Publ. Astron. Soc. Japan **42**, 785–792 (1990)

X-Ray Observations of OAO 1657−415 with Tenma and Ginga

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(Received 1990 June 11; accepted 1990 September 12)

Abstract

A pulse timing analysis of X-ray pulsar OAO 1657−415 with the Tenma and Ginga satellites is presented. The long-term pulse period history shows a spin-up trend with an average rate of $\dot{P}/P = -10^{-3}$ yr^{-1}. An upper limit to $a_{\rm x} \sin i$ of 3 lt-s was obtained for the projected semi-major axis for a range of orbital periods of 1 to 6 d. The X-ray spectrum obtained with Ginga was found to be typical of those of other binary X-ray pulsars.

Key words: OAO 1657−415; X-ray binaries; X-ray pulsars.

1. Introduction

The Galactic X-ray source OAO 1657−415 was discovered by Polidan et al. (1978) and was identified as being an X-ray pulsar with a period of 38 s (White and Pravdo

1979). Subsequently, Parmar et al. (1980) reported a large spin-up trend within a 1-yr interval. This large spin-up indicates that OAO 1657−415 involves a magnetized neutron star and is powered by mass accretion from its binary companion. A previously suggested optical counterpart, V861 Sco (Polidan et al. 1978, 1979), proved to be incorrect (White and Pravdo 1979; Armstrong et al. 1980; Parmer et al. 1980; Byrne et al. 1981). Thus, there has yet to be a correct optical identification, in spite of the accurate X-ray positions determined from HEAO-A3 (Armstrong et al. 1980) and Einstein (Parmar et al. 1980) measurements. Furthermore, no binary nature of this X-ray pulsar has been reported, partly because previous observations were of limited time coverage (< 1 d).

We observed OAO 1657−415 with the Tenma and Ginga satellites. A brief summary of the Tenma results was given by Nagase et al. (1984). Since OAO 1657−415 lies near the Galactic center ($l = 17^\circ$, $b = 0^\circ\!.5$), the X-ray spectra previously reported often suffered from both nearby X-ray sources and Galactic ridge emission (Koyama et al. 1986; Koyama 1989). However, the Ginga observation of the Galactic plane yielded an almost contamination-free spectrum of OAO 1657−415. This paper gives a detailed report on the Tenma timing analysis and a spectrum analysis based on the Ginga data.

2. Observations

The Tenma observation was made with the two groups of Gas Scintillation Proportional Counters (GSPC), called SPC-A and SPC-B. Their fields of view were $3^\circ\!.1$ and $2^\circ\!.5$ (FWHM), respectively. The total effective area was 640 cm^2 and the energy range 2–35 keV. Details of the Tenma and GSPC instruments have been given by Tanaka et al. (1984) and Koyama et al. (1984), respectively.

OAO 1657−415 was in the GSPC's field of view from 18 through 23 July 1983. Although 38-s pulsation was clearly detected throughout this period, the X-ray intensity of this pulsar remained uncertain due to heavy source confusion with nearby sources, including GX 349+2, 4U 1700−37, 4U 1702−42, 4U 1705−44, and the Galactic ridge emission. The Tenma data are therefore used mainly for timing analysis.

The Ginga data of OAO 1657−415 were taken with the Large Area proportional Counter (LAC) as a part of the Galactic plane scan program (Koyama 1988). The effective area of LAC is 4000 cm^2, with an energy range of 2–37 keV and field of view $1^\circ \times 2^\circ$ (FWHM). Further details concerning Ginga and LAC were given by Makino and the ASTRO-C team (1987) and Turner et al. (1989).

We selected the position of OAO 1657−415 as being terminal point of the Galactic plane scans. Thus, several pointed observations on OAO 1657−415 were available between these scans made on 17 March 1988, 7 April 1988, and 4 March 1989. Due to several constraints on the scan program, the pointing positions were not optimized, so as to avoid any source confusion. However, the data taken on 4 March 1989 were almost free from contamination from any nearby cataloged X-ray sources, except for the Galactic ridge emission and the Einstein IPC source. This position is shown in figure 1 together with the scan path during this observation. The observations of OAO 1657−415 with Tenma and Ginga are summarized in table 1.

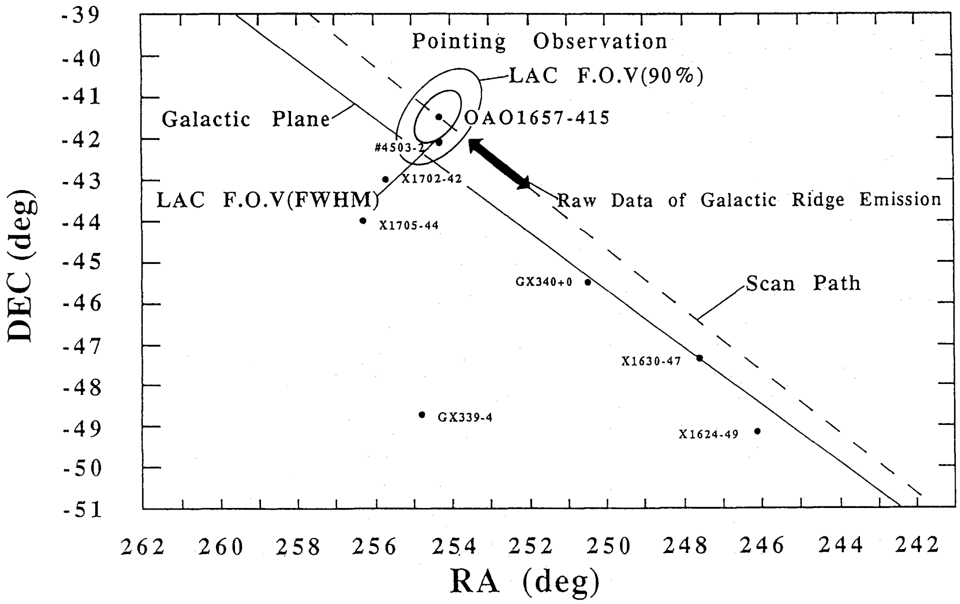

Fig. 1. Sky map near OAO 1657—415. The field of view of LAC is given by the solid circles with the scan path being indicated by the dashed line. The galactic plane is also shown by the solid line. A pointing arrow shows the region used to derive the galactic ridge background.

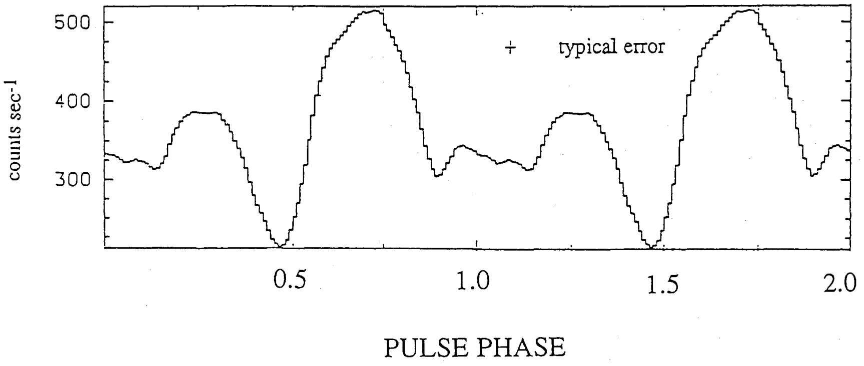

Fig. 2. Pulse profile of OAO 1657—415 observed on 4 March 1989 in the 1–20 keV energy band.

3. The Pulse Period Analysis

The pulse period was searched using a pulse folding method around the 38-s period. We first determined the mean pulse period from each observation independently. We performed a heliocentric correction on these mean pulse periods (table 1). A typical pulse profile has a complex shape, as shown in figure 2. We observed no significant difference in the pulse profile of different energy bands. A long-term pulse history

Table 1. Observations of Tenma and Ginga.

Date	JD(+2440000)	Period (s)	Instruments
18, 20–23 Jul 1983 ...	5536	37.885±0.001	Tenma SPC
17 Mar 1988 ...	7238	37.747±0.001	Ginga LAC
7 Apr 1988 ...	7259	37.725±0.001	Ginga LAC
4 Mar 1989 ...	7590	37.713±0.003	Ginga LAC

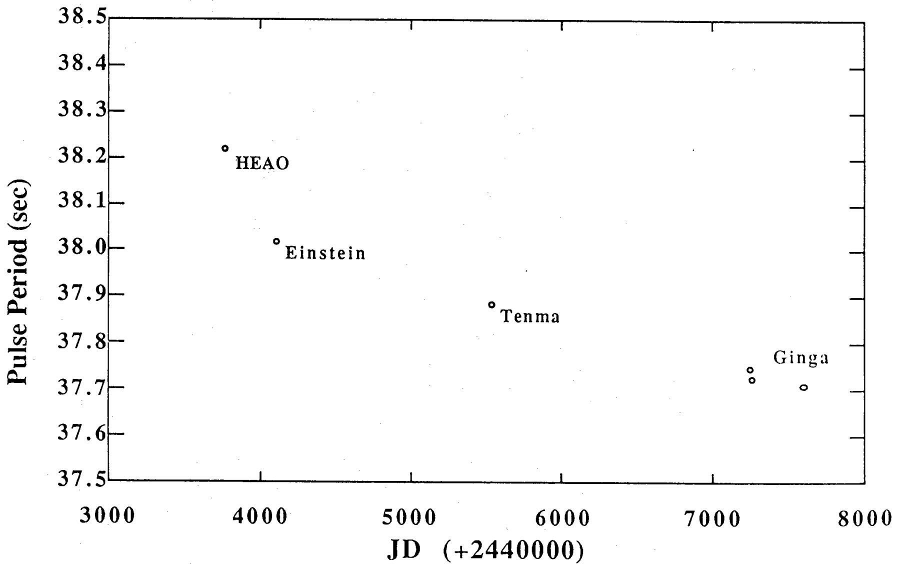

Fig. 3. Pulse period history of OAO 1657—415 observed with HEAO-1 A2 (White and Pravdo 1979), the Einstein Observatory (Parmar et al. 1980), Tenma and Ginga (this work).

which includes previous reports is given in figure 3. We found that a spin-up trend has continued for more than 10 yr with an average rate of $\dot{P}/P = -10^{-3}$ yr^{-1}.

In order to search for a binary signature, we carried out a pulse arrival time analysis. Figure 4 shows the heliocentric pulse arrival time of the Tenma data; in this data a constant-period term (table 1) was subtracted. We attempted χ^2-fitting, assuming a circular orbit for a trial period of 1 to 6 d, and determined the 90% upper limit of 3 lt-s for the projected semi-major axis of the X-ray star $a_{\rm x} \sin i$. We found no significant orbital effect with the Tenma data.

4. Spectrum Analysis

The Ginga data on 4 March 1989 were free from cataloged X-ray sources, except for Galactic ridge emission and a faint X-ray source reported with the Einstein

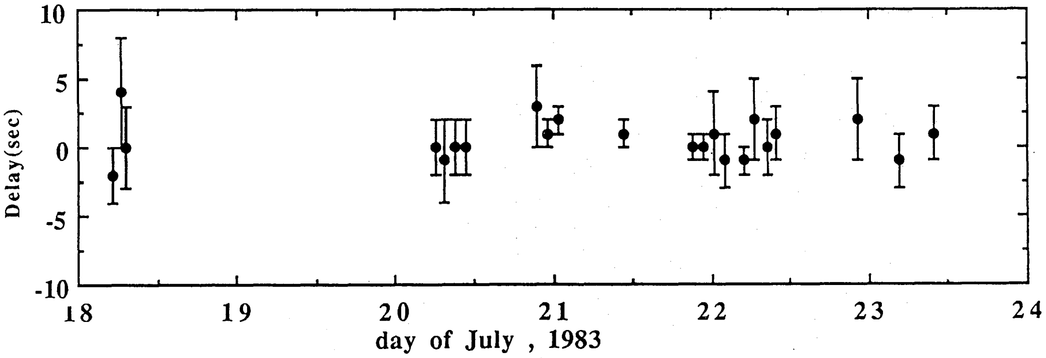

Fig. 4. Delay of the pulse arrival time obtained by a Tenma observation in July 1983.

IPC instrument. In order to estimate the Galactic ridge emission we constructed a model spectrum using data scanned from $l = 342\overset{\circ}{.}3$ to $l = 342\overset{\circ}{.}9$ at $b = 0\overset{\circ}{.}4$. This position is shown in figure 1. We fitted the ridge spectrum to a model of thermal bremsstrahlung plus the iron line at 6.7 keV. The best-fit temperature and iron line equivalent width (or intensity) of the ridge emission are 9.7 ± 1.2 keV and 0.9 ± 0.1 keV (5×10^{-3} counts s^{-1} cm^{-2}), respectively. We employed this model function for ridge emission at OAO 1657−415, since the raw data of ridge emission are statistically limited. In fact, the spectral parameters of the ridge emission used here are consistent with those of typical ridge emission (Koyama et al. 1986; Koyama 1989).

The X-ray spectrum of OAO 1657−415, after subtracting the background, was fitted by a conventional model comprising a power-law plus an exponential cutoff. We found a significant excess in the low-energy band below 3 keV. Adding a black-body spectrum of 0.3-keV temperature gave an acceptable fit. Since the intensity of this soft component is consistent with that of an IPC source [No. 4503-2 in the 0.2–3.5 keV band (Harris et al. 1989)], we regard the soft component as being due to this IPC source. In what follows we used the spectrum above 3 keV, since the soft excess was 10-times smaller than the observed X-ray spectrum above 3 keV. The spectrum of energies above 3 keV can be well fitted with the power law plus the exponential cutoff model, as shown in figure 5. The best-fit parameters are listed in table 2.

5. Discussion

The X-ray spectrum in the range 2–60 keV was detected with the HEAO-1 A2 instrument (White and Pravdo 1979). No evidence was found for a high-energy cutoff in the energy range 2–60 keV; the present Ginga data requires a cutoff at about 5 keV. White and Pravdo (1979) also reported a significantly larger iron line equivalent width (550 ± 100 eV) than the present observation (240 ± 30 eV). Furthermore, the iron energy was at 6.7 ± 0.1 keV, which is slightly higher than that of our observation (6.60 ± 0.08 keV). These inconsistencies may be partly due to possible contamination of the Galactic ridge emission detected by the HEAO-1 A2 instrument. As we have already noted, the Galactic ridge emission near OAO 1657−415 has an iron line at 6.7 keV with an intensity of about 5×10^{-4} counts s^{-1} cm^{-2} in the $1^\circ \times 2^\circ$ field of

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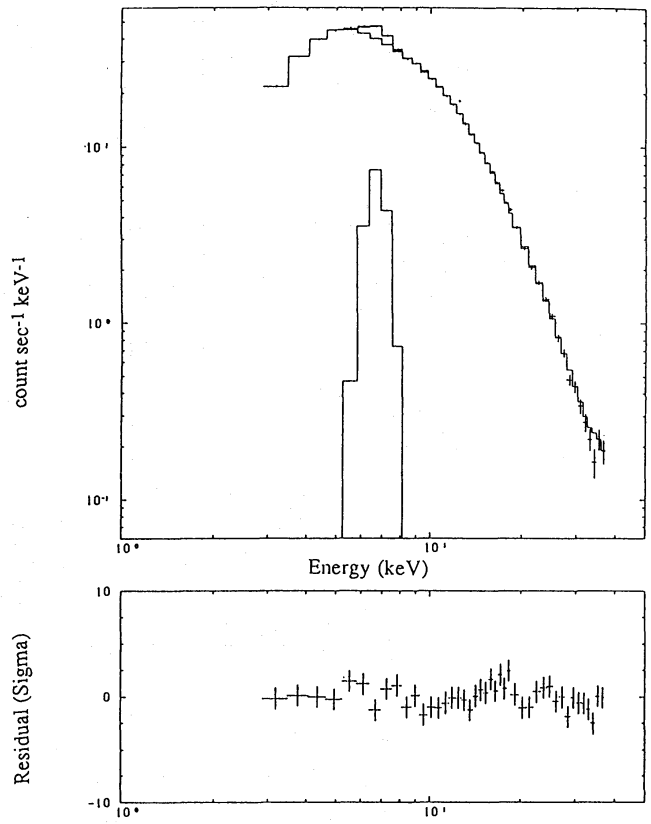

Fig. 5. Upper panel: Pulse height spectrum of OAO 1657−415 obtained with Ginga in March 1989 (crosses). The histogram shows the best-fit model spectrum convolved with the LAC response function. Lower panel: Residuals from the best-fit model.

view (FWHM). Since the field of view of the HEAO-1 A2 instrument is larger than the LAC, we estimated that the contribution of the ridge emission in the HEAO-1 A2 field of view is about 10^{-3} counts s^{-1} cm^{-2}. This value is more than half the iron line intensity of OAO 1657−415 reported by White and Pravdo (1979). We therefore suggest that if the Galactic ridge emission is properly subtracted, the iron line equivalent width and its energy would become consistent with our results. Apart from this possible contamination, we would make allowance for some spectral change in each observation, since the observed flux from Ginga on 4 March 1989 was 2 times larger than that of the HEAO-1 A2 observation. In fact, we found some hints of a spectral change between each observation listed in table 1, although the former three observations suffered some source confusion.

Though the cutoff energy near 5 keV is rather small, the power-law photon index ($\alpha \sim 0.6$) is typical of those of binary X-ray pulsars. Typical binary X-ray pulsars emit a 6.4 keV iron line from cold matter surrounding the pulsar, while the energy of the iron line emission from OAO 1657−415 is 6.6 ± 0.1 keV. This may indicate that the gas around this X-ray pulsar is highly ionized, at least on 4 March 1989.

The present observations confirm a long-term spin-up trend that has persisted for

Table 2. The best-fit parameters on 4 March, 1989.

Photon index	0.60±0.07
Cutoff energy (keV)	< 5.0 (5.0±0.7; 1σ error)
Folding energy (keV)	17.0±1.5
Fe line intensity (counts s^{-1} cm^{-2})	$(3.0\pm0.4)\times10^{-3}$
Fe line center energy (keV)	6.60±0.08
Equivalent hydrogen column density (cm^{-2})	$(7.2+0.9/-0.6)\times10^{22}$
Equivalent width of Fe line (keV)	0.24±0.03
Reduced χ^2	1.27 (d.o.f.=36)

Error is one-parameter 90% confidence level unless otherwise specified.

more than 10 yr. This result together with the X-ray spectrum strongly indicates that OAO 1657−415 is an accretion-powered binary X-ray pulsar. Still, we have failed to detect any significant evidence of orbital motion of the X-ray source, even with extended observations. We are only able to set an upper-limit. Thus, if the primary is massive (> a few solar masses), OAO 1657−415 must have either a relatively long (e.g., > 30 d) binary period like GX 301−2 and A0535+26, or a very small inclination angle of less than 5°. If, instead, the primary is a low-mass star, the constraints on the orbital parameters are much more relaxed. This system can be either an ultra-compact binary with a binary separation < 3 lt-s (like 4U 1626−67), or a wide binary separation having a late-type giant primary like, GX 1+4.

The long-term spin-up trend of $\dot{P}/P = -10^{-3}$ yr^{-1} is rather large among binary pulsars; this may indicate that the accretion torque (or X-ray luminosity) is fairly large. If the gas accretion onto OAO 1657−415 is due to a Roche-lobe overflow, we can apply the spin-up/luminosity relation found by Rappaport and Joss (1977). We then obtain an order-of-magnitude estimation of the X-ray luminosity, namely 10^{37} erg s^{-1}. Since the observed flux with Ginga was about 10^{-9} erg s^{-1} cm^{-2}, OAO 1657−415 should be about 10 kpc away, indicating that OAO 1657−415 lies in the Galactic bulge region. The N_H value of 10^{23} cm^{-2} obtained with the Ginga observation is consistent with this large distance. However, one may argue that the HEAO-1 A2 experiment reported a small N_H value, giving a distance smaller than a few kpc. At this small distance, the X-ray luminosity would be less than 10^{36} erg s^{-1}. This is still typical of binary X-ray pulsars, but is significantly smaller than those of X-ray pulsars during fast spin-up episodes.

Note added to the manuscript: After this paper was almost completed the *Granat* Team reported a spin-down episode (*IAU Circular* No. 5017, 1990) from OAO 1657−415. This indicates that the accretion torque changed after the Ginga observation, suggesting that the accretion is more likely to be wind-fed from a massive companion. In this case, the spin-up/luminosity relation described by Rappaport and Joss (1977) is not applicable.

The authors thank Professor Hale Bradt for his useful comments and review of

this manuscript. The data analysis was carried out with the M380 computer of the High Energy Laboratory of Nagoya University.

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