ON THE X-RAY SOURCE LUMINOSITY DISTRIBUTIONS IN THE BULGE AND DISK OF M31: FIRST RESULTS FROM THE XMM-NEWTON SURVEY

SERGEY P. TRUDOLYUBOV,1 KONSTANTIN N. BOROZDIN,1 AND WILLIAM C. PRIEDHORSKY
Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87545

KEITH O. MASON
Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Dorking, Surrey RH5 6NT, UK

AND

FRANCE A. CORDOVA
Department of Physics, University of California at Santa Barbara, Broida Hall, Building 572, Santa Barbara, CA 93106-95306

Received 2002 March 13; accepted 2002 April 10; published 2002 April 19

ABSTRACT

We present luminosity distributions for the X-ray sources detected with XMM-Newton in the bulge and disk of the Andromeda galaxy (M31). The disk is clearly lacking the bright sources that dominate X-ray emission from the bulge. This is the first convincing evidence of a difference between bulge and disk X-ray populations in M31. Our results are in good qualitative agreement with the luminosity distributions for low- and high-mass X-ray binaries recently obtained by Grimm, Gilfanov, & Sunyaev for our Galaxy. The data presented here confirm that X-ray population of the disk of M31 is dominated by faint high-mass X-ray binary sources, while the bulge is populated with bright low-mass X-ray binaries.

Subject headings: galaxies: individual (M31) — X-rays: galaxies — X-rays: stars

1. INTRODUCTION

Multiple observations of external galaxies starting with Einstein have shown convincingly that the X-ray emission of normal spiral galaxies similar to our own Milky Way is dominated by X-ray binaries (Fabbiano 1995). An X-ray binary contains either a neutron star or a black hole; it can be classified as a low-mass X-ray binary (LMXB) or a high-mass X-ray binary (HMXB) according to the spectral type of the companion star. It is well known that in our Galaxy, most HMXBs lie in the Galactic plane, while the LMXBs have a more spherical distribution, with a conspicuous concentration toward the Galactic center. LMXBs and HMXBs demonstrate very similar X-ray spectra in some of their states; therefore, it is difficult to discriminate between them in a single spectral observation. Recently, Grimm, Gilfanov, & Sunyaev (2001) demonstrated the difference between X-ray luminosity distributions of LMXBs and HMXBs in the Milky Way, providing a method for discriminating between the two populations in other galaxies.

M31 (the Andromeda galaxy) is of special importance for extragalactic astronomy because at a distance of 760 kpc (van der Bergh 2000), it is the closest spiral galaxy to our own. M31 is believed in many respects to be similar to the Milky Way. By observing M31, we can sample hundreds of X-ray sources at a nearly uniform distance and less obscured by interstellar gas and dust than those in the Galaxy because of the favorable orientation of M31. It is therefore quite interesting to look at the luminosity distributions for various populations of X-ray sources in M31 and compare them with our Galaxy. However, earlier attempts to find the difference between luminosity distributions of X-ray sources in the bulge and disk of M31 were unsuccessful (Trinchieri & Fabbiano 1991). In this Letter, we report on the difference between the disk and bulge X-ray source populations of M31, as observed with XMM-Newton in the course of the most sensitive X-ray survey of a neighboring galaxy to date.

1 Also at the Space Research Institute, Russian Academy of Sciences, Profsoyuznaya 84/32, Moscow 117810, Russia.

2 See http://xmm.vilspa.esa.es/user.
from the telescope axis) and subtracted as background the spectrum of adjacent source-free regions. We corrected the count rates for the vignetting of the XMM telescope based on the Current Calibration Files provided with SAS. The EPIC count rates were converted into energy fluxes using analytical fits to the spectra of brighter sources ($L_X > 5 \times 10^{36}$ ergs s$^{-1}$). Detailed spectral analysis for individual bright sources will be presented elsewhere. For faint sources, we estimated energy fluxes with WebPIMMS,$^3$ assuming an absorbed simple power-law spectral shape with photon index $\alpha = 1.5$ and an equivalent absorbing column of $7 \times 10^{25}$ cm$^{-2}$ (Galactic value for the direction to M31).

3. RESULTS AND DISCUSSION

Altogether we detected 230 X-ray sources in the three fields of M31: 118 sources in the core and 112 in the North1 and North2 fields. These include unidentified background and foreground sources, as discussed below. The properties of the individual sources are presented elsewhere (Shirey et al. 2001; Osborne et al. 2001; S. Trudolyubov et al. 2002, in preparation). Here we discuss the source populations and their luminosity distributions. We have noticed that the brightest X-ray sources are concentrated toward the center of M31, while the fainter ones are distributed much more uniformly (Figs. 1c and 1d). Furthermore, we have mentioned that all remaining bright sources in the North1 and North2 fields can be identified with globular clusters (Fig. 1b). Our data prove, for the first time, that M31 resembles our Galaxy in the distribution of its X-ray source populations (i.e., LMXBs and HMXB; see Fig. 1 in Grimm et al. 2001).

3.1. Luminosity Distributions of X-Ray Sources

We have built differential and cumulative luminosity distributions of the detected X-ray sources for the central part of M31 and the combined North1 and North2 fields assuming a distance of 760 kpc (Fig. 2). In order to minimize the contribution from a nondisk X-ray population, the sources identified with globular clusters were excluded from the North1/North2 sample. Taking into account the sensitivity as a function of off-axis distance, the different exposure times, and the effect of diffuse X-ray emission (in the M31 core field), we estimate a flux completeness limit of our sample of $\sim 10^{36}$ ergs s$^{-1}$ (indicated by the dotted line in Fig. 2b).

Some of the objects in the M31 fields must be background and foreground sources lying outside M31 (i.e., a background active galactic nucleus and Galactic K and M stars). Based on Chandra and XMM-Newton deep field results (Giaccconi et al. 2001; Hasinger et al. 2001), one might expect to detect nine background sources in each field with an apparent luminosity above $10^{36}$ ergs s$^{-1}$, while the estimated number of unidentified foreground Galactic stars is less than five sources per field (Shirey et al. 2001).

As it is clearly seen from both panels of Figure 2, the population of the northern disk regions of M31 is dominated by relatively faint objects with luminosities below $\sim 10^{37}$ ergs s$^{-1}$. The overall shape of the unbinned differential luminosity distribution for luminosities above $10^{36}$ ergs s$^{-1}$ can be presented with a simple power law with a slope of $-2.3 \pm 0.2$ (errors quoted are 68% confidence limits).$^4$ The corresponding cumulative luminosity distribution has a slope of $-1.3 \pm 0.2$ and normalization of 41 sources at $10^{36}$ ergs s$^{-1}$. Correction for the background objects (Giacconi et al. 2001; Hasinger et al. 2001) leads to the flattening of the integral distribution, changing its slope from $-1.3$ to $-1.1$ for luminosities above $10^{36}$ ergs s$^{-1}$. Incompleteness of our sample reveals itself in the flattening of the cumulative distribution at luminosities below $10^{36}$ ergs s$^{-1}$ (Fig. 2b).

In contrast to the northern disk regions, bright X-ray sources contribute significantly to the population in the central region of M31 (Fig. 2a). The shapes of both cumulative and differential luminosity distributions for the central region of M31 (Fig. 2) indicate the presence of a cutoff and can be described by a broken power-law model or a cutoff power-law model. We fitted the cumulative luminosity distribution with two power laws at luminosities below and above $1.5 \times 10^{37}$ ergs s$^{-1}$. For source luminosities between $10^{36}$ and $1.5 \times 10^{37}$ ergs s$^{-1}$, we obtain the slope of $-0.5 \pm 0.1$ with normalization of 104 sources at $10^{36}$ ergs s$^{-1}$, while for the higher luminosities, the integral slope is $-1.2_{-0.1}^{+0.2}$ (shown as dotted lines in Fig. 2b). We also fitted the unbinned differential luminosity distribution with a power-law model with exponential cutoff: $L^\alpha \exp \left(-L/L_{\text{cut}}\right)$. The resulting values of $\alpha$ and the cutoff luminosity $L_{\text{cut}}$ are $1.1_{-0.3}^{+0.1}$ and $8.7_{-3.7}^{+8.2} \times 10^{37}$ ergs s$^{-1}$, respectively. Correction for the background/foreground objects leads to the insignificant change in the slope of the integral luminosity distribution for the luminosities above $10^{36}$ ergs s$^{-1}$. There is again some flattening of the cumulative distribution toward the faint source end (Fig. 2b), probably caused by the incompleteness of our sample. These results for the M31 core field are in general agreement with previous studies of the central part of M31 (Primini, Forman, & Jones 1993; Supper et al. 2001; Shirey et al. 2001; Kong et al. 2002).

3.2. Comparison with Previous Results

Studies of the luminosity distributions began as soon as individual X-ray sources in nearby galaxies were resolved (see Fabbiano 1995 for a review of early results). More sensitive

$^3$ See http://heasarc.gsfc.nasa.gov/Tools/w3pimms.html.

$^4$ We fitted unbinned differential and cumulative luminosity distributions using a maximum likelihood method.
surveys with *ROSAT* and *Chandra* significantly increased the number of sources detected (see Read, Ponman, & Strickland 1997 for *ROSAT* review and Fabbiano 2001 for *Chandra* review). Most previous studies, however, differ from our present work in two important aspects: (1) for most external galaxies, sensitivity limits were above or around $10^{37}$ erg s$^{-1}$, while in our case we are able to study in detail a population of sources between $5 \times 10^{35}$ and $10^{37}$ ergs s$^{-1}$; (2) previous studies of luminosity distributions in M31 (Trinchieri & Fabbiano 1991; Kong et al. 2002) were restricted to the central $17'$–$20'$. Since the inner region of M31 ($r < 15'$) is dominated by the bulge and spheroid populations, the disk population was not well sampled in previous surveys. Our results, however, can be directly compared with the luminosity distributions for Galactic sources obtained by Grimm et al. (2001). The comparison shows that the luminosity function that we obtain for the core region is close to the luminosity function of LMXBs in our Galaxy; both distributions have a characteristic change in the slope at luminosities

Fig. 1.—Combined XMM-Newton/EPIC-MOS1 images of the M31 core, North1, and North2 fields. (a) Optical image of M31 from the Digitized Sky Survey with the EPIC-MOS1 FOV shown as circles for each of the observations. The X-ray emission intensity is shown by a logarithmic gray scale (black is the maximum) in panels b–d that represents the enlarged central (M31 core; $r < 15'$) and northern parts of the galaxy (North1 and North2 fields). The positions of identified globular cluster candidates (Battistini et al. 1987; Barmby & Huchra 2001) are shown as small circles in (b). Identified supernova remnants (Blair et al. 1981; Magnier et al. 1995) are marked with small boxes in the same panel. In (c), we circled all detected sources with luminosities greater than $10^{37}$ ergs s$^{-1}$. Fainter sources are shown in (d). Some of the sources that are shown lie outside the EPIC-MOS1 sensitive area but were detected with the EPIC-MOS2 or EPIC-pn detectors. It is evident that the brightest sources are concentrated toward the center of the galaxy, while the fainter sources are distributed throughout the disk. A few bright sources in the disk regions (North1 and North2 fields) are identified with globular clusters and hence belong to the nondisk subsystem of the galaxy.
above a few times $10^{37}$ ergs s$^{-1}$ and can be described by a broken power-law model or a cutoff power-law model with a cutoff luminosity of $\sim 10^{38}$ ergs s$^{-1}$. The luminosity distribution for the two northern fields of M31 resembles the luminosity function for Galactic HMXBs: both have a power-law–like form with a slope steeper than that of the corresponding M31 bulge/Galactic LMXB luminosity distributions; the M31 disk/Galactic HMXB distributions terminate at much lower luminosities ($\sim 10^{37}$ ergs s$^{-1}$) than M31 bulge/Galactic LMXB luminosity distributions ($>10^{38}$ ergs s$^{-1}$). We conclude therefore that the population of fainter X-ray sources that we found in disk of M31 is probably dominated by the HMXBs, while the bulge region inside 15′ is dominated by LMXBs by analogy with the Milky Way. Our results confirm that, as in Milky Way and other nearby galaxies, the younger population of HMXBs in M31 is typically less luminous than the older populations of LMXBs and globular clusters (see also Helfand & Moran 2001 for a discussion of HMXB luminosities). In our study, we see no evidence that the brightest sources in M31 are associated with young populations; in fact, we see the opposite effect. This is in contrast to Soria & Wu (2002), who invoke a population of bright young binaries to explain a large number of high-luminosity objects observed in the starburst galaxies. That effect can be probably attributed to the differences in galaxy type and in the ranges of X-ray luminosities under study.

4. CONCLUSIONS

We analyzed XMM-Newton data for the three M31 fields and detected a total of 230 pointlike sources. We built luminosity distributions separately for the bulge (inner 15′) and disk regions. A striking difference between the bulge and disk populations has been demonstrated for the first time. We report on the discovery of a lower luminosity population in the disk of M31. Comparison of our results with the luminosity function obtained by Grimm et al. (2001) for the Milky Way allows us to conclude that a lower luminosity population in the disk is probably dominated by HMXBs and that the luminosity distributions of X-ray sources in the bulge and disk of M31 are similar to the corresponding parts of our Galaxy.

We have used data obtained with the XMM-Newton satellite. XMM-Newton is an ESA science mission with instruments and contributions directly funded by ESA Member States and the US (NASA). We are grateful to the personnel of the XMM-Newton Science Operations Centre at VILSPA, Spain, for satellite operations and the expedited data preparation for scientific analysis. We are thankful to our colleagues from the PV data analysis team for a fruitful collaboration in an earlier analysis of M31 PV observations (Shirey et al. 2001; Osborne et al. 2001). We are especially indebted to M. Watson, PI of the M31 PV program.

REFERENCES

Barmby, P., & Huchra, J. P. 2001, AJ, 122, 2458
Battistini, P., Bonoli, F., Braccesi, A., Frederici, L., Fusi Pecci, F., Marano, B., & Bormgen, F. 1987, A&AS, 67, 447
Blair, W. P., Kirshner, R. P., & Chevalier, R. A. 1981, ApJ, 247, 879
Fabbiano, G. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 390
Fabbiano, G. 2001, talk given at the Vulcano Workshop on Galaxy and Cluster Evolution, 2000 May 14–18, Vulcano, Italy (astro-ph/0109391)
Giacconi, R., et al. 2001, ApJ, 551, 624
Grimm, H.-J., Gilfanov, M., & Sunyaev, R. 2001, A&A, submitted (astro-ph/0109239)
Hasinger, G., et al. 2001, A&A, 365, L45
