A LUMINOUS RECURRENT SUPERSOFT X-RAY SOURCE IN NGC 300

A. K. H. KONG1 AND R. DI STEFANO1,2

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ABSTRACT

We report the results of XMM-Newton observations for an especially luminous supersoft X-ray source (SSS) with a bolometric luminosity of 10^{39} ergs s^{-1} in the spiral galaxy NGC 300. The source was detected as an SSS in 1992 and disappeared in subsequent X-ray observations. The source was active again during recent XMM-Newton observations. It appeared to be very soft (kT \sim 60 eV) and very luminous (\sim 10^{39} - 10^{40} ergs s^{-1}). The two XMM-Newton observations also reveal that the source went from a “high” state to a “low” state in 6 days. We also found a 5.4 hr periodicity during the low state. We consider white dwarf, black hole, and neutron star models in order to explain the nature of the source.

Subject headings: galaxies: individual (NGC 300) — X-rays: binaries — X-rays: galaxies

1. INTRODUCTION

Supersoft X-ray sources (SSSs) form a distinct class of objects, first established through ROSAT observations. The hallmarks of SSSs are very soft X-ray emission (typically kT < 100 eV) and bolometric luminosities of 10^{36} - 10^{38} ergs s^{-1}. The advent of Chandra and XMM-Newton has provided good opportunities to detect and study SSSs in nearby galaxies. Luminous (10^{38} - 10^{40} ergs s^{-1}) SSSs have been found in several nearby galaxies, including M31 (Kong et al. 2002; Di Stefano et al. 2002a), M81 (Swartz et al. 2002), M101 (Pence et al. 1992), NGC 4697 (Sarazin, Irwin, & Bregman 2001; DK03), NGC 4697 (Sarazin, Irwin, & Bregman 2001; DK03), M51 (DK03), and M83 (Soria & Wu 2003; DK03).

NGC 300 is an SA(s)d galaxy, seen near face-on (with an inclination angle of 46°; Tully 1988) at a distance of 2.0 Mpc (Freedman et al. 2001). The galaxy has been observed 5 times from 1991 to 1997. A detailed analysis of the ROSAT data was done by Read & Pietsch (2001). Briefly, the data sets consist of two Position Sensitive Proportional Counter (PSPC) and three High Resolution Imager (HRI) pointings. The exposures range from ~9 to ~37 ks. The luminous supersoft source was only detected in a 37 ks PSPC observation taken on 1992 May and June (see Read & Pietsch 2001). Spectral analysis was also done by Read et al. (1997). We have reanalyzed the PSPC spectrum taken on 1992 May/June and have used other data to set upper limits on the luminosity for the long-term light curve.

We extracted the source spectrum from a 30′ circular region, while background was from an annulus region (45″ and 60″ radii) centered on the source. The spectrum was grouped into at least 20 counts per spectral bin to allow \chi^2-statistics to be used.

2. OBSERVATIONS AND DATA REDUCTION

2.1. ROSAT

NGC 300 was observed by ROSAT 5 times from 1991 to 1997. A detailed analysis of the ROSAT data was done by Read & Pietsch (2001). Briefly, the data sets consist of two Position Sensitive Proportional Counter (PSPC) and three High Resolution Imager (HRI) pointings. The exposures range from ~9 to ~37 ks. The luminous supersoft source was only detected in a 37 ks PSPC observation taken on 1992 May and June (see Read & Pietsch 2001). Spectral analysis was also done by Read et al. (1997). We have reanalyzed the PSPC spectrum taken on 1992 May/June and have used other data to set upper limits on the luminosity for the long-term light curve.

We extracted the source spectrum from a 30′ circular region, while background was from an annulus region (45″ and 60″ radii) centered on the source. The spectrum was grouped into at least 20 counts per spectral bin to allow \chi^2-statistics to be used.

2.2. XMM-Newton

The XMM-Newton instrument modes were full-frame, medium filter for the three detectors of the European Photon Imaging Camera. The first observation was taken on 2000 December 26 for 37 ks, and the second observation was on 2001 January 1 for about 47 ks. After rejecting intervals with a high background level, we considered a good time interval of ~28 and ~40 ks for the first and second observation, respectively. Data were reduced and analyzed with the XMM-Newton SAS package, version 5.3.3.

We used here the MOS images to determine the position of the source because the spatial resolution of the MOS detector is slightly better than that of the pn detector. The source is located at R.A. = 00\,55\,10\,7, decl. = −37°38′55″ (J2000), ~4′ (2.4 kpc) from the galactic center; the derived positions from the two XMM-Newton observations agree with each other. This position is about 5′ off from previous ROSAT PSPC observations and is consistent with the positional error (7′′/3) quoted by Read & Pietsch (2001).

Source spectra and light curves of XMMU J005510.7−373855 were extracted with the SAS task XMSELECT. Source-free regions were used for background to avoid the chip boundary and a nearby faint source. In order to allow \chi^2-statistics to be used, all the spectra were binned such that there are at least 20 counts per spectral bin. Response matrices were created by RMFGEN and ARFGEN.

3. ANALYSES AND RESULTS

Spectral analysis was performed by making use of XSPEC, version 11.2. Table 1 shows the best-fitting spectral parameters for the three ROSAT and XMM-Newton observations.

For the ROSAT observation, the spectrum (see Fig. 1) can be fitted with a blackbody model with N_H = 1.1 \times 10^{21} cm^{-2} and kT = 48.7 eV; the 0.2–2 keV luminosity is 10^{39} ergs s^{-1}. We note that Read et al. (1997) fitted the spectrum with a thermal bremsstrahlung model with a temperature of 0.1 keV, and we confirmed that it is also an acceptable model. Using the thermal bremsstrahlung model, the luminosity becomes 3.8 \times 10^{39} ergs s^{-1} (the luminosity quoted by Read et al. 1997 is 1.6 \times 10^{37} ergs s^{-1}, which is an absorbed luminosity corrected for absorption in our own Galaxy), a factor of 2.5 lower than the blackbody model. While we cannot distinguish between the two models statistically, we prefer the blackbody model as subsequent XMM-Newton observations confirm the supersoft nature of the source.
(see below). Also, the XMM-Newton observations would have detected the high-energy photons associated with the thermal bremsstrahlung model had the model been correct. Finally, the XMM-Newton observations provide more photons than ROSAT.

We fitted the pn, MOS1, and MOS2 data simultaneously with several single-component models with interstellar absorption (including absorbed power-law, thermal bremsstrahlung, blackbody, and Raymond-Smith models); only the blackbody model provides an acceptable fit. The blackbody temperature of both observations ranges between 57 and 67 eV, while the \( N_H \) varies from 1.5 \( \times 10^{21} \) cm\(^{-2}\) in the first observation to 5.3 \( \times 10^{20} \) cm\(^{-2}\) in the second observation. The 0.2–2 keV luminosity also drops from 9 \( \times 10^{38} \) to 1.2 \( \times 10^{38} \) ergs s\(^{-1}\), indicating that the source is a variable on a timescale of days. The spectra of the two observations are shown in Figure 1.

The combined ROSAT and XMM-Newton long-term light curve of the SSS is shown in Figure 2, which is constructed from a series of ROSAT and XMM-Newton pointings. The source was below the detection limit of other ROSAT observations. In these cases, we estimated the 3 \( \sigma \) limits, assuming a blackbody model with mean \( N_H \) (10\(^2\) cm\(^{-2}\)) and \( kT \) (58 eV). The value of \( N_H \) plays an important role in estimating the luminosity. For instance, if we lower the \( N_H \) to 5.3 \( \times 10^{20} \) cm\(^{-2}\), as found in the second XMM-Newton observation, the upper limits decrease by a factor of \( \sim 3 \). In other words, the source varies by as much as factor of 30 between the “low” state and the “high” state spanning 8.5 yr.

To search for short-term variability, we computed the Lomb-Scargle periodogram (LSP; Lomb 1976; Scargle 1982), a modification of the discrete Fourier transform that is generalized to the case of uneven spacing. In each observation, we extracted the combined background-subtracted light curve from pn and MOS detectors to increase the signal-to-noise ratio. Individual light curves from each of the three detectors were also used to verify the result. By applying the LSP to the combined light curve, we found that there is a sharp peak at 5.4 hr in the low-state observation (see Fig. 3). Independent checks from the pn and MOS data also confirmed the periodicity. We determined the 99.9% confidence level by generating Gaussian noise data sets with the same time intervals and variance as the true data, and then we performed the LSP analysis on the resulting data sets (see Kong, Charles, & Kuulkers 1998). The peak power in each periodogram (which must be purely due to noise) was then recorded. This was repeated 10,000 times to obtain good statistics. The peak at 5.4 hr is well above the 99.9% confidence level. The folded light curve of the low-state data in 5.4 hr is also shown in Figure 3.

Similar analysis was also carried out in the high-state data, but there is no significant peak in the LSP. The folded light curve shows no obvious periodic variability at 5.4 hr (see Fig. 3). It is not clear whether it is due to geometric effect, but the exposure time of the high state covers less than 8 hr, corresponding to 1.4 cycles of the 5.4 hr period in contrast to the 2.1 cycles in the low state. We therefore performed a Kolmogorov-Smirnov test to test for variability and found significant variability at the 99.9% levels. We also searched for variability of the hardness ratio, but no significant change was found in both observations.

We also examined an Digitized Sky Survey image of NGC 300 to search for a possible optical counterpart. Within a 4° error circle of the XMM-Newton position, there is no obvious optical counterpart with limiting \( B \) and \( R \) magnitudes of 21 and 18.1, respectively. However, the source is surrounded by \( H \) regions (Deharveng et al. 1988; Blair & Long 1997), OB associations (Pietrzynski et al. 2001), and supernova remnants (Blair & Long 1997). The nearest \( H \) region (source 136; Deharveng et al. 1988) is located about 20″ (~200 pc) southeast of the X-ray source. Within 50″ (~500 pc) of the SSS, we found an OB association (AS 99; Pietrzynski et al. 2001), two supernova remnant candidates (N300-S21 and N300-N23; Blair & Long 1997), and a \( H \) region (N300-H20; Blair & Long 1997). We also looked for a UV counterpart from the Optical Monitor (OM) image (see Soria & Kong 2003 for details of the OM observations); no counterpart is found at the position of the SSS in both observations.

4. DISCUSSION

It is clear from the spectral fits of all ROSAT and XMM-Newton observations that the XMMU J005510.7–373855 is very soft (\( kT \sim 48–67 \) eV) and is highly variable. Such a soft spectrum is consistent with SSSs seen in our own Galaxy, the Magellanic Clouds, M31 (Greiner 2000), and several nearby galaxies (see § 1). Since the Galactic and Magellanic Cloud SSSs are conjectured to be white dwarfs (WDs), it is reasonable to consider a WD model for the source in NGC 300. Since, however, the luminosity in the high state may be too large to be consistent with the standard SSS WD model, we also consider black hole (BH) and neutron star (NS) models.

The X-ray emission of the SSS could come from a WD that burns accreting hydrogen in a quasi-steady manner. The maximum luminosity is the Eddington luminosity for a 1.4 \( M_\odot \) object. WD models therefore seem to be ruled out by the high bolometric luminosities during two of the observations. It is nevertheless worth noting that the WD model temperatures are comparable to those we observed and that X-ray variability by a factor of a few over times of days and months has been observed in SSSs. (see, e.g., Greiner & Di Stefano 2002 and references therein.) If the 5.4 hr variation detected during the X-ray low state corresponds to an orbital period, then this system may be similar to 1E 0035.4–7230, a Magellanic Cloud SSS that appears to have a 4 hr period (Kahabka 1996). In such a short-period binary, it is likely that a radiation-driven wind plays an important role in the binary evolution (see, e.g.,

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### TABLE 1

| Date          | \( N_H \) \((\times 10^{21} \text{cm}^{-2})\) | \( kT \) \((\text{eV})\) | \( L_{\text{bol}}^{\text{a}} \) \((\times 10^{39} \text{ergs s}^{-1})\) | \( L_{\text{bol}}^{\text{b}} \) \((\times 10^{39} \text{ergs s}^{-1})\) | \( \chi^2/\text{dof} \) |
|---------------|---------------------------------|-----------------|---------------------------------|-----------------|-----------------|
| 1992 May 26...| 1.08 \( \pm \) 0.31                           | 48.7 \( \pm \) 1.1 | 10                             | 20               | 0.74/11          |
| 2000 Dec 26...| 1.50 \( \pm \) 0.32                           | 56.8 \( \pm \) 2.2 | 9                              | 15               | 1.07/39          |
| 2001 Jan 1....| 0.53 \( \pm \) 0.05                           | 66.5 \( \pm \) 3.5 | 1.1                            | 1.9              | 1.15/48          |

Note.— All quoted uncertainties are 1\( \sigma \); dof = degree of freedom.

\(^a\) The 0.2–2 keV X-ray luminosity, assuming a distance of 2 Mpc.  
\(^b\) Bolometric luminosity.
SSS emission is expected from accreting BHs. Modeling the accretion disk as a thin disk that is optically thick, we can derive a relationship between the minimum mass of the accretor and the observed temperature and luminosity (Frank, King, & Raine 2002). Using $kT = 60$ eV and $L_X = 10^{38} \text{ergs s}^{-1} (10^{39} \text{ergs s}^{-1})$, we find that the accretor mass is greater than $\approx 890 M_\odot (2800 M_\odot)$. Although the fact that the observed luminosity is $10^2$--$10^3$ times smaller than the Eddington luminosity may call the validity of the disk model into question, this calculation suggests that the accretor is an intermediate-mass BH. If the accretor is a BH, we may use $\dot{m} = \frac{1}{0.1 \eta}$, where $\dot{m}$ is the accretion rate and $\eta$, the efficiency factor, is likely to be close to 0.1. This yields $\dot{m} \approx 1.8 \times 10^{-3} M_\odot \text{yr}^{-1} (1.8 \times 10^{-7} M_\odot \text{yr}^{-1})$ for $L_{\text{obs}} = 10^{38} \text{ergs s}^{-1} (L_{\text{obs}} = 10^{39} \text{ergs s}^{-1})$. This would be consistent with an irradiation-driven wind from a low-mass donor. Measurement of the orbital period could provide supporting evidence. Indeed, if the donor fills its Roche lobe, then $P_p \approx (8.9 \text{ hr}) (M_J/3 M_\odot)$, where $M_J$ is the mass of the donor star. If $P_p = 5.4 \text{ hr}$, then $M_J \approx 0.61 M_\odot$.

It is of course possible that the observed emission emanates from an accreting NS. In this case, the SSS emission would presumably emanate from a photosphere that is much larger than the NS itself. The photospheric radius would be different in each observation: $R_p \approx 93.7 \times 10^{-6}$ cm during the ROSAT observation, $2.6 \times 10^{-6}$ cm during the XMM-Newton high-state observation, and $6.8 \times 10^{-6}$ cm during the XMM-Newton low-state observation, corresponding to the different temperatures and luminosities.

At this point, NS models seem conceptually unattractive because there is no obvious explanation for why the photosphere should achieve these relatively large sizes, and no way to relate them to the system’s fundamental physical parameters. In addition, just as in the WD models, the luminosity appears to be super-Eddington during two of the observations, unless the NS
Fig. 3.—(a) LSP of XMMU J005510.7−373855 as obtained by XMM-Newton on 2001 January. The horizontal dotted line is the 99.9% confidence level. (b) Folded light curve of the low state (2001 January) data on a period of 5.4 hr. (c) Folded light curve of the high state (2000 December) data on a period of 5.4 hr. The $T_0$’s of both light curves are set at the time of the first data point.

has a mass as large as $3–4 \, M_\odot$. In this case, if the efficiency of turning accretion energy into X-rays is the same during all three observations, then the accretion rate must have changed by an order of magnitude, approaching $10^{38}$ and $10^{39}$ erg s$^{-1}$. During the low state, the source showed a 5.4 hr periodicity. If we consider that the periodicity is due to the orbital period, then the X-ray emission can be explained by WD, BH, and NS models. However, WD and NS models appear unlikely to be due to the high X-ray luminosity during the high state. Further repeated X-ray observations of the SSS in different states may permit discrimination among these models.

5. SUMMARY

We have studied a recurrent luminous SSS in NGC 300 with XMM-Newton. The source was seen by ROSAT in 1992 and fell below the detection limit in subsequent ROSAT observations. It reappeared in recent XMM-Newton observations with bolometric luminosities between $10^{38}$ and $10^{39}$ ergs s$^{-1}$. During the low state, the source showed a 5.4 hr periodicity. If we consider that the periodicity is due to the orbital period, then the X-ray emission can be explained by WD, BH, and NS models. However, WD and NS models appear unlikely to be due to the high X-ray luminosity during the high state. Further repeated X-ray observations of the SSS in different states may permit discrimination among these models.

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