \(n_{\text{He}}/n_{\text{H}} = 0.1\) gives \(M_{\text{cool}} \approx 0.01 M_{\odot} \text{yr}^{-1}\). If we now consider the mass of the anomalous H\(_{\text{I}}\), a typical size of 10 kpc, and the measured infall velocity of 10–20 km s\(^{-1}\), we estimate the infalling rate of H\(_{\text{I}}\) to be \(M_{\text{H}_{\text{I}}} \approx 0.3–0.6 M_{\odot} \text{yr}^{-1}\) larger than the cooling rate of the hot gas. However, such a value for cooling rate is probably representative only for the disk component and would vary substantially once the gas has left the disk itself.

A more useful quantity is the outflowing rate of the hot gas. Considering the mass and the thermal velocity determined above and assuming a continuous cycle between hot and neutral gas, such an escaping rate turns out to be \(M_{\text{hot}} \approx 0.1–0.2 M_{\odot} \text{yr}^{-1}\), of the same order as the infalling H\(_{\text{I}}\). Therefore, it is possible that the cooling of the X-ray–emitting gas in NGC 2403 and its motion via a galactic fountain could produce the observed H\(_{\text{I}}\) p-v pattern.

It has been suggested that the anomalous H\(_{\text{I}}\) is common among spiral galaxies (Fraternali et al. 2001). Similarly, the hot X-ray–emitting gas is probably present in several spiral galaxies with a high rate of star formation. One can argue, therefore, that the hot gas and the anomalous H\(_{\text{I}}\) are, generally, connected as in NGC 2403. Finally, this discovery of diffuse X-ray–emitting gas in NGC 2403 also has interesting implications for the study of our Galaxy. The anomalous H\(_{\text{I}}\) in NGC 2403 is analogous to at least some of the high-velocity clouds (Wakker & Van Woerden 1997) of our Galaxy. The suggested relation between the neutral and the hot gas in NGC 2403 supports the possibility that galactic fountains also play an important role in the Milky Way.

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