ULTRALUMINOUS X-RAY SOURCES IN M51

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Abstract

We present the results of Chandra observations of off-nuclear X-ray sources in the spiral galaxy M51 (NGC 5194). 113 X-ray sources have been detected in the field of view and 84 among them project within the disk of NGC 5194. Six and twenty eight sources have luminosities exceeding \(1 \times 10^{39}\) ergs s\(^{-1}\) and \(1 \times 10^{48}\) ergs s\(^{-1}\) in the 0.5–8 keV band, respectively. The number of luminous sources is much higher than normal spiral and elliptical galaxies and similar to galaxies experiencing starburst activity. X-ray spectra of most of the detected sources are consistent with a power law with a photon index between 1 and 2, while one source has an extremely hard spectrum and two sources have soft spectra. The spectra of three ultraluminous sources are consistent with both a power law and a multicolor disk blackbody (MCD) model, while a power law model is preferable to a MCD model in two objects. One luminous object which shows a remarkable spectrum, including emission lines, is also found and discussed.

Key words: galaxies: active — X-rays: galaxies — galaxies: X-rays

1. Introduction

X-ray emission from spiral galaxies consists of various components, namely discrete sources such as X-ray binaries, hot gas, an active galactic nucleus, if present, and so on. One of the most intriguing and puzzling classes of X-ray sources in spiral galaxies is ultraluminous compact X-ray sources (ULXs) whose luminosities (> \(10^{39}\) erg s\(^{-1}\)) well exceed the Eddington luminosity of neutron stars.

The nearby (8.4 Mpc; Feldmeier et al. 1997) spiral galaxy NGC 5194 (M51) is one of the best targets to study an X-ray source population including ULXs since previous observations with the ROSAT PSPC and HRI have shown the presence of several luminous X-ray sources whose luminosities exceed \(10^{39}\) ergs s\(^{-1}\) (Marston et al. 1995; Ehle, Pietsch, & Beck 1995; Roberts & Warwick 2000). In this paper, we present results of two Chandra observations and discuss the source population, time variability, and spectra of luminous X-ray sources. The detailed results can be found in Terashima & Wilson (2002).

2. Observations and Source Detection

Chandra observations of M51 were performed on 2000 June 20 and 2001 June 23 with the ACIS-S3 chip, with effective exposure times of 14.9 ksec and 26.8 ksec, respectively.

A true color image is shown in Fig. 1. In this image, we see extended emission distributed along the spiral arms of the host galaxy of NGC 5194, a bright nuclear region, and many discrete sources. The companion galaxy NGC 5195 also show discrete sources and diffuse emission. The color indicates that the diffuse emission has a very soft spectrum, while the discrete sources show a variety of spectral hardness. We performed X-ray source detection using wavdetect in the CIAO software package for the first, second, and combined data sets, and detected 113 source in the field of view. 84 and 12 objects are spatially coincident with NGC 5194 and NGC 5195, respectively. According to the log \(N - \log S\) derived from Chandra deep surveys, 8–12 background sources are expected in the field of view of the S3 chip. Most of the discrete sources in NGC 5194 are located on or near the spiral arms and few sources are seen between the arms.

We used the combined data to measure the luminosity function of the X-ray sources in NGC 5194. Band ratios (2–8 keV / 0.5–2 keV) were used to estimate the spectral shapes and to calculate source luminosities (Fig. 2). X-ray spectra of most sources are consistent with a photon index between 1 and 2 if a power law spectrum modified by the Galactic absorption is assumed. The luminosity function is shown in Fig. 3. The slope in the luminosity range above \(10^{38}\) erg s\(^{-1}\), which is virtually free from incompleteness, is –0.89. This slope is in the range often observed in disk galaxies and starburst galaxies, and significantly flatter than those observed in ellipticals and lenticulars.

Next we searched for short-term and long-term variability. Within each observation, three sources were found to be time variable on a time scale of several 1000 s. About one-third (26) of discrete sources in NGC 5194 indicate time variability at greater than the 3\(\sigma\) level in the 0.5–8 keV band between the two observations separated a year. Four objects among them show a large amplitude (a factor of ten or more) variability suggesting their transient nature.
3. Ultra Luminous X-ray Sources

Spectral fits were performed for relatively bright objects. Here we present the results for six ULXs with 0.5–8 keV luminosities exceeding $10^{39}$ ergs s$^{-1}$ in at least one observation. Two models - a power law and a multicolor disk blackbody (MCD) - were examined. The results are summarized in Table 1. The errors are 90% confidence for one parameter of interest ($\Delta \chi^2 = 2.7$).

3.1. ULXs with a Power law Spectrum

The spectra of NGC 5194 #82 = CXOM51 J133007.6+471106 and NGC 5194 #37 = CXOM51 J132953.3+471042 in the second observation are better fitted with a power law than a MCD (the source names are taken from Terashima & Wilson 2002). The ASCA spectra of ULXs studied by Makishima et al. (2000) are successfully explained by a MCD rather than a power law, while ULXs whose spectra are better fitted by a power law have been found in recent observations (sources in IC 342, Kubota et al. 2001; CXOU J112015.8+133514 in NGC 3628, Strickland et al. 2001; in NGC 4565 (RXJ 1236.2+2558 = XMM J123617.5+285855, Foschini et al. 2002; NGC 5204 X-1, Roberts et al. 2001). Thus it appears that these objects constitute a class of ULXs whose spectra are a power law.

The power law spectrum may be accounted for in several models: (1) the “hard” state of a black hole, in which a power law spectrum with a photon index of 1.4–2 (e.g., Tanaka 1996, Done 2001) is found, (2) beamed X-ray emission in “micro quasars” (Körding, Falcke, & Markoff 2002), and so on.

NGC 5194 #37 is detected only in the second observations which indicates the photon flux increased by a factor of more than 100 in the 0.5–8 keV band. On the other hand, NGC 5194 #82 is detected and spectral information is available in both observations. The spectrum flattened ($\Gamma = 2.26$ to 1.86) accompanied by a flux decrease by 40%. This behavior is similar to that of Galactic BHCs in the hard state which have steeper spectra in brighter-flux states.

3.2. Spectral Steepening in NGC 5194 #69

NGC 5194 #69 = CXOM51 J133001.0+471344 shows a remarkable spectral variability (Fig. 4). The photon flux in the 2–8 keV band decreased by a factor of more than 13. The first spectrum is relatively hard, with a photon index $\Gamma = 1.24_{-0.12}^{+0.17}$ or $kT_{\text{in}} = 2.3_{-0.5}^{+1.0}$ keV, while the second spectrum is extremely soft, with $\Gamma > 5.1$, $kT_{\text{in}} = 0.17_{-0.06}^{+0.13}$ keV (MCD), or $kT = 0.16_{-0.06}^{+0.08}$ keV (black body). If we adopt a power law model and a MCD model for the first and second spectra, respectively, the intrinsic luminosity...
Table 1. Spectral Fit to Ultra Luminous X-ray Sources

| Source Name | $N_H$ | $\Gamma$ | $kT_{\text{in}}$ | $\chi^2$/dof | $L_X^d$ |
|-------------|------|--------|----------------|-------------|--------|
| 5 (1)       | 0.18 ± 0.11 | 1.37±0.38 | ...       | 11.8/12    | 1.2    |
|             | 0.099±0.10   | ...       | 1.85±0.85 | 10.6/12     | 1.2    |
| 5 (2)       | 0 (<0.073)   | 1.17±0.20 | ...       | 12.3/8     | 0.55   |
|             | 0 (<0.038)   | ...       | 1.58±1.13 | 13.6/8      | 0.41   |
| 26 (1)      | 5.8±6.9      | ...       | 1.8±2.1   | 3.2/3       | 2.9    |
| 26 (2)      | 3.6±2.0      | ...       | 1.55±0.86 | 12.2/14     | 4.0    |
| 37 (2)      | 0.11±0.04    | 1.55±0.19 | ...       | 25.0/33    | 1.5    |
|             | 0 (<0.023)   | ...       | 1.76±0.29 | 35.9/33     | 1.3    |
| 41 (1)      | 0.11 (<0.18) | 1.50±0.38 | ...       | 6.8/11     | 1.1    |
|             | 0.018 (<0.11)| ...       | 1.43±0.67 | 5.5/11      | 0.84   |
| 41 (2)      | 0.090±0.057  | 1.32±0.17 | ...       | 27.1/23    | 1.1    |
|             | 0.0012 (<0.042)| ...| 2.20±0.68 | 26.6/23     | 1.0    |
| 69 (1)      | 0.12±0.03    | 1.24±0.12 | ...       | 34.9/28    | 2.7    |
|             | 0.034 (<0.073)| ...| 2.34±0.97 | 37.0/28     | 2.4    |
| 69 (2)      | 0.83±0.81    | ...       | 0.17±0.13 | 3.3/6       | 0.56   |
| 82 (1)      | 0.16±0.05    | 2.26±0.24 | ...       | 52.7/47    | 3.1    |
|             | 0 (<0.021)   | ...       | 0.87±0.09 | 60.5/47     | 2.1    |
| 82 (2)      | 0.097±0.041  | 1.86±0.17 | ...       | 66.0/47    | 1.8    |
|             | 0 ...        | 1.11      | 91.9/47   | ...        | ...    |

(a): (1) and (2) denote the first and second observations, respectively. (b): Absorption column density in unit of $10^{22}$ cm$^{-2}$. (c): Inner temperature for multicolor disk blackbody model in unit of keV. (d): X-ray luminosity in the 0.5–8 keV band in unit of 10$^{39}$ ergs s$^{-1}$ corrected for absorption. (e): Maximum-likelihood fit using C-statistic.

of this source declined by a factor of 3500 in the 2–10 keV bands.

Such a drastic steepening of spectra accompanied by a large flux decline is seen in soft X-ray transients which show very soft spectra ($kT = 0.2 – 0.3$ keV for a black body model) when the luminosity goes down below $10^{34}$ ergs s$^{-1}$ (Tanaka 1996, Tanaka & Shibazaki 1996). Such luminosities, however, are much lower than we observed in the source NGC 5194 #69 in the second observation ($5.6 \times 10^{38}$ ergs s$^{-1}$ in 0.5–8 keV and $7.4 \times 10^{35}$ ergs s$^{-1}$ in 2–10 keV). Galactic black hole candidates are in a hard state, with spectral described by a power law with a photon index of 1.5–2.0, for such a luminosity. Thus, it is not clear whether the similarity of the spectral shape between the quiescent state of soft X-ray transients and the NGC 5194 source in the second observation has any physical significance.

3.3. The Hard Source NGC 5194 #26

One source (CXOM51 J 132950.7+471155 = NGC 5194 #26) has the hardest spectrum among the detected sources. This source can be seen as a very blue (= very hard) source to the NW of the nucleus in Fig. 1 of Terashima & Wilson (2001).

This source shows a remarkable spectrum and variability. In the first observation, the spectrum is apparently flat and virtually no photons are detected in the low energy band below 2 keV. Since there are indications of emission lines, we added four Gaussians to represent these features to an absorbed power law continuum ($\Gamma = 1.6, N_H = 4.6 \times 10^{22}$ cm$^{-2}$) (Fig. 5 top). The intrinsic luminosity is $3.4 \times 10^{39}$ ergs s$^{-1}$ in the 0.5–8 keV band. On the other hand, emission line features are not clear in the spectrum of the second observation (Fig. 5 bottom). The continuum is fitted with a partially covered power law model ($\Gamma = 1.8, N_H = 4.5 \times 10^{22}$ cm$^{-2}$, covering fraction = 0.988). The intrinsic luminosity ($5.0 \times 10^{39}$ ergs s$^{-1}$ in 0.5–8 keV) is 50% higher than that in the first observation.

Emission lines with large equivalent widths from highly ionized atoms are observed in eclipses of high-mass X-ray binaries, when the direct emission from the compact object is blocked by the companion star, and only emission from and scattered by the photoionized medium surrounding the system (such as a stellar wind from the companion) is observed. However, the observed luminosity is too large for such scattered emission from ordinary binaries. This dichotomy could be reconciled if the compact object...
is an ULX or the irradiating emission is anisotropic. The spectrum without strong emission lines and with a larger luminosity in the second observation appears to be dominated not by scattered emission but by direct emission from the compact object and suggests that the possibility of beaming to explain the emission lines in the first observation.

Figure 5. Chandra spectra of NGC 5194 # 26 in the first (top) and second (bottom) observation.

3.4. Two Other ULXs

The spectra of the two ULXs NGC 5194 #5 = CXOM51 J132939.5+471244 and NGC 5194 #41 = CXOM51 J132953.7+471436 can be represented by either a power law or a MCD model. The luminosity of the former source decreased by a factor of 2.5, while that of the latter remained the same between the two observations. Their spectra flattened. The trend of the spectral variability of NGC 5194 #5 (flatter in lower flux state) is similar to both the hard state of Galactic black hole candidate, and ULXs whose spectra are described by a MCD model (Mizuno, Kubota, & Makishima 2001). The spectral slope for the power law fit and $kT_{in}$ for the MCD fit are in the range for previously known ULXs.

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