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DISCOVERY OF PERIODIC ECLIPSES IN THE X-RAY PULSAR 1H 0253+193

YUICHI KAMATA AND YUZURU TAWARA
Department of Astrophysics, School of Science, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-01, Japan
AND
KATSUKI KOYAMA
Department of Physics, Faculty of Science, Kyoto University, Kitashirakawaoiwake-cho, Sakyo-ku, Kyoto 606-01, Japan
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ABSTRACT

Periodic intensity dips with a period of 21,829 s were discovered in the X-ray light curve of the 206 s pulsar 1H 0253+193. The X-ray flux outside of the dips was 2×10^{-11} ergs cm^{-2} s^{-1} (in the 2–10 keV energy band), while the X-ray flux during the dips was below the detection limit of 2×10^{-12} ergs cm^{-2} s^{-1}. The duration of the intensity dips and the transient time from normal to intensity dip (or vice versa) were 1990 and 50 s, respectively. The periodic dips indicate that the X-ray pulsar 1H 0253+193 is an X-ray binary source, and the dips are naturally explained by an eclipse by the companion star. We have estimated the stellar radii of the binary system and the orbital separation. We conclude that the system is a DQ Her–type cataclysmic variable.

Subject headings: pulsars — stars: X-rays — X-rays: binaries

1. INTRODUCTION

The dark cloud Lynds 1457 (=MBM 12; Magani, Blitz, & Mundy et al. 1985) is the nearest known molecular cloud. In the dirction of the intensity peak of the ^{12}CO ($J = 1$–0) map, an X-ray source 1H 0253+193 was discovered by the *Einstein* IPC instrument at the position $\alpha = 2^h53^m20\overset{s}{.}5 \pm 2.0$, $\delta = 19°14'38'' \pm 32''$ (Halpern & Patterson 1987). The *Ginga* satellite observed 1H 0253+193 on January 1989 and discovered a coherent pulsation with a period of 206.3 ± 0.1 s (Takano et al. 1989; Koyama et al. 1991). This indicates that 1H 0253+193 contains a strongly magnetized compact object such as a white dwarf or a neutron star. Since the association of a magnetized compact star in a molecular cloud is rather unusual, several possibilities such as an isolated compact star powered by gas accretion from the dense cloud, an RS CVn system, and a cataclysmic variable have been proposed (see, e.g., Clemens & Leach 1989; Patterson & Halpern 1990; Koyama et al. 1991). In order to study the nature of 1H 0253+193, we have made further X-ray observations paying special attention to signs of a binary nature. This paper reports the discovery of periodic intensity dips and discusses the nature of 1H 0253+193.

2. OBSERVATIONS AND RESULTS

The observation was done with the LAC (Large Area Proportional Counters) on board the *Ginga* satellite. The energy band of the LAC is 2–37 keV with an effective area of 4000 cm^2. Details of the *Ginga* satellite and the LAC are presented by Makino & the ASTRO-C team (1987) and Turner et al. (1989). The data were sampled in 48 energy channels in the 2–37 keV energy band (MPC-1 and MPC-2 mode) during a total exposure time of about 70,000 s. Since the main objective of the observation was to search for a binary nature from 1H 0253+193, the exposure time was divided over a long time span of about 9 days.

In Figure 1 the X-ray light curve after the background subtraction and aspect correction is given. The X-ray flux was variable with an average flux of 10 counts s^{-1} (2×10^{-11} ergs cm^{-2} s^{-1}). First, we performed a folding analysis of the data from the 5 day observation. We found a clear peak at a period of 206.298 ± 0.001 s with a 61 σ level as shown in Figure 2. Then we divided the data into five sets and determined a pulse period for each data set. The results are listed in Table 1.

From the table, it is evident that the pulse period was constant during the present observation and equal to the period obtained by *Ginga* observations in 1987 and 1989 (Takano et al. 1989; Koyama et al. 1991). We have examined the pulse period further in shorter time bins; however, we have found no variations of the pulse period or orbital Doppler effects. Therefore, from these pulse timing analysis, no evidence for a binary nature was obtained.

As indicated in Figure 3, we found six intensity dips which fall below the detection limit of less than 1 counts s^{-1} (2×10^{-12} ergs cm^{-2} s^{-1}). Plots with higher time resolution for each dip are given in Figure 3 (Nos. 1–6), where the horizontal axis shows the arrival time of X-ray photons corrected to the barycenter of the Sun. We found that the time intervals between the intensity dips is nearly a multiple of 6 hr. Therefore the intensity dips are likeiy to have a periodicity with a fundamental period of about 6 hr. From Figure 3 we derive that the rapid intensity transition to and from the dip occurs with a time scale of 50 s (rise time or decay time from half the average X-ray intensity).

In order to determine a more accurate period of the intensity dips, we defined as usual the epoch of ingress (egress) of the dip to be the time of the first (last) zero intensity data bin corrected to the Sun's center and indicated by arrows in Figure 3. The errors are taken to be the length of one data bin of 32 s. The heliocentric epochs of ingress or egress are listed in Table 2. Since the shortest interval between two consecutive dips (No. 2–No. 3, No. 4–No. 5) is about 21,800 s, we tried a linear fit of the egress and ingress times of the dips assuming a periodicity of about 21,800 s. The fitting formula used for the ingress and egress times is $t = \alpha n + \beta$ and $t = \alpha n + \gamma$, respectively, where t, α, and n are the arrival time of the ingress (egress), the period-

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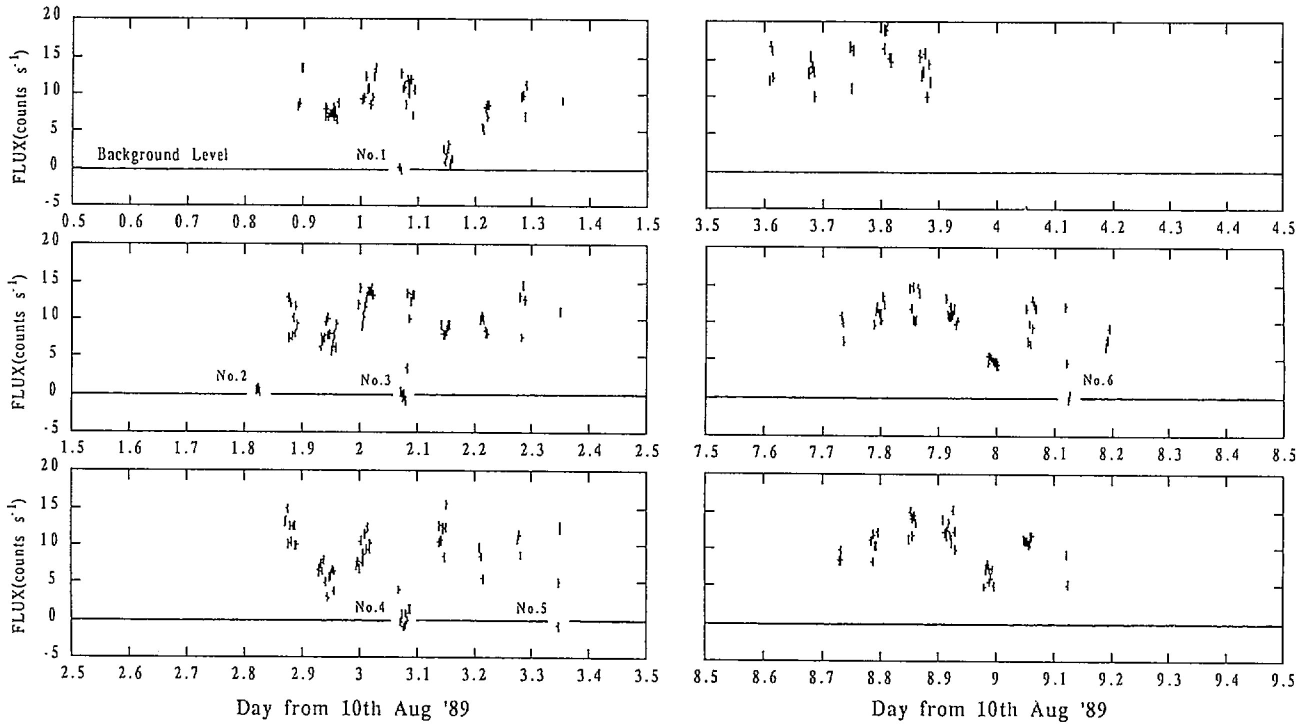

FIG. 1.—All background-subtracted X-ray light curves obtained from 5 days of observation in the 1–19 keV energy band. Zero level is shown by a solid line, and the sequential numbers of the observed dips are also shown in this figure. Horizontal axis is time from 1989 August 10 0:00 UT in units of 1 day. Periodic intensity dips with about 6 hr intervals are visible.

icity, and the sequential number of the dip, respectively. Here β and γ are the basic epochs of ingress and egress, respectively. The period (α) and duration (γ-β) of the dip determined this way were 21,829 ± 3 and 1990 ± 30 s, respectively. Figure 4 shows the residuals from the best fit as a function of the sequential number of the dip.

We have folded the light curve and hardness ratio (the ratio between the X-ray flux in the 6–10 keV and 1–6 keV band) with a period of 21,829 s as shown in Figure 5. Since the folded light curve is a smooth function showing only a single dip structure, we conclude that the 21,829 s period is really fundamental. We could not find a significant change of the hardness ratio during the transition to/from the dip; therefore, the dip is likely due to an occultation by an optically thick "rigid body" with a small scale height.

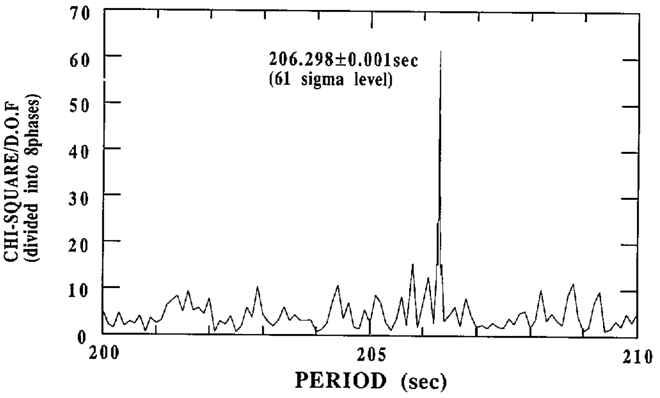

FIG. 2.—χ^2-values for the pulse period search with folding analysis obtained from 5 days of observation after heliocentric correction. Clear peak of the coherent pulsation is detected at the period of 206.298 s with 61 σ confidence level.

We divided the folded X-ray data with the period of 21,829 s into four segments (I–IV) with segment I centered on the eclipse. The data in each segment was folded with the pulse period of 206.3 s. Then we examined the phase shift of the pulse profile between the pair of segment I and segment II and found

TABLE 1

PULSE PERIODS OBSERVED WITH *Ginga*

Observation (date)	Pulse Period (s)
1987 Jul 28.8–29.3	206.1 ± 0.2
1989 Jan 23.0–23.4	206.3 ± 0.1
1989 Aug 10.9–11.4	206.3 ± 0.1
1989 Aug 11.8–12.3	206.4 ± 0.1
1989 Aug 12.9–14.0	206.3 ± 0.1
1989 Aug 17.7–18.2	206.3 ± 0.1
1989 Aug 18.7–19.1	206.3 ± 0.1

TABLE 2

EPOCHS AND DURATIONS OF OBSERVED DIPS

Period of Ingress and Egress (s from 00:00 1989 Aug 11)	Sequential Number of Dips[a] (assuming 21800 period)	Duration (s)
6638 (egress)	0	>400
93962 (egress)	4	>1000
179301 (ingress)	8	>1700
203124 (egress)	9	>300
615792 (ingress)	28	>700

[a] For numbers 1, 3, 4, 5, and 6, respectively.

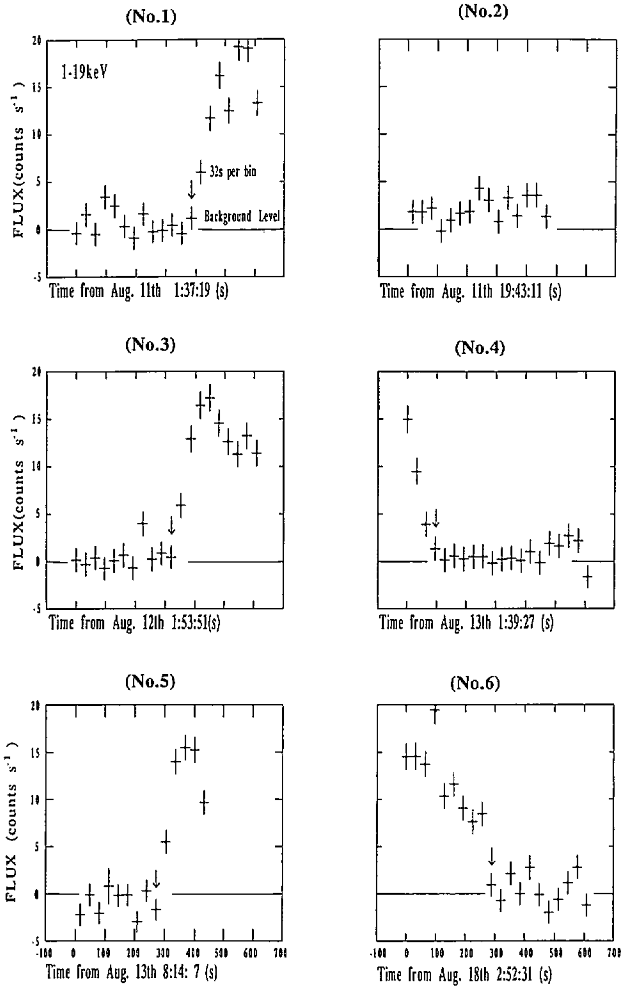

FIG. 3.—High time-resolution plot (32 s bins) of the six observed eclipses in the 1–19 keV energy band. Major time tide marks each 100 s. Numbers are same as in Fig. 1. The structure of ingress or egress of the observed eclipses is visible.

no significant phase shift larger than 30 s with a 3 σ confidence level.

3. DISCUSSION

We have discovered intensity dips with a duration of 1990 s and a periodicity of 21,829 s. Since the periodicity is very accurate and the dip is likely due to an occultation of an optically thick "rigid body," we can conclude that 1H 0253+193 is an X-ray binary, where the dip is caused by an eclipse of the X-ray source (a compact star) by a companion star. In the following discussion, we adopt this binary picture. Assuming that the system has a circular orbit with an orbital period of 21,829 s, we can estimate that the orbital separation between the primary and the secondary (companion) is 1.7 $R_\odot$ $(m_1 + m_2)^{1/3}$, where $R_\odot$, m_1, and m_2 are the solar radius, the mass of primary compact star, and the mass of the secondary star (in units of $M_\odot$), respectively. If the orbital separation is 1.7 $R_\odot$ $(m_1 + m_2)^{1/3}$, the phase shift of the pulse profile due to the orbital motion should be less than $4(m_1 + m_2)^{1/3}$ s. This is consistent with the observed upper limit of 30 s.

Using the duration of the eclipse of 1990 s, a lower limit to the radius, R_s, of the companion star is $R_s > 0.6$ $R_\odot$ $(m_1 + m_2)^{1/3}$. The duration of the ingress and egress of the eclipse of 50 s gives a size of the X-ray–emitting region of $< 1.7 \times 10^9 (m_1 + m_2)^{1/3}$ cm. Since the X-ray size depends only upon the total mass of the system, we can safely conclude that the X-ray–emitting region of the compact star is of the order of less than 2×10^9 cm, a typical size for a white dwarf. The existence of the eclipses leads us to conclude that the system has a large inclination angle, and possibly a nearly edge-on geometry. Assuming that the inclination angle is about 90°, the size of the companion star is about 0.6 $R_\odot$, which is typical for a late-type main-sequence star.

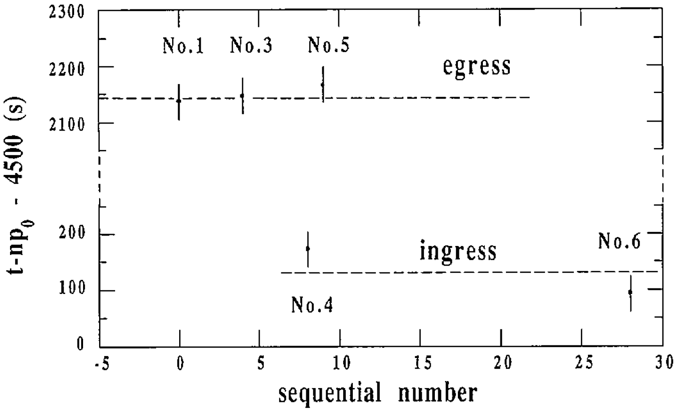

FIG. 4.—Residuals of a linear fit to the five observed ingression (or egression) times. Horizontal axis shows the sequential number of each eclipse assuming 21,829 s orbital period. We obtained a best-fit value of 21,828.5 ± 2.5 s for the orbital period and 1990 ± 30 s for the duration of the eclipse.

Since the typical size of the X-ray–emitting region of the magnetized compact star in 1H 0253+193 is found to be similar to that of a white dwarf, and since the orbital period is larger than the spin period, we conclude that 1H 0253+193 is an intermediate polar cataclysmic variable (DQ Her type). The

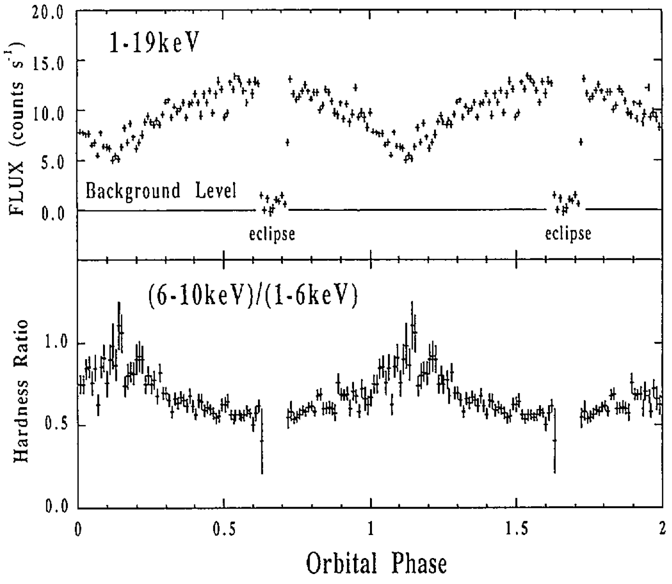

FIG. 5.—Light curve in the 1–19 keV energy band and (6–10 keV)/(1–6 keV) hardness ratio, folded with the orbital period of 21,829 s. Two full periods are shown. Figure shows sharp ingress and egress and an anticorrelation between X-ray flux and hardness ratio. This indicates that the orbital X-ray intensity modulation is due to absorption changes in each orbital phase.

orbital and spin period of 21,829 and 206 s and the late-type main-sequence companion star are also typical for the majority of DQ Her–type cataclysmic variables. Assuming that 1H 0253+193 has an X-ray luminosity of 10^{33} ergs s^{-1}, a typical value for DQ Her–type CVs (Patterson 1984), we estimate that the distance is about 300 pc. The distance of the molecular cloud MBM 12 was reported to be 65 pc (Hobbs, Blitz, & Magnani 1986), therefore 1H 0253+193 is probably a background DQ Her–type binary, which accidentally coincides with the center of the molecular cloud.

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