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ROSAT OBSERVATIONS OF A NEW X-RAY TRANSIENT IN THE SMALL MAGELLANIC CLOUD

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ABSTRACT

We describe *ROSAT* observations of a new X-ray transient and its probable optical companion in the Small Magellanic Cloud. The transient, designated RX J0117.6−7330, appeared at a position ∼5′ southeast of the X-ray pulsar, SMC X-1, in 1992 October 1–2 PSPC observations centered on the pulsar. It was detected again in a similar observation 246 days later at a counting rate diminished by a factor of 270, which corresponds to an average *e*-folding decay time of 44 days. No periodic pulsations have been detected. The average 1992 flux level would be produced by a source radiating isotropically with a luminosity of 1.6×10^{37} $(D/50 \text{ kpc})^2$ ergs s^{-1} in the energy range 0.2–2.5 keV. The 5″ radius positional error circle includes the probable optical counterpart in the form of a magnitude $V = 14.2$ star with the spectral characteristics of type Be.

Subject headings: galaxies: Magellanic Clouds — novae, cataclysmic variables — stars: individual (RX J0117.6−7330) — X-rays: binaries — X-rays: stars

1. INTRODUCTION

Of the 71 transient X-ray binaries containing neutron stars or black holes listed in a 1992 catalog of high- and low-mass X-ray binaries (van Paradijs 1995), three are in the Small Magellanic Cloud (SMC) and two are in the Large Magellanic Cloud (LMC), of which one is a 69 ms pulsar. The optical companions have *V* magnitudes in the range 14–17 mag, and all have been characterized as early-type giants or subgiants of type Be. *ROSAT* observations have revealed additional Magellanic transients: a pulsar in the LMC with a period of 4.0635 s and a Be-type companion (Schmidtke et al. 1995), and three transients with certain or likely Be-type companions in the SMC (Kahabka & Pietsch 1996), of which one is a 2.7632 s pulsar with an unusually soft X-ray spectrum (Hughs 1994). All of these transients are believed to be neutron stars in binary systems in which episodes of enhanced accretion cause outbursts of X-ray emission that last from weeks to months.

Among the galactic transients is a subclass of nonpulsing X-ray sources with masses that exceed 3.0 $M_\odot$, the causality limit on the mass of a neutron star. These objects (see Tanaka & Lewin 1995), the so-called black hole X-ray novas (BHXN), typically have an "ultrasoft" spectrum characterized by a much higher ratio of the flux between 1 and 3 keV to the flux between 3 and 10 keV compared to that for pulsars, a high-energy tail detectable in some cases to more than 100 keV, a maximum luminosity of the order of 10^{38} ergs s^{-1}, and *e*-folding decay times in the range 30–60 days. They are strongly concentrated toward the galactic plane, with a mean value of $|b^{II}| < 5°$, and their companions have all been identified as late-type dwarfs or subgiants. None have yet been observed in the Magellanic Clouds.

In this Letter, we describe observations of a new X-ray transient in the SMC (Clark, Remillard, & Woo 1996). Spectroscopy of its probable optical counterpart (Charles, Southwell, & O'Donoghue 1996) has shown a spectrum with the characteristics of a massive Be star, which makes it likely that the transient is another example of an accretion-powered neutron star with a Be-type companion. At the same time, the transient has some of the X-ray characteristics of a BHXN.

2. OBSERVATIONS AND DATA ANALYSIS

Observations were made with the Position Sensitive Proportional Counter (PSPC) at the focal plane of the X-Ray Telescope on board the *ROSAT* X-Ray Observatory. Details of the observatory have been described by Trümper (1983), Pfeffermann et al. (1987), and Aschenbach (1988).

The observations were centered on the binary X-ray pulsar SMC X-1 and were carried out during 1991 October 7.2–8.1, 1992 September 30.7 to October 2.6, and 1993 June 3.0–4.4 with total exposures of 16955 s, 8984 s, and 11864 s, respectively. No vignetting corrections were made because the transient image was near the center of the field of view in the region of flat response. (SMC X-1 was in eclipse during most of the 1992 and 1993 observations.)

Counting rate contour maps of the central region of the XRT/PSPC images from the three observations are displayed in Figure 1. The 1991 image shows SMC X-1 at the center and the coronal X-ray star, HD 8191, identified by Seward & Mitchell (1981). The transient source appears in the 1992 image as a bright object at a position approximately 5′ southeast SMC X-1. The 1993 image shows the transient source with greatly diminished intensity. We adopt the designation RX J0117.6−7330 for this object.

2.1. *Position and Optical Identification*

The angular separations of the transient from SMC X-1 and HD 8191 in the 1992 X-ray image are 293″.6 ± 1″.1 and 404″.7 ± 1″.4, respectively. The coordinates of the point that lies at these angular separations from the optical positions of Sk 160 and HD 8191, derived from the Digital Sky Survey (DSS), are $01^h17^m40^s.12 \pm 1^s.17$, −73°30′48″ ± 5″. Figure 2 (Plate L13) is a 2′ × 2′ portion of the DSS, with the position of the transient indicated as a 90% confidence error circle centered at the derived position with a radius of 5″. The error circle encloses a blue star of magnitude $V \approx 14$. Its position, derived from the DSS, is $01^h17^m40^s.30 \pm 0^s.23$, −73°30′50″.3 ± 1″.

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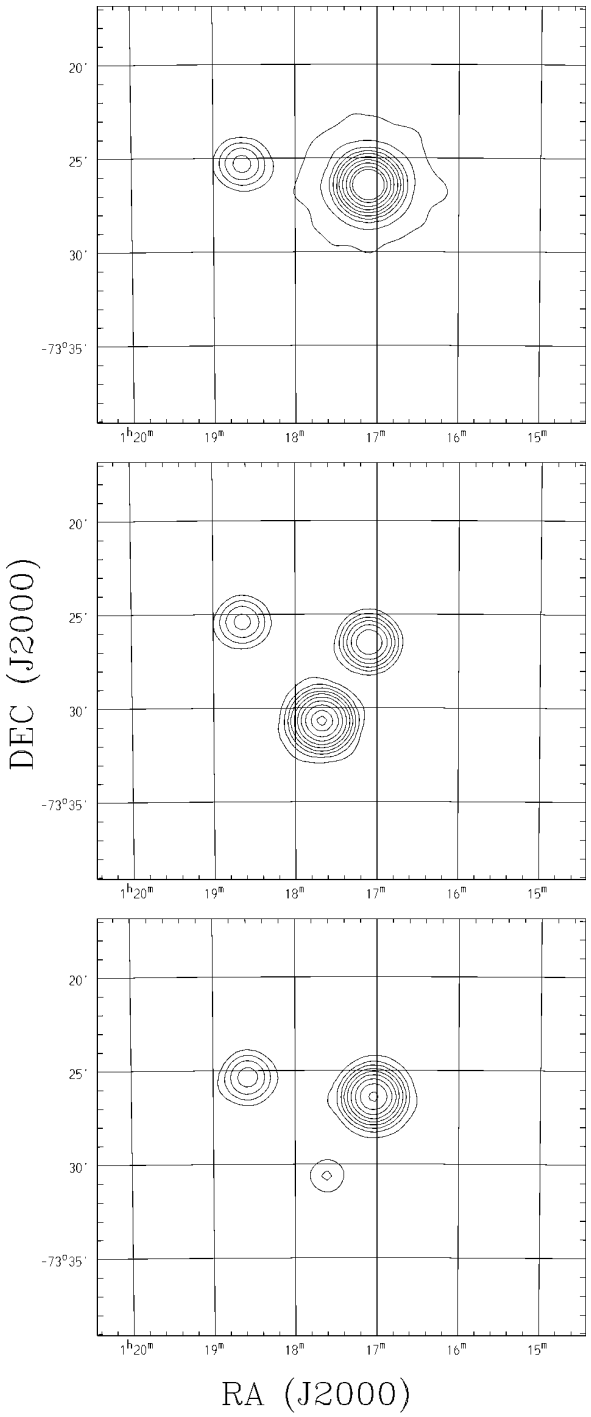


FIG. 1.—Contour maps of smoothed counts per unit area in the central region of the *ROSAT* images recorded in three observations of SMC X-1. Contour levels differ by factors of 2. *Top*: 1991 HD 8191 ~7′ east of SMC X-1. *Middle*: 1992 transient 5′ southeast of SMC X-1. *Bottom*: 1993 transient faded.

Figure 3 displays the average of two spectra of the star obtained on 1996 May 17 and 18 with the Cassegrain spectrograph (3″ slit) at the Cerro Tololo Inter-American Observatory (CTIO) 1.5 m telescope. It shows the strong, narrow emission lines of Hα and Hβ on the blue continuum of a star of magnitude $V = 14.2$, as reported by Charles et al. (1996), and Hδ and higher order H lines in absorption—all characteristics of a Be star.

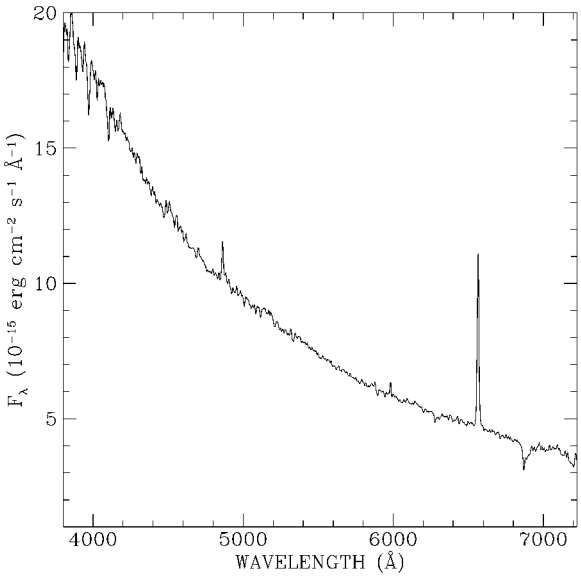


FIG. 3.—Spectrum of the candidate optical companion of RX J0117.6−7330.

2.2. *Variability*

For timing analysis, the event times were converted to barycenter times. Events within a circle of radius 1.′67 centered on the transient's image were counted as source plus background. Background rates were determined from the numbers of events in a concentric annulus of inner and outer radii 1.′67 and 2.′5, respectively. We found no statistically significant variations in the average background rates, which were equal to 0.9% and 58% of the source plus background rates in the 1992 and 1993 observations, respectively.

The light curve from the 1992 observation is shown in Figure 4*a* as a plot of average background-subtracted count rates in 18 subsets of the data comprised of the events from continuous 400 s portions of the exposure. The subset duration was set equal to the approximate period of the controlled wobble in the pointing direction of the spacecraft in order to minimize

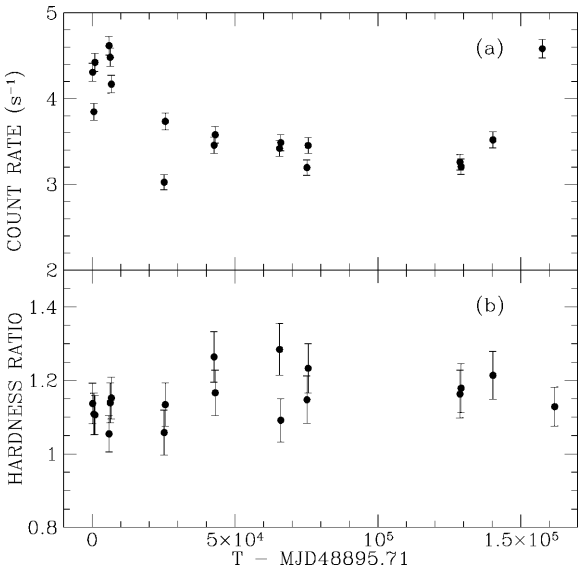


FIG. 4.—(*a*) Count rates and (*b*) hardness ratio of RX J0117.6−7330 during the 1992 observation, averaged in 400 s intervals and plotted against MJD.

TABLE 1

UPPER LIMITS ON THE FRACTIONAL AMPLITUDES OF SINUSOIDAL PULSATIONS IN THE 1992 DATA

			FREQUENCIES (Hz)				
T (s)	M	n	0.1	1.0	10	100	150
400....	18	17	0.10	0.10	0.10	0.12	0.15

the effects on the average rate of variations in the effective detection efficiency for a point source as its image passes over the grid structure of the PSPC window. The count rate varies about the overall average of 3.79 counts s^{-1} on timescales from several minutes to hours. (For comparison, we cite the maximum count rate of SMC X-1, recorded shortly after eclipse egress in the 1992 observation, which was 4.8 counts s^{-1}.)

We searched for evidence of periodic pulsations in the 1992 data by Fourier analysis according to the procedure described by Leahy et al. (1983). The data were divided into M subsets of continuous exposure of length T. Events within the 1.′67 circle were binned in intervals of length $\delta T = T/2^n$. The fast Fourier transform was applied to each of the binned subsets, and the average of the normalized power density (PD) spectra was computed. In the case of $T = 400$ s with $M = 18$, we set $n = 17$. In the frequency range from 0.1 Hz to the Nyquist frequency at 163.84 Hz, the mean and variance of the power density are 2.000 and 0.224, consistent with purely Poisson fluctuations for which the expected mean and variance are 2 and 4/18. The largest PD in that frequency range is $P_{max} = 4.34$. The expected number of PDs greater than 4.34 in a spectrum of Poisson noise is ~3. Thus, there is no evidence of a PD that cannot be attributed to Poisson noise.

In the frequency range below 0.1 Hz, there is a rise in the average PD caused by low-frequency variations in detection efficiency due to the quasi-periodic spacecraft wobble and by nonperiodic variations of the source intensity. The two highest PDs, other than the expected one at 0.0025 Hz, are at 0.0100 and 0.0125 Hz with values of 5.98, and 5.87, respectively. They are also probably caused by the wobble. Discounting these features of the low-frequency PD spectrum, we find no evidence of a source periodicity in the frequency range from 0.01 to 163.84 Hz. In Table 1, we list the estimated 99% confidence upper limits on the fractional amplitudes of sinusoidal variations that would have escaped detection. We derived the limits by analyzing sets of fake data generated with an average count rate of 4 s^{-1}, modulated by sinusoids of various amplitudes and frequencies.

The mean count rate of background-subtracted events in the 1993 data was 0.014 s^{-1}—a reduction by a factor of 270 from the mean rate during the 1992 observation, and too small to allow a significant search for periodicity. The reduction corresponds to an e-folding decay time of 44 days.

2.3. *Spectrum*

Figure 4*b* is a plot of the hardness ratios of the 1992 background-subtracted pulse-height distributions (PHD), calculated as the ratio of the average rates in pulse-height channels corresponding to the energy ranges 0.3–1.0 keV and 1.0–2.5 keV. The lack of correlation between changes in the hardness ratio and the count rate indicates that the rate change is caused by variations in the intrinsic luminosity of the source and not by variable absorption.

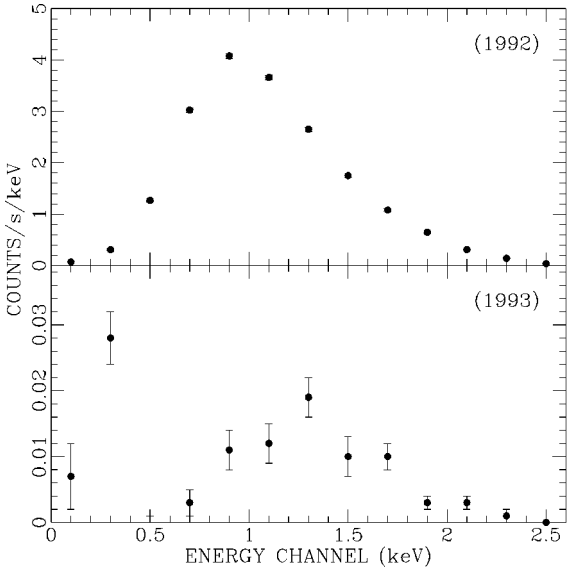


FIG. 5.—Background-subtracted pulse-height distributions from the 1992 and 1993 observations.

The spectrum of the transient as characterized by its hardness ratio is softer than that of SMC X-1; the average value was 1.14 ± 0.02 compared to 1.36 ± 0.01 for SMC X-1 in the 1991 observation of the uneclipsed pulsar. To characterize the spectrum in more detail, we fitted the PHD of the 1992 data (Fig. 5) with various trial spectrum functions. The results are summarized in Table 2. None of the simple trial functions yields a satisfactory fit; neither does the disk blackbody (DBB) model of Mitsuda et al. (1984). Good fits are obtained with a power law added to either a bremsstrahlung function or blackbody function. The latter combination yields the more plausible power-law index and a plausible blackbody temperature. However, the narrow energy range and poor resolution of the spectral data poorly constrain such multiple parameter fits, so no certain conclusion can be drawn regarding the actual presence of a blackbody component. The good fits imply an incident energy flux of $(5.3 \pm 0.3) \times 10^{-11}$ ergs cm^{-2} s^{-1} in the energy range 0.2–2.5 keV.

The background-subtracted PHD of the 1993 data (Fig. 5), though sparse, shows evidence of a flux below the carbon edge of the detector response at 0.28 keV. To check whether this might be the result of an error in background subtraction, we replaced the concentric annulus background PHD with the PHD of events in a circle of radius 1.′67, centered on a position at the same declination as the transient, and as far west of SMCX-1 as the transient was east of it. No significant difference in the background-subtracted PHD was found. The ratio of the rate in channels corresponding to calibration energies from 0.1 to 0.3 keV to the rate above 0.3 keV is 0.045, whereas the ratio in the 1992 data is 0.0008. Thus, it seems that the proportion of an ultra–low-energy component in the total spectrum increased as the total intensity decayed. To evaluate the incident energy flux, we fitted spectrum functions in the form of a power law plus a blackbody function to the PHD with the column density fixed at 5×10^{20} H-atoms cm^{-2}, which is the approximate value implied by the 0.26 mag optical extinction of the nearby Sk 160 (van der Klis et al. 1982). The low-energy (<0.28 keV) and high-energy (>0.28 keV) portions of the PHD can be fitted separately by the tail of a cool

TABLE 2

FITS OF MODEL PHOTON NUMBER SPECTRA TO THE PULSE-HEIGHT DISTRIBUTION OF THE 1992 DATA

Spectrum Form	N_H (10^{21} cm^{-2})	Index	kT (keV)	Flux (10^{-11} ergs cm^{-2} s^{-1})	χ^2_ν
PE*PL	2.4 ± 0.1	2.7 ± 0.1	...	5.1	2.1
PE*BR	1.5 ± 0.1	...	1.22 ± 0.06	5.0	2.5
PE*BB	0.07 ± 0.04	...	0.299 ± 0.003	4.5	8.0
PE*DBB	1.16 ± 0.05	...	0.467 ± 0.010	4.8	4.2
PE*(PL+BR).....	6.9 ± 0.7	6.6 ± 0.5	10[a]	5.3	1.2
PE*(PL+BB).....	1.2 ± 0.2	0.23 ± 0.08	0.21 ± 0.02	5.4	1.3

NOTE.—PE stands for photoelectric absorption; PL means power law; BR means thermal bremsstrahlung; BB is Planck blackbody; DBB is disk blackbody.

[a] Fixed.

blackbody function with $kT < 0.07$ keV plus a hard power law with index 0, respectively. Alternatively, the low- and high-energy protons can be fitted by a soft power law with index 4 plus a hot blackbody function with $kT = 3$ keV, respectively. Both fits are so poorly constrained that little physical significance can be attached to them. However, they yield consistent, although crude, estimates of the incident flux: in the energy range 0.10–0.28 keV, the flux is $(1.7 \pm 0.5) \times 10^{-15}$ ergs cm^{-2} s^{-1}; and in the entire range 0.10–2.5 keV, it is $(3.4 \pm 0.5) \times 10^{-13}$ ergs cm^{-2} s^{-1}.

3. DISCUSSION

Above 2 mcrab, the occurrence frequency of high-latitude Galactic X-ray transients associated with nearby stars is roughly 1 order of magnitude greater than the frequency of X-ray transients in the Magellanic Clouds. However, given the small solid angle subtended by the SMC, about 2.5×10^{-4} of the celestial sphere, a robust transient observed in the direction of the SMC, such as RX J0117.6−7330, is much more likely to be located in the SMC than in the Galaxy. The absence of a bright, red star near the X-ray position further limits the probability that the X-ray source is a Galactic object. Moreover, within the 5″ radius positional error circle of the X-ray transient there is a likely optical counterpart in the form of a Be star with a magnitude consistent with a location in the SMC. Thus, it appears almost certain that the transient lies in the SMC.

If the transient is at a distance D and radiates isotropically, then the received energy flux implies an average luminosity in the 0.2–2.5 keV range of $\sim 1.6 \times 10^{37} (D/50 \text{ kpc})^2$ ergs s^{-1} during the 1992 observation, consistent with the typical luminosities of accretion-powered X-ray sources.

The column density of hydrogen in front of the transient during the 1992 observation, although poorly constrained by the data, appears to exceed 1.0×10^{21} cm^{-2}. This is more than the column density implied by the optical extinction toward nearby Sk 160. The appearance of a component below 0.28 keV in the spectrum of the transient 8 months later suggests that the column density inferred from the 1992 data was of circumstellar matter that dissipated as the transient faded.

Although it seems likely that RX J0117.6−7330 is another example of a neutron star with a Be-type companion, it is worthwhile to consider the possibility that it is a BHXN. Its apparent e-folding decay time of 44 days is within the range typical of BHXN. We have found no evidence of periodic variation. Its spectrum during the 1992 observation was softer than that of SMC X-1, although the narrow energy range of the PSPC precludes a definitive comparison of the transient's spectrum with the characteristics of typical BHXNs. Thus, the apparent decay time, the apparent absence of pulsation, and a spectrum that is substantially softer than the nearby pulsar are consistent with the properties of identified BHXN. To be sure, the likely optical counterpart is not a late-type dwarf or subgiant like the companions of the known BHXN. However, there seems to be no reason, in principle, why the companion of a stellar black hole cannot be a Be star. A determination of the mass function of the system or a more sensitive search for pulsations during a recurrence of an X-ray outburst might settle the question.

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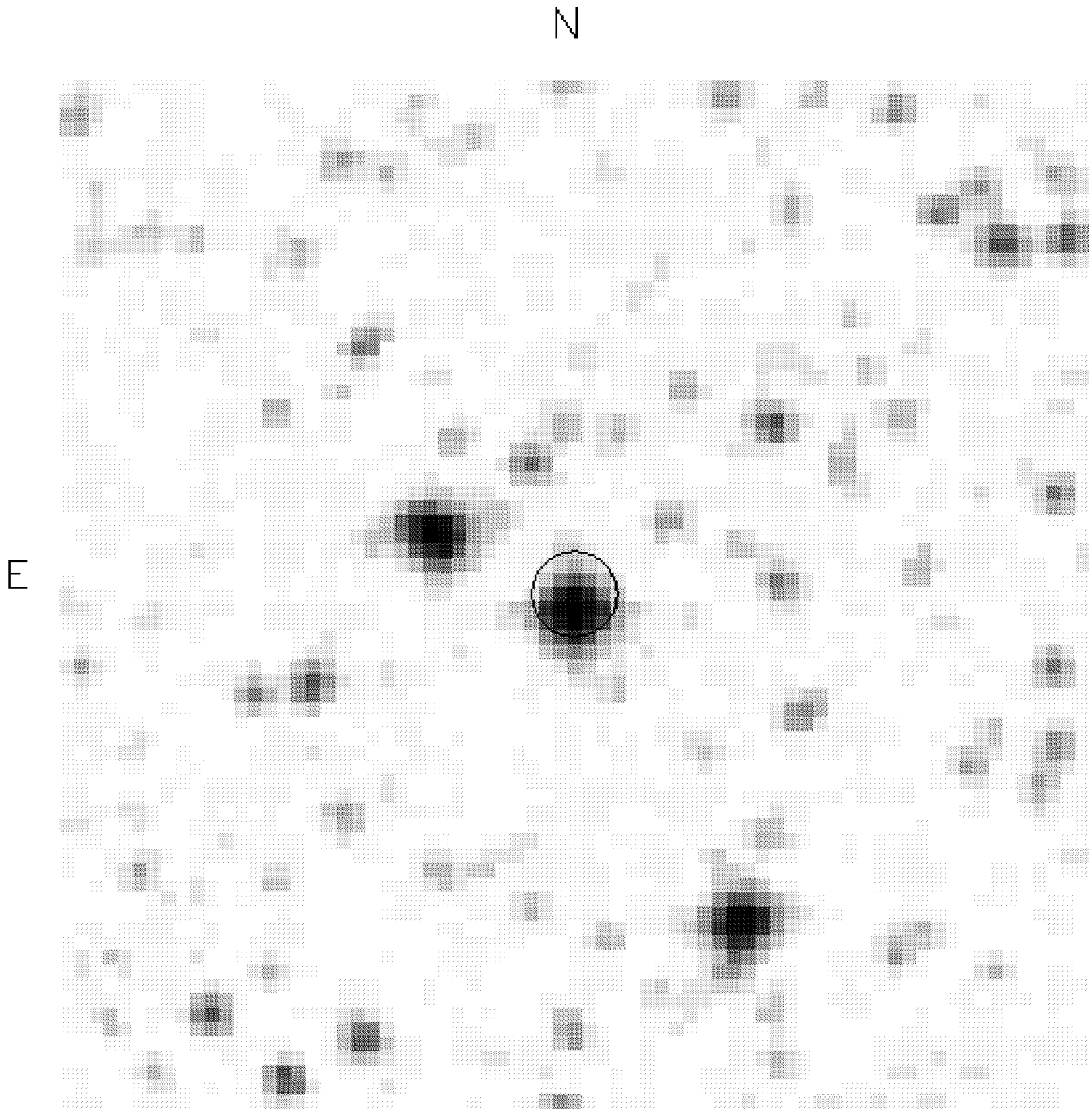


FIG. 2.—2′ × 2′ portion of the Digital Sky Survey with the 5″ radius error circle of the X-ray position of RX J0117.6−7330

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