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A NEW X-RAY PULSAR GS 2138+56 (CEPHEUS X-4)

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ABSTRACT

A transient X-ray pulsar was discovered with the *Ginga* satellite at the position of $\alpha(1950) = 21^h38^m \pm 1^m$, $\delta(1950) = 56°50' \pm 6'$ (designated as GS 2138+56). The error box includes the previously reported transient source Cep X-4. An X-ray pulsation with a heliocentric pulse period of 66.2490 ± 0.0001 sec (at MJD = 4,7263.5) was discovered. Assuming no intrinsic change of the pulse period during the observation, we get a lower limit of the orbital period of 23 days and projected semiaxis of 9 lt-sec. The X-ray spectrum has a typical shape for X-ray pulsars having power-law index of about 1.0 with an exponential cutoff at an energy of about 16 keV. We suggest, based on circumstantial evidence, that GS 2138+56 is likely to be Be star binary.

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

1. INTRODUCTION

The transient X-ray source Cep X-4 was discovered with the *OSO 7* satellite in 1973 June–July at a position of $\alpha(1950) = 21^h37^m$, $\delta(1950) = 56°47'$ with an error circle of 0°.4 radius (Ulmer et al. 1973; Markert et al. 1973). The X-ray spectrum was hard (20 keV with an exponential fit) and resembled those of the X-ray binary pulsars such as Her X-1 and Cen X-3. The X-ray flux was variable with a time scale of less than 1 day. However, no regular pulsation was discovered with Fourier analysis or with folding. After the discovery with *OSO* 7, no X-ray flux from Cep X-4 was reported. In 1988 March, we discovered an X-ray outburst from the error region of Cep X-4 (Makino and the *Ginga* Team 1988a). Shortly after, we found 66.25 s pulsation from this X-ray source (Makino and the *Ginga* Team 1988b). A short report on this source can be found in the recent review paper by Nagase (1989). In this *Letter*, we report further on the source identification, pulse timing analysis, and the spectral study of this new X-ray pulsar.

2. OBSERVATIONS AND RESULTS

The X-ray observations were made with the Large Area Proportional Counter (LAC) and the All Sky Monitor (ASM) on board the *Ginga* satellite. The LAC covers the energy range 2–37 keV with a maximum effective area of 4×10^3 cm^2. The energy range of the ASM is 1–20 keV and the maximum effective area is 70 cm^2. The normal mode of LAC operation is the pointed observation, while that of the ASM is the scanning observation. However, in the present observations, we also used the scanning mode of the LAC as well as the pointed observation with the ASM. Further details of the instruments and the observation modes are given in separate papers (Makino and the ASTRO-C Team 1987; Turner et al. 1989; Tsunemi et al. 1989).

2.1. *Source Identification*

An X-ray emission near the transient source Cep X-4 was noted on 1988 March 19 during a routine all-sky survey with the ASM, at an intensity level of about 50 mCrab. In order to determine the position more accurately, we scanned the sky region near the Cep X-4 with the LAC in two different directions on 1988 April 4 and 14. The field of view of the LAC is 1° (FWHM) along and 2° (FWHM) perpendicular to the scan path. The two independent scan paths and the error region of the peak intensity are illustrated with solid boxes in Figure 1. The overlapping region of these two boxes is a 90% confident error region of the position of the X-ray transient source. The most probable position is found to be $\alpha(1950) = 21^h38^m \pm 1^m$, $\delta(1950) = 56°50' \pm 6'$. We thus rename GS 2137+57 (Nagase 1989) as GS 2138+56, based on the present improved position. The error box of GS 2138+56 is within the error box of Cep X-4 (Fig. 1, *open circles*). Since no cataloged X-ray source other than Cep X-4 is found in the error box and the X-ray spectrum of GS 2138+56 was found to be similar to that of the Cep X-4 (see § 2.4), we identify GS 2138+56 with Cep X-4.

2.2. *Long-Term X-Ray Light Curve*

Long-term intensity variations were monitored with the ASM in its scanning mode once every few days. The light curve in the 1–20 keV energy range with the ASM is given in Figure 2 together with points from the LAC in the same energy range. We have no information on the X-ray intensity of GS 2138+56 before March 19 because the source had been out of the field of view of the ASM as well as that of the LAC. Since the source was observed for only a few seconds in the scanning mode of the ASM, the intensity taken with ASM should be regarded as a snapshot of a few seconds.

The maximum intensity of about 100 mCrab appeared

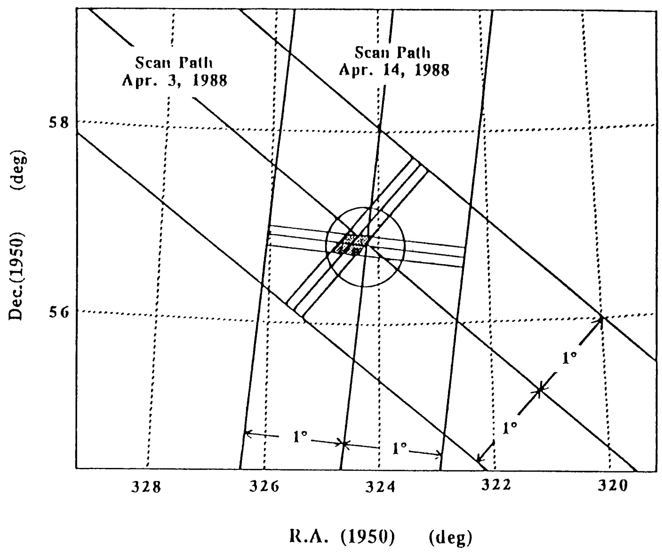

FIG. 1.—Error region of GS 2138+56 determined by the present observation (*hatched box*) together with that of Cep X-4 (*circle*) by Ulmer et al. (1973).

around the beginning of 1988 April. After 1988 April 11, the intensity dropped below the detection limit of the ASM in its scanning mode. On April 22, we carried out a pointing observation with the ASM and set an upper limit of the source intensity of 6 mCrab. Thus the duration of the X-ray outburst from GS 2138+56 in 1988 was considered to be about 1 month. This would be the second observation of an X-ray outburst from GS 2138+56 (Cep X-4) since 1973. The X-ray intensity and duration in 1988 are roughly the same as that of 1973.

2.3. *Discovery of Coherent Pulsation*

Timing and spectral studies were made with the LAC during the pointed observation on 1988 April 3–4, 8–10, and 14–15. The overall temporal variation was investigated using the standard Fourier analysis in the 1–38 keV range. The shape of the power density spectrum, in the frequency range of 0.01–1 Hz, is approximated by a power-law function with an index of -1.3. We integrated the power spectrum density over 0.01–1 Hz, and took the root mean square. This "fraction of the aperiodic variation" is found to be about 6% of the average flux.

In addition to the aperiodic variation, a coherent pulsation of about 66.25 s and higher harmonics are clearly noted in the Fourier spectrum. We have searched for the pulsation around

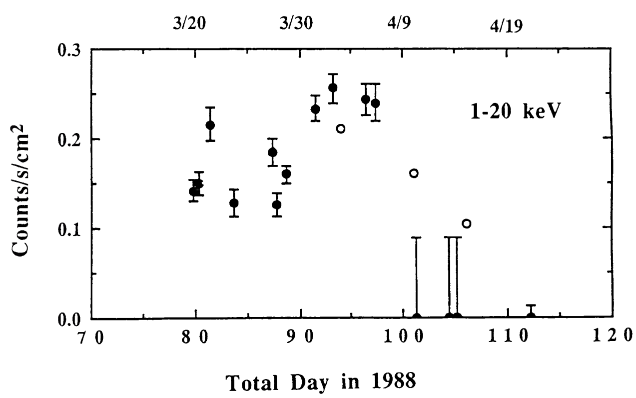

FIG. 2.—X-ray light curve (1–20 keV) from GS 2138+56 (Cep X-4) obtained with ASM (*filled circle*) and LAC (*open circle*).

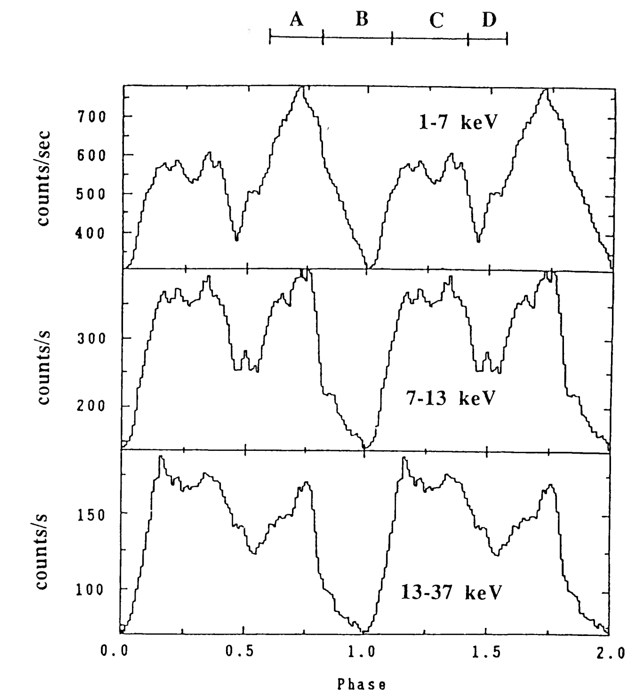

FIG. 3.—Pulse profiles in the three energy bands: 1–7 keV, 7–13 keV, and 13–37 keV.

66.25 s with a folding technique. Then the pulse period of 66.2490 ± 0.0001 s at the epoch of MJD = 4,7263.5 was found. The folded pulse profile is given in Figure 3 with three energy bands of 1–7, 7–13, and 13–37 keV. We found a significant change of the pulse profile with the incident energy.

We examined the delay of pulse arrival time from the averaged period to be 66.2490 s. This is given in Figure 4. The fitting of the pulse arrival time with a constant p is rejected with 99% confidence level, although the best-fit $\dot{p}/p$ of -2×10^{-3} yr^{-1} is within the range of the intrinsic pulse period change of a typical binary X-ray pulsar.

It is difficult to separate this possible spin-up trend from the change due to the orbital Doppler effect from the limited data coverage of the present observation. Therefore we assume, for simplicity, a circular orbit and no intrinsic period change ($\dot{p} = 0$) and carried out orbital Doppler fitting. This simple

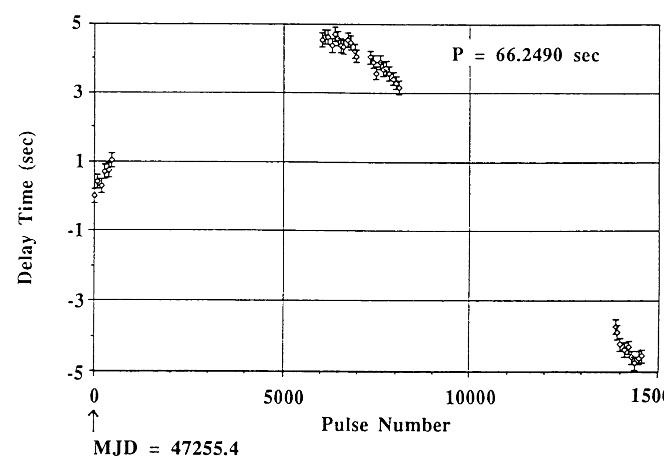

FIG. 4.—Delay of the pulse arrival time is given as a function of the pulse number.

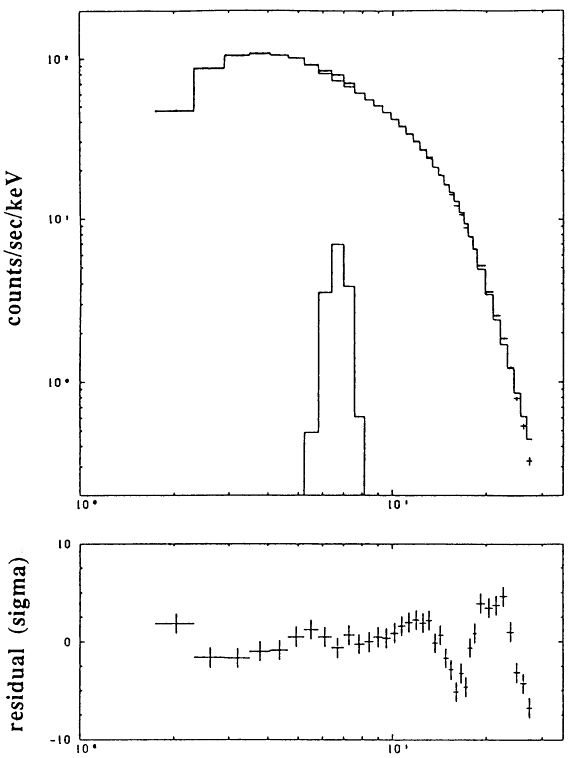

FIG. 5.—Pulse-averaged X-ray spectrum on 1988 April 4. The histogram is the best-fit model curve. The residuals from the best-fit curve are given in the lower panel.

model gives a satisfactory fit to the data (reduced $\chi^2 = 0.76$). We can set lower limits of p_{orb} and $a_x \sin i$ to be 23 days and 9 lt-sec, respectively. The assumption of circular orbit is probably unrealistic for the transient pulsar GS 2138+56. An X-ray flare of transient pulsar having an eccentric orbit usually take place during the small portion of the orbital phase near the periastron passage. If this is the case for GS 2138+56, the orbit in the limited phase near the periastron passage can be approximated as circular. Therefore the lower limit of the orbital period and projected semiaxis of 23 days and 9 lt-sec, which are derived with the assumption of a circular orbit, may be correct in the first approximation. In fact the flare durations in 1973 and 1988 are both about 1 month, suggesting that the orbital period is much larger than 1 month.

2.4. *Energy Spectrum*

We have made pulse-averaged energy spectra for three separate observations on 1988 April 3–4, 8–10, and 14–15. For each spectrum, we fitted the conventional power-law plus exponential cutoff with iron emission line. The free parameters are normalization factor (A), photon-index (α), cutoff energy (E_c), *e*-folding energy (E_F), iron line energy (E_{Fe}), and intensity (I_{Fe}) (or equivalent width; EW) and hydrogen column density (N_H). As an example, the X-ray spectrum on 1988 April 4 and its best-fit model are given in Figure 5. The fit is formally rejected with systematic deviation near the cutoff energy as is shown in Figure 5. This deviation is due to an artificial break of the model curve. Makishima et al. (1990) reported similar deviations from other X-ray pulsars. They attempted to improve the fitting assuming the cyclotron absorption model. This approach gives better fit to GS 2138+56 with a cyclotron absorption energy at about 31 keV. However, in order to compare the spectral structure of GS 2138+56 to other cataloged X-ray pulsars, we will discuss based on the analysis using the conventional model of power-law plus high-energy cutoff. The best-fit parameters for each observation are listed in Table 1. We found no significant change of the energy spectrum.

We then carried out spectral analysis for four separate pulse phases corresponding to the main peak (A), main valley (B), subpeak (C), and subvalley (D). This phase designation is given in Figure 3. The fitting procedure was the same as that of the pulse-averaged spectrum. The best-fit parameters for spectra A, B, C, and D are given in Table 2. The power-index of phase A and B is significantly steeper than those of phase C and D, while the cutoff energy, *e*-folding energy, and iron line intensity are almost constant throughout the pulse phase.

3. DISCUSSION

The X-ray spectrum of GS 2138+56 is typical of those of the binary X-ray pulsars. Indeed, a coherent pulsation of 66.25 s was discovered. The pulse profile of GS 2138+56 shows rather complex energy dependent structure, which is also often observed in other X-ray binary pulsars. From the simplified analysis of pulse arrival time, we found that the orbital period

TABLE 1

BEST-FIT PARAMETERS FOR PULSE PHASE-AVERAGED SPECTRUM

Date (1988 Apr)	Normalization (A)	Index	log (N_H)	E_c (keV)	E_F (keV)	E_{Fe} (keV)	EW (keV)	Iron Intensity (counts s^{-1})	χ^2 (30 dof)
4	654 ± 16	1.10 ± 0.01	22.02 ± 0.03	16.2 ± 0.1	8.0 ± 0.2	6.58 ± 0.11	0.12 ± 0.03	10.1 ± 1.9	243
8–9	529 ± 14	1.09 ± 0.01	22.03 ± 0.03	16.3 ± 0.1	7.9 ± 0.2	6.54 ± 0.13	0.10 ± 0.03	6.8 ± 1.4	252
14–15	317 ± 8	1.14 ± 0.01	22.02 ± 0.03	16.9 ± 0.2	8.2 ± 0.3	6.42 ± 0.16	0.08 ± 0.03	3.0 ± 0.8	197

TABLE 2

BEST-FIT PARAMETERS FOR PULSE PHASE-DIVIDED SPECTRUM

Phase	Normalization (A)	Index	log (N_H)	E_c (keV)	E_F (keV)	E_{Fe} (keV)	EW (keV)	Iron Intensity (counts s^{-1})	χ^2 (30 dof)
A.........	794 ± 23	1.21 ± 0.01	22.07 ± 0.03	15.0 ± 0.2	9.9 ± 0.4	6.50 ± 0.19	0.07 ± 0.03	5.9 ± 1.8	106
B.........	568 ± 17	1.35 ± 0.01	22.07 ± 0.03	16.9 ± 0.3	8.4 ± 0.6	6.60 ± 0.10	0.16 ± 0.03	6.9 ± 1.0	42
C.........	452 ± 13	0.90 ± 0.01	22.09 ± 0.03	15.8 ± 0.1	7.8 ± 0.2	6.47 ± 0.13	0.10 ± 0.03	8.6 ± 1.8	203
D.........	339 ± 10	0.93 ± 0.01	21.49 ± 0.12	16.4 ± 0.2	7.3 ± 0.4	6.56 ± 0.13	0.12 ± 0.03	7.1 ± 1.4	202

would be larger than 23 days. The long orbital period is consistent with the flare interval of about 1 month.

From the transient nature, GS 2138+56 would be a Be star binary (Rapparport and van den Heuvel 1982; Koyama et al. 1989). Corbet (1986) shows a linear relation between spin and orbital period in the Be star binary pulsars. According to this relation, the spin period of 66.25 s for GS 2138+56 gives an orbital period of about 100 days, a value consistent with a possible long orbital period based on the pulse arrival time analysis and flare durations. If we assume that the orbital period is 100 days, the mass of the neutron star is 1.4 $M_{\odot}$ and that the apparent spin period change is solely due to the orbital Doppler effect, then we can estimate that the mass of the companion star is about 10 $M_{\odot}$. This is consistent with the initial assumption that GS 2138+56 is a Be star binary source.

No significant spectral changes during the observational period were found. We note that the iron line equivalent width is also constant from day to day. These facts indicate that the geometry of the X-ray beam and surrounding gas does not change much, although the X-ray flux changed by more than a factor of 2. On the other hand, we found a significant variation of photon index from pulse phase to phase, whereas no significant difference of cutoff energy was observed. This fact suggests that the cutoff energy represents a physical parameter intrinsic to a neutron star, and it is possibly related to the cyclotron energy or to the intensity of the magnetic field near the magnetic pole.

The iron line of an X-ray pulsar is produced by the fluorescence of matter around the neutron star such as stellar wind and the photosphere of the primary and circumstellar gas. The iron line intensity of GS 2138+56 was found to be constant in different pulse phases. This fact may suggest that the matter distribution is spherically uniform. Thus a likely site of the fluorescence is spherically distributed circumstellar gas. However the $N_{\rm H}$ value of GS 2138+56 was only about 10^{22} cm^{-2}. In this case, the equivalent width of iron line should be lower than about 10 eV (Inoue 1985) which is significantly smaller than the observed value of more than 100 eV. The same sort of puzzle has been also observed in other X-ray pulsars such as Her X-1 and Vela X-1 (Nagase 1989).

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