DIFFUSE X-RAY EMISSION FROM M101

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ABSTRACT

The ROSAT PSPC observation of the face-on spiral galaxy M101 shows conclusive evidence for diffuse X-ray emission. While the emission is strongest in the $\frac{1}{4}$ keV band (sensitive to thermal emission near $10^6$ K), it is also apparent at $\frac{3}{4}$ keV (sensitive to thermal emission at a few $10^5$ K). The emission is clearly visible over the inner 7' radius ($\sim 15$ kpc with a distance to M101 of 7.2 Mpc), or roughly 60% of the D$_{25}$ radius. In addition to the emission, a thick spiral arm at roughly an 8' radius in the southwest quadrant is correlated with a depression in surface brightness relative to the region of the observation external to the galaxy. The depression is consistent with the absorption of the entire previously observed extragalactic background at $\frac{1}{4}$ keV.

The observed $\frac{1}{4}$ keV band intensity of M101 varies over the inner 7' of the galaxy with an average value of $\sim 790 \times 10^{-6}$ counts s$^{-1}$ arcmin$^{-2}$, and is peaked toward the center of the galaxy. The R2/R1 band ratio implies an emission temperature of $\sim 10^{5.8}$ K. After correction for absorption by material associated with Milky Way H I, this implies an intensity of $\sim 3280 \times 10^{-6}$ counts s$^{-1}$ arcmin$^{-2}$. This emission most likely originates in the halo of M101 (similar to the $\frac{1}{4}$ keV emission detected by ROSAT in NGC253). If so, it would require an average filling factor of $\sim 1$ of regions similar to the bright $\frac{1}{4}$ keV halo emission observed in our own galaxy in the direction of Draco. The emission is unlikely to originate in confined regions in the disk of M101, similar to the Local Hot Bubble ($T \sim 10^6$ K, $\sim 1.5 \times 10^{20}$ cm$^{-2}$ overburden of H I), since the required filling factor of such regions would be much greater than unity and the implied emission temperature would be relatively low ($\sim 10^{5.5}$ K). Compared to the Milky Way, either intrinsically brighter but cooler regions or a highly clumped ISM, or both, would be required if the emission originates in the disk.

This detection of extensive diffuse X-ray emission from the halo of a galaxy similar to the Milky Way has implications for our own galaxy, as well as for M101 itself. By analogy, it implies that the X-ray halo that we observe in our own Galaxy has a low filling factor outside of the Galactic center region. This is consistent with the apparent patchiness in the solar vicinity.

Running title: Diffuse X-ray Emission from M101
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1 INTRODUCTION

The extent of hot, X-ray emitting plasma in the Milky Way and similar galaxies is of great importance due to the linkage with galactic energy balance and dynamics and SNR evolution (cf. Cox & McCammon 1986). However, while considerable emission by \( \sim 10^6 \) K plasma is predicted by many models (e.g., Cox & Anderson 1982; Jakobsen & Kahn 1986), the Galactic plane is relatively opaque to X-rays of greatest use in studying this emission: \( \sim \frac{1}{4} \) keV. One optical depth is \( \sim 10^{20} \) H cm\(^{-2}\), limiting observations of the Milky-Way disk to a few hundred parsecs. Nevertheless, the X-ray sky is relatively bright at \( \frac{1}{4} \) keV and is dominated by galactic emission from the Local Hot Bubble (LHB; Cox & Reynolds 1987; McCammon & Sanders 1990; Snowden et al. 1990), patchy emission in the Galactic “halo” (for these purposes, emission from beyond most if not all of the galactic H\(_1\), irregardless of the height above the plane; cf. Snowden et al. 1994a), and emission from nearby discrete enhancements (SNRs or stellar wind bubbles) such as the Loop I/North Polar Spur complex, the Monoceros-Gemini enhancement, and the Eridanus enhancement. The LHB extends from \( \sim 50 \) pc to \( \sim 250 \) pc from the Sun depending on direction, and contains a hot plasma at \( \sim 10^6 \) K. The \( \frac{1}{4} \) keV band intensity from the LHB probably ranges from \( \sim 250 \times 10^{-6} \) counts s\(^{-1}\) arcmin\(^{-2}\) to \( \sim 650 \times 10^{-6} \) counts s\(^{-1}\) arcmin\(^{-2}\) (Snowden 1993), although the known range could be extended as more ROSAT data are processed. The galactic-halo emission, while patchy, can contribute \( > 500 \times 10^{-6} \) counts s\(^{-1}\) arcmin\(^{-2}\) to the observed flux (cf. Burrows & Mendenhall 1991; Snowden et al. 1991; Snowden et al. 1994a).

Since we can’t survey our own galaxy in the appropriate energy band, the next best approach is to study nearby galaxies of similar type to the Milky Way. We proposed for and were granted ROSAT (Trümper 1983) X-ray Telescope (Aschenbach 1988) Position Sensitive Proportional Counter (PSPC, Pfeffermann et al. 1987) observations of a number of face-on and edge-on spirals in directions of low galactic neutral hydrogen column density. The use of face-on spirals reduces the model dependence on the distributions of hot X-ray emitting plasma and cool X-ray absorbing gas in the halo of the target galaxy. The selection on low Milky Way neutral hydrogen column density and nearby galaxies (and therefore larger solid angle) increases the sensitivity of the search.

The face-on Sc supergiant spiral M101 (NGC5457) is the premier candidate galaxy for a face-on study (see Table 1), and indeed was studied with Einstein: McCammon & Sanders (1984) for analysis of diffuse emission and Trinchieri, Fabbiano, & Romaine (1990) for all components. However, the relatively small effective area, poor energy and spatial resolution, and high noncosmic background of the Einstein IPC relative to ROSAT PSPC limited the result to only the possible existence of diffuse emission; the emission could be mimicked by a few strategically located point-like sources.

We present here the results of the ROSAT observation of M101 concerning diffuse emission. Another paper (Pietsch et al. 1995) will present the point sources and small-scale extended sources observed in M101. Section 2 describes the data, § 3 describes the analysis, and § 4 discusses the results.

2 DATA

M101 was observed on 1991 June 8 – 9 with the PSPC during the reduced pointing phase of ROSAT operations. During the reduced pointing phase, observations of a given target were continuous except for breaks due to Earth blockage, passage of the satellite through Earth’s particle belts and the South Atlantic Anomaly (high particle count rates will damage the proportional counter if it is operating), and violation of the atomic oxygen constraint (the observation ram angle must be > 28° to avoid damage to the thin plastic entrance window of the PSPC). The total observation time was \( \sim 34500 \) s and the data
were processed in a similar manner to the observation of the high latitude molecular cloud MBM 12 (Snowden, McCammon, & Verter 1993) using the methods suggested in Snowden et al. (1994b) and the noncosmic background calibrations of Snowden et al. (1992), Plucinsky et al. (1993), and Snowden & Freyberg (1993). The observation was strongly contaminated by scattered solar X-rays, a long-term noncosmic background enhancement, and presumed auroral X-rays. After exclusion of particularly bad intervals of contamination, there was a net observation time of \( \sim 25600 \) s. While there undoubtedly remains some contamination over the field, the data reduction is simplified since the \( D_{25} \) diameter of M101 (the diameter at \( V = 25 \) mag arcsec\(^{-2} \)) covers only the inner 23.8' (Tully 1988) of the PSPC and the intensity can be compared to an external annulus for background subtraction (both cosmic and noncosmic components).

We identified point sources in the image using a sliding-box algorithm which incorporated the variation of the point response function with off-axis angle. We considered the hard and soft bands separately and set the two different selection thresholds for each band. For the coarse radial profiles of M101, we set the selection thresholds so that all sources to a constant limiting count rate would be identified out to a 50' radius with a significance threshold such that we expect no more than one false identification. For the more detailed analysis of the inner region of M101, we did the same except for using the 25' radius. (This lowered the count-rate threshold by a factor of two.) The count-rate thresholds and excluded areas are listed in Table 2.

The exposure and vignetting correction is critical for this observation and was discussed as an example in Snowden et al. (1994b). Figure 1 shows images of M101 at 21 cm (a; see below) and three different X-ray energy bands: (b) \( \frac{1}{4} \) keV band (R1+R2 bands; Snowden et al. 1994b), (c) \( \frac{3}{4} \) keV band (R4+R5 bands), and (d) 1.5 keV bands (R6+R7 bands). While diffuse emission from M101 dominates in the \( \frac{1}{4} \) keV band, point-like sources become more important with increasing energy. The \( \frac{3}{4} \) keV band still shows extended emission but point-like sources start to dominate the field. At 1.5 keV, only point-like sources are readily apparent. To be more quantitative, \( \sim 35\% \) of the \( \frac{1}{4} \) keV emission from M101 comes from resolved sources, \( \sim 54\% \) of the \( \frac{3}{4} \) keV band, and 85% of the 1.5 keV band. Figure 2 shows a contour overlay of the \( \frac{1}{4} \) keV data on an optical image of M101 (Arp 1966).

The H\textsc{i} data (Fig. 1a) have been previously described in van der Hulst & Sancisi (1988) and Kamphuis, Sancisi, \& van der Hulst (1991). We have only recast the total M101 column density into the same pixel size and projection used for the X-ray data to allow comparison of the region where \( \frac{1}{4} \) keV X-rays are apparently shadowed.

3 ANALYSIS

3.1 Apparent \( \frac{1}{4} \) keV Absorption Feature

Figure 3 shows the radial profiles for the three X-ray images in Figure 1, after the resolved point sources were excluded. The horizontal lines show the average surface brightness for the 25' - 50' annulus, whose inner radius is slightly more than twice the \( D_{25} \) radius. Before analyzing the \( \frac{1}{4} \) keV diffuse emission from M101, we first examine a possible absorption feature, suggested by the slight dip in the radial profile at \( \sim 8' \), where disk material (the thick spiral arm in the lower right quadrant of the H\textsc{i} image indicated by the arrow in Fig. 1a) is apparently shadowing unresolved emission of a more distant origin. We use the average surface brightness in the 25' to 50' annulus, \( 1666 \pm 5 \times 10^{-6} \) counts s\(^{-1} \) arcmin\(^{-2} \), as the background level. Figure 4 shows a binned X-ray versus \( N_{\text{H}} \) plot for the data in the lower right quadrant of the 7' to 25' annulus. The horizontal line shows the average intensity for the 25' - 50' annulus. As can be seen, the surface brightness at high column density is lower than
that at lower columns. If we take the average surface brightness for column densities above $4 \times 10^{20}$ H I cm$^{-2}$ (the highest $N_H$ point, where the column is essentially opaque to $\frac{1}{4}$ keV X-rays, assuming solar abundances intrinsic in the Morrison & McCammon 1983 absorption cross sections), the foreground surface brightness is $1527 \pm 53 \times 10^{-6}$ counts s$^{-1}$ arcmin$^{-2}$. This implies a surface brightness originating beyond M101 of $139 \pm 53 \times 10^{-6}$ counts s$^{-1}$ arcmin$^{-2}$; a 2.6 $\sigma$ detection of a shadow. The existence of any $\frac{1}{4}$ keV emission from the high-$N_H$ region of M101 would cause this number to be an underestimate of the true depth of the shadow. When corrected for absorption by the H I of our own galaxy ($1.1 \times 10^{20}$ H I cm$^{-2}$ for a transmission of 0.365, assuming the extragalactic $E^{-1.96}$ photon number spectrum of Hasinger et al. 1993 and absorption cross sections of Morrison & McCammon 1983), this yields a surface brightness of $381 \pm 145 \times 10^{-6}$ counts s$^{-1}$ arcmin$^{-2}$. This is within 1 $\sigma$ of the $484 \times 10^{-6}$ counts s$^{-1}$ arcmin$^{-2}$, the value for the extragalactic flux derived in Snowden et al. (1994a) from the results of Hasinger et al. (1993), before the uncertain correction for absorption by the high-$z$ distribution of H II in our own galaxy (Reynolds 1991). (The He associated with the H II is not ionized and can provide significant absorption.) However, the H II distribution is not well mapped and we will ignore it for the purposes of this paper. This is not altogether unreasonable when comparing this observation to the results of Snowden et al (1994a) as M101 and the Ursa Major region are at roughly the same galactic latitudes and separated by only $\sim 25^\circ$ on the sky.

The value of $381 \pm 145 \times 10^{-6}$ counts s$^{-1}$ arcmin$^{-2}$ for the intensity converts to an energy flux of $27 \pm 10$ keV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ keV$^{-1}$ (using the scale factor listed in Cui et al. 1995). Correcting to an infinite source cutoff (i.e., putting back the average contribution of extragalactic sources with fluxes above our source-detection threshold) adds $\sim 1$ keV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ keV$^{-1}$, implying a detection of $\sim 28 \pm 10$ keV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ keV$^{-1}$. This value is consistent with the 95% confidence lower limit of $28 \pm 10$ keV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ keV$^{-1}$ derived by Cui et al. (1995) using a sample of face-on galaxies. It is also consistent with the upper limit of $40$ keV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ keV$^{-1}$ derived Barber & Warwick (1994) which searched for a shadow cast by H I associated with the galaxy pair NGC4725/4747. The M101 shadow, while not of overwhelming statistical significance, is certainly consistent with all of the unresolved extragalactic $\frac{1}{4}$ keV flux originating beyond the 7.2 Mpc of M101. This is cosmologically reassuring as the resolved sources in Hasinger et al. (1993) are typically distant QSOs with redshifts of between 1 and 2.

Since there apparently exists an unresolved flux originating beyond M101, and since the H I column density of M101 is sufficiently thick over much of its inner region to absorb a significant fraction of this flux, any emission from M101 must first "fill" the deficit caused by the absorbed flux, in order to be observed as an enhancement. Thus, even a flat radial distribution would be indicative of emission from the galaxy. We therefore correct the surface brightness of the image for the absorption for the absorption of the extragalactic flux. We use the Snowden et al. (1994a) value in the following $\frac{1}{4}$ keV band analysis (as it is probably of greater reliability than that derived here) to add, on a pixel-by-pixel basis, an amount determined using the H I data and the band-averaged Morrison & McCammon (1983) cross sections appropriate for an $E^{-1.96}$ power-law spectrum. We use the surface brightness in the $20' - 25'$ annulus as the estimate for the non-M101 background. The radial profiles of Figure 3 for this annulus are consistent with larger annuli and the average M101 H I column density is $3 \times 10^{18}$ cm$^{-2}$ so the extragalactic flux is unaffected.

3.2 Diffuse $\frac{1}{4}$ keV Emission or a Superposition of Point Sources

The question of whether the unresolved emission from M101 is truly diffuse or is due to the superposition of point sources below the threshold of our point-source removal must be considered. For this purpose, we divided the $\frac{1}{4}$ keV band data into the R1 and R2 bands
in order to determine the emission temperature. For the inner 7.5 radius region of M101, the observed, background-corrected R2/R1 ratio is 1.10. If we assume no absorption of the emission by material associated with M101, i.e., that it originates in the halo of M101, and if we correct for the foreground absorption by Milky Way H I (1.1 × 10^20 H I cm^-2), this implies an emission temperature of 10^5.83 K. The M101 count rate in the \( \frac{1}{4} \) keV band is \( \sim 0.13 \text{ counts s}^{-1} \) yielding an absorption-corrected flux of \( 2.1 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1} \), and a luminosity of \( \sim 1.3 \times 10^{46} \text{ ergs s}^{-1} \) using the distance to M101 of 7.2 Mpc. On the other hand, if the source of the M101 emission is placed behind the average half thickness of the M101 H I within the 7.5 radius, 1.8 × 10^20 H I cm^-2, an emission temperature of 10^5.46 K is required, with an absorption-corrected flux of \( 1.7 \times 10^{-10} \text{ ergs cm}^{-2} \text{ s}^{-1} \) and a luminosity of \( \sim 1.1 \times 10^{42} \text{ ergs s}^{-1} \). (We note here that there is some discussion about the actual distance to M101 and therefore our distance-dependent results are uncertain to that level. While we use the value of 7.2 Mpc given by Sandage & Tammann 1974, Buta & de Vaucouleurs 1983 give the value 4.7 Mpc.)

Unfortunately, even though this is a 25 ks observation, there are only a limited number of events in any \( 0.5 \times 0.5 \) resolution element. On average, there are only \( \sim 14 \) events per element in the inner 7.5 radius, of which only \( \sim 4 \) are from M101. This effectively rules out the use of fluctuation analysis to set any significant limits on the required source density beyond a relatively crude level. Even so, if the excess emission is due to a superposition of point sources, there must be at least a few sources in each resolution element (\( \sim 1 \text{ kpc}^2 \)). The average luminosity from a resolution element is \( 1.8 \times 10^{37} \text{ ergs s}^{-1} \) if the sources are in the halo. No known population of sources, including normal stars and M dwarfs, can provide this emission with a characteristic temperature of 10^5.83 K. The difficulty is even more severe if the emission is assumed to originate in the disk with the temperature of 10^5.46 K and luminosity of \( 1.6 \times 10^{40} \text{ ergs s}^{-1} \) in a resolution element. Also the new class of super-soft X-ray sources may only explain a small fraction of the diffuse emission as will be shown in the discussion section (see \S 4.1).

3.3 Diffuse \( \frac{1}{4} \) keV Emission from M101

We now consider the data in 2.5 annuli centered on M101. Table 3 lists the average \( \frac{1}{4} \) keV surface brightness for the annuli (excluding the contributions of point sources), both before and after correction for the absorption of the more distant extragalactic flux. Before correction, the annuli with \( > 7.5 \) radii show no evidence for diffuse emission. After correction, however, while there is still a distinct fall off in surface brightness with increasing radii, there is evidence for extended emission out to 17.5. Even the 17.5–20' annulus shows a suggestion of emission at slightly more than 2 \( \sigma \). Of course, the average intensity is strongly peaked toward the center circle (as is easily seen in Fig. 3a).

After using the data in the 20' to 25' annulus to determine the background level of the image, Table 3 also lists the average \( \frac{1}{4} \) keV band surface brightness of M101 after correction for absorption by the H I of our own galaxy (transmission of 0.241, Morrison & McCammon 1983 absorption cross sections) assuming thermal emission from a 10^5.83 K plasma (Raymond & Smith 1977; Raymond 1991). Assuming that there is no overburden of H I in M101, we have also calculated the average emission measure and total flux for each annulus and listed the results in Table 3.

To compare these results to possible conditions in the Milky Way, we consider the bright region of implied halo emission visible in the direction of Draco which has an unabsorbed surface brightnesses of \( \sim 3000 \times 10^{-6} \text{ counts s}^{-1} \text{ arcmin}^{-2} \) (Snowden et al. 1991). The ratios of the M101 surface brightness in the different annuli to this value can be interpreted as an effective surface filling factor (ignoring the actual distribution of the emission, i.e., small or large scale heights or uniformity of distribution) for such regions in the halo of M101, and are
listed in Table 3. The values for this surface filling factor are near 1 with the expected fall-off with increasing radius. The lower values at higher radii could be an indication of a patchy halo, similar to that observed in the Milky Way in the solar neighborhood (Snowden et al. 1994a). The filling-factor values greater than one should simply be interpreted as implying a larger emission measure of the emitting gas than found in the local halo (e.g., higher scale height, higher pressure, or larger volume filling factor).

The values for the halo emission measures and fluxes of Table 3 are probably lower limits for the actual values for M101. They could possibly be increased by over a factor of two if absorption by the high-z H II component of our own galaxy and an assumed similar component in M101 are considered. The amount of halo emission could also be independently increased by nearly a factor of two in the likely case of similar emission from the far side of M101 (for the most part not visible due to absorption by the disk material of M101). Thus, the total luminosity of M101 in $\frac{1}{4}$ keV emission from hot gas in its halo is likely to be in the range $10^{40} - 10^{41}$ ergs s$^{-1}$.

3.4 The $\frac{3}{4}$ keV and 1.5 keV Bands

Table 4 shows the $\frac{3}{4}$ keV band and 1.5 keV band average count rates in the 2'5 annuli. Since the column density of M101 is relatively transparent to X-rays above 0.5 keV, we have not corrected the count rates for absorption of the extragalactic flux of a more distant origin. The corrections would be $\lesssim 10 \times 10^{-6}$ counts s$^{-1}$ arcmin$^{-2}$ for the inner (higher column density) annuli, roughly the level of the statistical uncertainty. Both bands show significantly enhanced intensities in the inner 7'5 radius ($\sim 60\%$ of the D$_{25}$ radius, $\sim 16$ kpc) over the level external to the galaxy, even after the resolved point sources have been removed, although it is quite possible that a significant amount of the residual 1.5 keV enhancement is due to point-like sources below the detection threshold.

The R5/R4 band ratio of M101 emission averaged over the inner 7'5 radius implies an effective emission temperature of $10^{6.53}$ K for the $\frac{3}{4}$ keV band. The unresolved excess count rate from M101 in the $\frac{3}{4}$ keV band is 0.027 counts s$^{-1}$ (152 $\times 10^{-6}$ counts s$^{-1}$ arcmin$^{-2}$ averaged over the inner 7'5 radius) yielding a flux of $5.8 \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$ and an integrated luminosity of $3.6 \times 10^{39}$ ergs s$^{-1}$. Temperatures such as this are suggestive of stellar emission such as from M-dwarfs. However, using the results of Schmitt & Snowden (1990), we would expect only a surface brightness of $\sim 20 \times 10^{-6}$ counts s$^{-1}$ arcmin$^{-2}$ from these stars. While the population of M dwarfs will not produce the emission observed in the inner 7'5 of the galaxy, they could be the origin of the slight enhancements in the 7'5 - 20' annuli over the 20' - 25' annulus.

4 DISCUSSION

Diffuse soft X-ray emission in the 0.1 - 1 keV band has been observed filling the inner 7' ($\sim 15$ kpc) radius of the face-on spiral galaxy M101 with the ROSAT PSPC. While the emission is strongest at $\frac{1}{4}$ keV where it is peaked towards the center but relatively smoothly distributed, it is also apparent at $\frac{3}{4}$ keV where the structure is more filamentary with a greater contribution from point sources. In the higher energy bands, some of the filamentary structure may be due emission from point-like sources below the detection threshold. This is particularly true at 1.5 keV where the unresolved sources may contribute most if not all of the remaining 15% of the observed flux.

4.1 The Contribution of Super-Soft Sources to the $\frac{1}{4}$ keV Emission

Luminous super-soft X-ray sources (SSS) have been established as a new and distinct
class of X-ray objects by *ROSAT* (cf. Kahabka, Pietsch, & Hasinger 1994) with luminosities of up to $\sim 10^{38}$ ergs s$^{-1}$ and effective temperatures of $\sim 4 \times 10^8$ K. Five sources have been detected each in the LMC and SMC. The most promising scenario explains these sources as compact binary systems involving mass transfer from a main-sequence or subgiant donor star onto a white dwarf (van den Heuvel et al. 1992). The temperatures observed in SSS nicely match the temperatures derived for the diffuse emission in M101 under the assumption that the sources lie in the disk and have no intrinsic absorption. The intrinsic spectra of SSS are, however, not well constrained by *ROSAT* due to the limited energy resolution of the PSPC and typically large foreground absorption which strongly suppresses the observed flux in the $\frac{1}{4}$ keV band.

We used spectral parameters and count rates from the Magellanic Cloud SSS detections to estimate the expected count rate for SSS at the distance of M101. Taking into account the low galactic foreground absorption in the direction of, and the distance to M101, we derive a count rate of $(10^{-4} - 10^{-3})$ counts s$^{-1}$ for a SSS that is not absorbed either intrinsically or by the interstellar medium of M101. The $\frac{1}{4}$ keV band count rate of 0.13 counts s$^{-1}$ (see section 3.2) would be explained by 130 – 1300 unabsorbed sources. However, the additional absorption by the interstellar medium in M101 and intrinsic to the sources must be considered and therefore the required number of SSS is much higher. The average overburden of H i in M101 (see § 3.2) alone would require nearly two orders of magnitude more sources: $\geq 10000$.

From evolution arguments, Rappaport, Di Stefano, & Smith (1994) argue that more than $\sim 1000$ such systems should be active in the Galaxy or M31. For the LMC and SMC they postulate $\sim 100$ and $\sim 15$, respectively. However, most of the sources would produce little observable emission if they are absorbed by column densities of a few times $10^{21}$ cm$^{-2}$, either in the intervening interstellar medium or in matter surrounding the sources. The *ROSAT* detection of only 5 SSS in LMC and SMC is consistent with this scenario.

For M101, we would expect a similar number of SSS as proposed for the Galaxy. After absorption, $\lesssim 100$ sources would be expected to contribute to the apparent diffuse emission, and even so, these sources will be partly absorbed. We therefore conclude that SSS should contribute less than 10% to the diffuse $\frac{1}{4}$ keV band emission. Only if SSS are considerably more numerous in M101 compared to the Galaxy could they provide a significant contribution to the observed flux.

4.2 Diffuse Emission

If the $\frac{1}{4}$ keV diffuse emission originates in the galactic disk in regions of hot plasma similar to that surrounding the Sun, the implied filling factor for the inner 7'5 is much greater than unity. This strongly favors an origin in the halo where an average surface filling factor of $\sim 1$ of regions similar to the bright emission in our own galaxy toward Draco would be required. Evidence for diffuse emission continues out to larger radii, even the 17'5 – 20' (38 – 44 kpc) annulus shows a 2 $\sigma$ enhancement with an implied surface filling factor for the halo emission of 0.06.

The strongest diffuse $\frac{1}{4}$ keV emission covers the same area, the inner 4' radius, where Kenney et al. (1991) report the detection of CO emission from a molecular bar and star-forming disk. They discuss enhanced star formation in the inner disk that could have fed the central halo region via the outbreak of hot gas from shells via galactic fountains (cf. Norman & Ikeuchi 1989 and references therein). Multifrequency radio observations (Gräve, Klein, & Wielebinski 1990) show enhanced radio emission in the inner $\sim 7'$ radius and have been used to separate thermal and nonthermal radio emission in this part of M101. There is an overall correspondence to our measurements of hot halo gas.

This detection of diffuse emission from a spiral galaxy similar to the Milky Way has significant implications for the study of our own galaxy. While there is considerable emission
in the inner region of the galaxy, by the time the equivalent radius of the solar circle is reached ($\sim 8.3$, using $8$ kpc for the solar circle and $11.5$ kpc for the $D_{25}$ radius of the Milky Way; de Vaucouleurs & Pence 1983), the emission is much reduced. The patchy halo emission observed in the solar vicinity may therefore be an indication of significantly greater emission nearer the galactic center. Furthermore, the X-ray brightness at energies $> 0.5$ keV of the central $5'$ radius of M101 may have a counterpart in the Milky Way. While not visible at $\frac{1}{4}$ keV due to the high opacity of the galactic disk at this energy, the $\frac{3}{4}$ keV and $1.5$ keV bands show large solid-angle enhancements in the general direction of the Galactic center ($30^\circ > l > 300^\circ, |b| < 25^\circ$). While some fraction of these enhancements may be associated with emission from Loop I (a nearby, $\sim 150$ pc, large solid-angle SNR), it is likely that much of the enhancements have a more distant, galactic bulge origin (i.e., well within the solar circle).

Diffuse X-ray emission in the $\frac{1}{4}$ keV and $\frac{3}{4}$ keV bands has also been detected by ROSAT for several other spiral galaxies selected for low foreground $N_{HI}$. For instance, the edge-on starburst galaxy NGC253 shows highly structured $\frac{1}{4}$ keV and also some $\frac{3}{4}$ keV emission filling both halo hemispheres (Pietsch 1992). Projected onto the disk of the galaxy (the geometry of the M101 observation), the emission originates from the inner 70% of the $D_{25}$ radius (compared to $\sim 60\%$ of the $D_{25}$ radius for M101). For the spiral galaxy NGC4258, which is well studied for its anomalous arms, the inner 50% of the $D_{25}$ radius shows diffuse X-ray emission (Pietsch et al. 1994). In both cases, the same region in the galaxies show the strongest radio emission, and there is no doubt that the diffuse X-ray emission stems mainly from the halo of the galaxies since the emission is partly shadowed by intervening spiral arms. From the examples reported above, it is suggestive that a galaxy must be active to show diffuse X-ray emission. The detection of hot halo gas for the edge-on galaxy NGC4565 (Pietsch 1993), which is not known for specific activity, contradicts this impression. Investigating a larger sample of ROSAT observed galaxies in a more systematic manner will hopefully help to answer the question whether hot gas in the halos of spiral galaxies is a common feature or restricted to galaxies showing specific activity.

4.3 Apparent $\frac{1}{4}$ keV Absorption Feature

We have also reported the observation of a $\frac{1}{4}$ keV absorption feature in M101: a spiral arm which apparently shadows a diffuse background of a more distant origin. The derived background intensity is consistent with the value for the $\frac{1}{4}$ keV extragalactic background discussed in Hasinger et al. (1993) and Snowden et al. (1994a). This implies that most if not all of the unresolved extragalactic $\frac{1}{4}$ keV background originates at distances greater than that of M101.

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Table 1: M101 Details

<table>
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<td>14\textsuperscript{h}03\textsuperscript{m}09\textsuperscript{s}.6, 54\degree 20\arcmin 24\arcsec</td>
<td>–</td>
</tr>
<tr>
<td>Type</td>
<td>Sc supergiant</td>
<td>van den Bergh (1960)</td>
</tr>
<tr>
<td>Distance</td>
<td>7.2 Mpc</td>
<td>Sandage &amp; Tammann (1974)</td>
</tr>
<tr>
<td>D$_{25}$</td>
<td>23.8</td>
<td>Tully (1988)</td>
</tr>
<tr>
<td>Size Scale</td>
<td>2.2 kpc arcmin$^{-1}$</td>
<td>–</td>
</tr>
<tr>
<td>Galactic H I Column Density</td>
<td>(1.1 \times 10^{20}) H I cm$^{-2}$</td>
<td>Dickey &amp; Lockman (1990)</td>
</tr>
</tbody>
</table>

Table 2: Point-source exclusion thresholds

<table>
<thead>
<tr>
<th>Band</th>
<th>Region Radius</th>
<th>Threshold (counts s$^{-1}$)</th>
<th>Excluded Area within (&lt; 25\arcmin)</th>
<th>Excluded Area within (&lt; 7\arcmin)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard$^a$</td>
<td>50\arcmin</td>
<td>0.004</td>
<td>4.0%</td>
<td>2.6%</td>
</tr>
<tr>
<td>Hard</td>
<td>25\arcmin</td>
<td>0.002</td>
<td>12.0%</td>
<td>5.0%</td>
</tr>
<tr>
<td>Soft$^b$</td>
<td>50\arcmin</td>
<td>0.007</td>
<td>4.2%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Soft</td>
<td>25\arcmin</td>
<td>0.0035</td>
<td>6.8%</td>
<td>6.8%</td>
</tr>
</tbody>
</table>

$^a$ROSAT bands R4 - R7  
$^b$ROSAT bands R1 - R2  

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Table 3: M101 Annuli 0.5 keV Diffuse Emission

<table>
<thead>
<tr>
<th>Annulus Limits</th>
<th>Observed Brightness(a)</th>
<th>EG Corr.(b)</th>
<th>MW Corr.(c)</th>
<th>EM(d)</th>
<th>Flux(f)</th>
<th>F(g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0(^{\prime}) - 2.5(^{\prime})</td>
<td>2910 (\pm) 97</td>
<td>3302 (\pm) 97</td>
<td>6810 (\pm) 400</td>
<td>0.0535</td>
<td>3.19</td>
<td>2.27</td>
</tr>
<tr>
<td>2.5 - 5(^{\prime})</td>
<td>2168 (\pm) 41</td>
<td>2584 (\pm) 41</td>
<td>3830 (\pm) 170</td>
<td>0.0301</td>
<td>5.38</td>
<td>1.28</td>
</tr>
<tr>
<td>5(^{\prime}) - 7.5(^{\prime})</td>
<td>1720 (\pm) 31</td>
<td>2112 (\pm) 31</td>
<td>1870 (\pm) 130</td>
<td>0.0147</td>
<td>4.38</td>
<td>0.62</td>
</tr>
<tr>
<td>7.5 - 10(^{\prime})</td>
<td>1650 (\pm) 25</td>
<td>2040 (\pm) 25</td>
<td>1570 (\pm) 100</td>
<td>0.0123</td>
<td>5.15</td>
<td>0.52</td>
</tr>
<tr>
<td>10(^{\prime}) - 12.5(^{\prime})</td>
<td>1642 (\pm) 22</td>
<td>1918 (\pm) 22</td>
<td>1070 (\pm) 90</td>
<td>0.0084</td>
<td>4.51</td>
<td>0.36</td>
</tr>
<tr>
<td>12.5 - 15(^{\prime})</td>
<td>1629 (\pm) 20</td>
<td>1792 (\pm) 20</td>
<td>540 (\pm) 80</td>
<td>0.0043</td>
<td>2.78</td>
<td>0.18</td>
</tr>
<tr>
<td>15(^{\prime}) - 17.5(^{\prime})</td>
<td>1664 (\pm) 19</td>
<td>1755 (\pm) 19</td>
<td>390 (\pm) 80</td>
<td>0.0031</td>
<td>2.37</td>
<td>0.13</td>
</tr>
<tr>
<td>17.5 - 20(^{\prime})</td>
<td>1658 (\pm) 20</td>
<td>1706 (\pm) 20</td>
<td>190 (\pm) 80</td>
<td>0.0015</td>
<td>1.33</td>
<td>0.06</td>
</tr>
<tr>
<td>20(^{\prime}) - 25(^{\prime})</td>
<td>1654 (\pm) 15</td>
<td>1661 (\pm) 15</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

\(a\)Units of 10\(^{-6}\) counts s\(^{-1}\) arcmin\(^{-2}\).
\(b\)Corrected for M101 absorption of the more distant extragalactic flux.
\(c\)Corrected for Milky Way absorption after subtraction of the off-M101 background intensity.
\(d\)No overburden of H\(^{\prime}\) in M101.
\(e\)Average emission measure, units of cm\(^{-6}\) pc.
\(f\)Annulus-integrated flux, units of 10\(^{39}\) ergs s\(^{-1}\)
\(g\)Surface filling factor relative to the Milky Way halo emission in Draco

Table 4: M101 Annuli Count Rates

<table>
<thead>
<tr>
<th>Annulus Limits</th>
<th>0.5 keV Band(a)</th>
<th>1.5 keV Band(a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0(^{\prime}) - 2.5(^{\prime})</td>
<td>572 (\pm) 39</td>
<td>403 (\pm) 32</td>
</tr>
<tr>
<td>2.5 - 5(^{\prime})</td>
<td>416 (\pm) 20</td>
<td>291 (\pm) 16</td>
</tr>
<tr>
<td>5(^{\prime}) - 7.5(^{\prime})</td>
<td>301 (\pm) 14</td>
<td>200 (\pm) 11</td>
</tr>
<tr>
<td>7.5 - 10(^{\prime})</td>
<td>234 (\pm) 11</td>
<td>170 (\pm) 8</td>
</tr>
<tr>
<td>10(^{\prime}) - 12.5(^{\prime})</td>
<td>234 (\pm) 10</td>
<td>152 (\pm) 7</td>
</tr>
<tr>
<td>12.5 - 15(^{\prime})</td>
<td>227 (\pm) 9</td>
<td>150 (\pm) 7</td>
</tr>
<tr>
<td>15(^{\prime}) - 17.5(^{\prime})</td>
<td>223 (\pm) 8</td>
<td>143 (\pm) 6</td>
</tr>
<tr>
<td>17.5 - 20(^{\prime})</td>
<td>232 (\pm) 9</td>
<td>149 (\pm) 6</td>
</tr>
<tr>
<td>20(^{\prime}) - 25(^{\prime})</td>
<td>220 (\pm) 7</td>
<td>159 (\pm) 5</td>
</tr>
</tbody>
</table>

\(a\)Units of 10\(^{-6}\) counts s\(^{-1}\) arcmin\(^{-2}\)
REFERENCES

Arp, H. 1966, Atlas of Peculiar Galaxies (Pasadena:California Institute of Technology)

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FIGURES

Fig. 1.—Images of M101: a) $N_{\text{H}}$ (Kamphuis et al. 1991), b) $\frac{1}{4}$ keV band, c) $\frac{3}{4}$ keV band, and d) 1.5 keV band. The projection and scale are the same for all images. The arrows in a) and b) indicate the general location of the $\frac{1}{4}$ keV absorption feature of § 3.1.

Fig. 2.—The $\frac{1}{4}$ keV X-ray contours superposed onto a digitized version of a blue photograph of M101 from the Atlas of Peculiar Galaxies (Arp 1966). The X-ray data have been smoothed with a Gaussian function of 42" FWHM. Contours are given for 2,3,4,5,7,9,11,13,17 sigma level above background (1 $\sigma$ corresponds to 220 x $10^{-6}$ counts s$^{-1}$ arcmin$^{-2}$).

Fig. 3.—Radial profiles of M101 after point source removal for the a) $\frac{1}{4}$ keV band, b) $\frac{3}{4}$ keV band, and c) 1.5 keV band. The horizontal line shows the average intensity for the 25' - 50' annulus.

Fig. 4.—Plot of binned data, $\frac{1}{4}$ keV intensity versus H I column density, for the lower right-hand quadrant of the 7" - 25" annulus. The horizontal line shows the average intensity for the 25' - 50' annulus.
X-RAY INTENSITY

\[10^{-6} \text{ counts s}^{-1} \text{ arcmin}^{-2}\]
X-RAY INTENSITY

\((10^{-6} \text{ counts s}^{-1} \text{ arcmin}^{-2})\)
X-RAY INTENSITY

\((10^{-6} \text{ counts s}^{-1} \text{ arcmin}^{-2})\)
X-RAY INTENSITY

\((10^{-6} \text{ counts s}^{-1} \text{ arcmin}^{-2})\)