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DISCOVERY OF 111 SECOND PULSATION FROM THE X-RAY SOURCE SCUTUM X-1

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ABSTRACT

We have discovered a 111 s period X-ray pulsation from Sct X-1. The pulse profile was found to exhibit double peaks. The X-ray spectrum of Sct X-1 is fitted by a single power-law function with a photon index of about 1.9. Evidence for extremely large absorption (greater than 10^{23} H cm^{-2}) has been found in the low-energy band and near the iron K-edge. When combined with the previous observations, we find that the X-ray flux has been variable over more than two orders of magnitude.

Subject headings: pulsars — X-rays: sources — X-rays: spectra

1. INTRODUCTION

Sct X-1 was discovered in 1973 with a sounding rocket by Hill et al. (1974). They reported an unusually large N_H value of greater than 10^{23} H cm^{-2} and an X-ray flux of about 15 mCrab. Soon after the discovery, Charles, Mason, & Davidson (1975) confirmed the existence of this unusual X-ray source at about the same flux level. X-ray emission from Sct X-1 at an intensity level of 30 mCrab was also detected in 1977 during *HEAO 1* A-2 scanning observations (Marshall et al. 1979). Two equally probable positions at (α_{1950}, δ_{1950}) = (278.71, −7.64) and (278.44, −7.65) were determined using the *HEAO 1* scanning modulation collimator (Reid et al. 1980). However, no positive flux from Sct X-1 was reported from the *EXOSAT* Galactic Plane survey above the detection limit of about 1 mCrab (Warwick et al. 1988). This suggest that Sct X-1 is a highly variable or transient X-ray source. Due possibly to this transient nature, not much is known about Sct X-1, although it was discovered at a very early stage of X-ray astronomy. With the *Ginga* satellite, we surveyed the Scutum region several times and also performed a pointed observation of Sct X-1 from which we found that Sct X-1 is indeed highly variable. Furthermore, we discovered a coherent 111 s pulsation from Sct X-1. A quick report of this discovery together with those of other new X-ray pulsars in the Scutum region has been given by Koyama et al. (1990). This *Letter* presents more details on the results of the observation and the nature of the new X-ray pulsar Sct X-1.

2. OBSERVATIONS

Observations were made with the Large Area Proportional Counters (LAC) on board the X-ray astronomy satellite *Ginga*. The energy range was 1–38 keV with a maximum effective area of 4000 cm^2. The normal mode of the LAC is a pointed observation. Scanning observations, however, are also available around the satellite's *Z*-axis, which is perpendicular to the LAC pointing direction. The LAC field of view is about 1° and 2° (FWHM) in the direction of and perpendicular to the scan path, respectively. The accuracy of attitude determination is better than 0°.1. Details concerning *Ginga* and the LAC have been given in separate papers (Makino and the ASTRO-C Team 1987; Turner et al. 1989).

The pointed observation was made on 1988 November 14.381–14.819 in the 48 energy channel mode (MPC-2) with a time resolution of 2 s. Since the Sun angle of the LAC (angle between the LAC pointing direction and the Sun) was less than 90°, contamination from solar X-rays scattered by the LAC collimator was possible and was indeed present in the low-energy band (see Hayashida et al. 1989). Of course data taken in Earth's shadow is free from solar X-ray contamination.

Several scanning observations (in 48 energy channel mode) were made on 1987 October 6–10 (MPC-1 mode) and on 1988 September 13 (MPC-2 mode). The scan speed was selected to be about 1° per minute and the time resolution was either 2, 4, or 16 s depending on the data mode (MPC-1 or MPC-2) and bit rate. For this scan speed and time resolution, the minimum angular size of data bins is less than 0°.2. The Sun angle during these scanning observations was larger than 90°, and thus no contamination from solar X-rays was found. The observation log together with the X-ray flux are summarized in Table 1.

The detector backgrounds (both non–X-ray and the cosmic X-ray background) were estimated using the method developed by Hayashida et al. (1989) and Awaki et al. (1991). In addition to this standard usual background, we find that the contribution of the diffuse Galactic ridge X-ray emission is not negligible near the Scutum arm. In fact, with our scanning observations, we found the X-ray flux in the LAC field of view from the Galactic ridge emission near Sct X-1 to be about 40 counts s^{-1} (1–38 keV), nearly the same rate as the off-plane background. Since the spectrum of the Galactic ridge emission can be well represented by a thin thermal hot plasma emission (Koyama et al. 1986; Koyama 1989), we fitted a thermal bremsstrahlung plus 6.7 keV iron line model to the scanning data near Sct X-1. The fit was acceptable ($\chi^2 = 21.5$ for 32 degrees of freedom) with a temperature of 9 ± 2 keV and an iron line equivalent width of 0.6 ± 0.2 keV (or 2.0 ± 0.5 counts s^{-1}). The errors quoted in this paper are 90% confidence level for a single parameter unless otherwise noted. The best-fit parameter values are within typical values of the Galactic ridge emission. Therefore, we used this best-fit model spectrum to describe the Galactic ridge background near Sct X-1, because the statistics of the raw Galactic ridge data near the Sct X-1 were limited.

3. RESULTS AND ANALYSIS

3.1. *Timing Analysis*

From examining the raw light curve (without background subtraction) of the pointed mode data, we saw clear pulsations at about 110 s. We used pulse period folding techniques on all the pointed data (excluding the energy band below 5 keV to

TABLE 1

Observations of Scutum X-1

Date (UT) (Start–Stop)	Mode	Data Mode	Flux (1–38 keV)[a] (counts s^{-1})
1987 Oct 6 13:49–22:04	Scan	MPC-1	22
1987 Oct 9 12:32–20:50	Scan	MPC-1	32
1988 Sep 12 1:00–Sep 13 4:26	Scan	MPC-2	<3
1988 Nov 14 9:08–19:40	Pointed	MPC-2	11–29

[a] Note.—1 mCrab intensity roughly corresponds to 10 counts s^{-1} (1–38 keV).

avoid solar X-ray contamination) to find a heliocentric pulse period of 111.001 ± 0.004 s at the epoch of 1988 September 14. The time span of the pointed observation was only 10 hr, and within this limited time coverage, we detected no change of pulse period. The folded pulse profile (from data taken in Earth's shadow) in the 1–5, 5–9, and 9–38 keV bands after background subtraction is shown in Figure 1. The pulse profile has two nearly equal peaks in the lower energy band, while at higher energies, one peak becomes more prominent than the other.

The background-subtracted light curve in 111 s time bins is given in Figure 2. As before, low-energy data taken in sunshine were excluded. Amplitude variations are observed in all three energy bands with a positive correlation among the energy bands. This suggests that the intensity variation is not due to a change in spectrum, such as an absorption effect, but is due to an intrinsic change in intensity. The average intensity in the 1–38 keV band was about 20 counts s^{-1}, corresponding to a flux of about 2 mCrab.

3.2. *Energy Spectrum*

We summed all the poined data taken in Earth's shadow and subtracted the off-plane background and our best-fit model for the Galactic ridge emission (see § 2). This X-ray spectrum was fitted with a single power-law plus an iron emission line and absorption due to a cold gas with cosmic abundances (Morrison & McCammon 1983). See Figure 3. For simplicity, we fixed the iron line energy to 6.4 keV, since the iron line from most X-ray pulsars has been observed to be at an energy of 6.4 keV (e.g., Nagase 1989). The best-fit parameters are given the second row of Table 2. Although the fit was formally unacceptable, we obtained no improvement in χ^2 value by including a high-energy cutoff (a conventional model for describing binary X-ray pulsars) within the 1–38 keV energy band.

In order to search for spectral variations, we divided the pointed mode data into three separate periods and examined each with the same spectral model. Although the X-ray flux changed by about 30%, we found no significant change in the photon index or the N_H value among the three subsets of the data.

3.3. *Scan Data*

Each scanning observation comprised several sequential scans, so an overall scan profile was constructed by an azimuthally folding of the sequential scans. From the scan profile, we found excess X-ray emission at the position of Sct X-1 on 1987 October 6 and 1987 October 9, respectively. Since the angular separation between the two probable positions of Sct X-1 is only about 0°.1 (Reid et al. 1980), we could not distinguish between these two positions with our scanning observation. The X-ray flux from Sct X-1 during the scanning

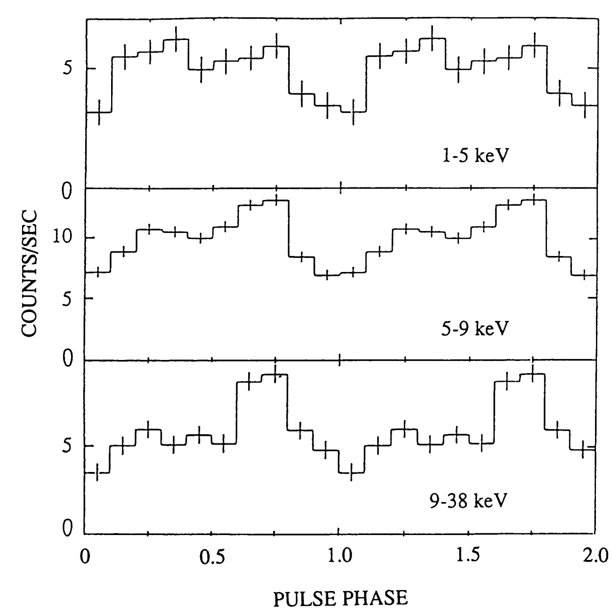

Fig. 1.—Pulse profile of Sct X-1 in three energy bands (1–5, 5–9, and 9–38 keV).

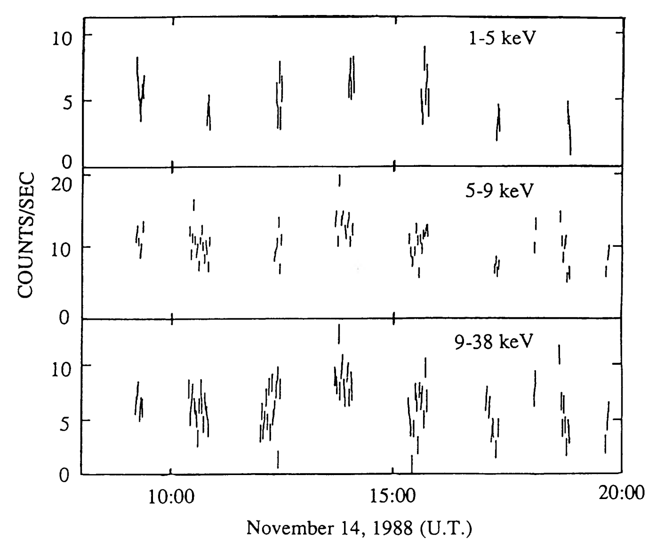

Fig. 2.—X-ray light curve of Sct X-1 in three energy bands (1–5, 5–9, and 9–38 keV). The data in the 1–5 keV band during sunlight portions of the orbit were not included because of a possible contamination from solar X-rays (see text).

TABLE 2

POWER-LAW MODEL OF SCUTUM X-1

Date	Photon Index (α)	log (N_H) (H cm^{-2})	Equivalent Width (keV)	Reduced χ^2 (d.o.f.)
1987 Oct 9	2.1 ± 0.2	23.6 ± 0.1	0.23 ± 0.17	1.2 (19)
1988 Nov 14	1.9 ± 0.1	23.3 ± 0.1	0.35 ± 0.11	2.3 (26)

NOTE.—Error is 90% confidence level for a single parameter.

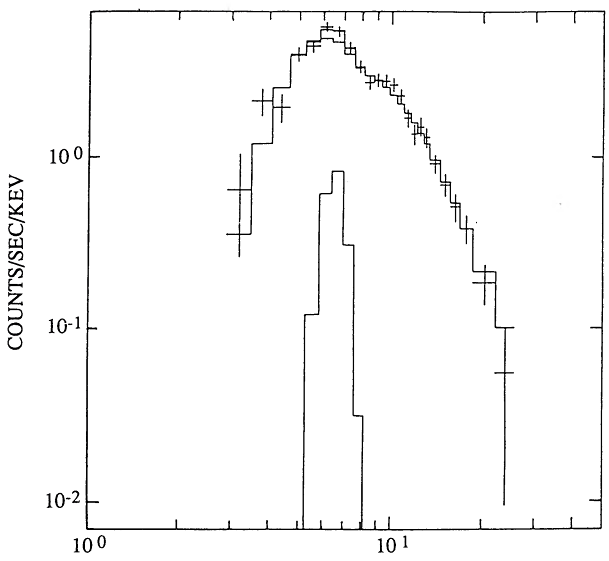

FIG. 3.—Energy spectrum of Sct X-1 from the pointed observation. The solid line represents the best-fit model (see text).

observations is given in Table 1. The X-ray fluxes quoted in the table were corrected for the collimator response assuming the position of Sct X-1 to be at (α_{1950}, δ_{1950}) = (278°44, −7°65). We note that the collimator transmission correction factors between the two probable positions of Sct X-1 are equal to within 10%. On 1988 September 13, we found no excess flux with an upper limit of 0.3 mCrab.

We fitted the scan data on 1987 October 9 with the same spectral model as for the pointed observation. The best-fit spectral parameters are consistent with those of the pointed observation and are listed in the first row of Table 2. Since the statistics of the scan data on 1987 October 6 were limited, we did not try spectral fitting.

4. DISCUSSION

We discovered a coherent pulsation of 111 s period from Sct X-1. The pulse profile has two peaks with an amplitude of about 50% (peak to bottom) of the average flux, a characteristic which has often been observed from other binary X-ray pulsars. The X-ray flux during a pointed observation and two scanning observations are at the level of 2–3 mCrab. However, we were able to set an upper limit of X-ray flux at 0.3 mCrab during the other scanning observation. Previous observations by Hill et al. (1974), Charles, et al. (1975), and Marshall et al. (1979) reported the X-ray flux to be about 30 mCrab. Therefore, together with the new Ginga observations, we conclude that the new X-ray pulsar Sct X-1 has varied over more than two orders of magnitude.

We confirmed the large N_H value of more than 10^{23} H cm^{-2} from the Sct X-1 X-ray spectrum. Some other X-ray pulsars such as GX 301+2 and Vela X-1 often show a large absorption of this magnitude (White, Swank, & Holt 1983; Nagase 1989). However, in these pulsars, the N_H values were observed to be variable in time or in orbital phase. Although the time coverage of Sct X-1 was not long enough and no orbital period was observed, the N_H value of Sct X-1 appears to have been always at a high level of (2–5) $\times 10^{23}$ H cm^{-2}, during both our observations and previous ones. This peculiar behavior of Sct X-1 is, however, not unusual among the newly discovered X-ray pulsars and hard X-ray sources in the Scutum region. Among seven new X-ray sources in the Scutum arm, six (including Sct X-1) exhibit N_H values of about 10^{23} H cm^{-2} (Koyama et al. 1990).

We have detected an iron line from Sct X-1 for the first time. The iron line intensity from Sct X-1 was 0.7 ± 0.2 counts s^{-1} during the pointed observation, while that from the Galactic ridge near Sct X-1 was found to be 2.0 ± 0.4 counts s^{-1}. Therefore the iron equivalent width of Sct X-1 has a large ambiguity caused by uncertainty in subtracting the Galactic ridge background. This systematic uncertainty and the large statistical error on the iron line intensity hamper any detailed discussion of the circumstellar gas structure around Sct X-1.

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