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SIGMA OBSERVATION OF THE PULSAR OAO 1657−415: PRECISE LOCALIZATION AT HARD X-RAY ENERGY AND DISCOVERY OF SPIN-DOWN

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ABSTRACT

The region of sky containing the 38 s X-ray pulsar OAO 1657−415 has been observed on 1990 March with Sigma, an imaging gamma-ray telescope exploiting the coded mask technique. This observation has yielded an accurate (∼arcminute-scale) localization for OAO 1657−415 at hard X-ray energy, confirming its association with a previously suggested soft X-ray candidate. A timing analysis of the 40–120 keV data has revealed for the first time a spin-down episode in OAO 1657−415, implying that an important change in the accretion torque experienced by this X-ray pulsar must have recently occurred.

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

1. INTRODUCTION

The X-ray source OAO 1657−415 was discovered in 1978 with the *Copernicus* satellite (Polidan et al. 1978). The initial association of this source with the massive binary star V861 Scorpii, suggested by correlated flux variations in the two objects (Polidan et al. 1979), was later disclaimed by the more precise localization of OAO 1657−415 obtained with the instruments on board the *HEAO 1* satellite (Byrne et al. 1979; Armstrong et al. 1980). However, an optical identification of the X-ray source was not possible, due to the large uncertainties in the localization obtained with these nonimaging instruments, also affected by the presence of nearby confusing X-ray sources. The *HEAO 1* observation also showed that the X-ray flux (2–60 keV) from this region of the sky had a very hard spectrum (power-law energy index ∼0.4) and was modulated with a period of 38.22 s (White & Pravdo 1979).

Images of the HEAO 1 error boxes in the soft X-ray band (0.5–3.5 keV) were obtained by Parmar et al. (1980), using the *Einstein Observatory* IPC instrument. These observations led to the discovery of two soft X-ray sources separated by 30′. Parmar et al. associated the pulsar OAO 1657−415 with the northern source, on the basis of its harder spectrum and its coincidence with one of the *HEAO 1* A-3 possible positions (Armstrong et al. 1980). Using the *HEAO 1* A-4 data, Byrne et al. (1981) derived a 0°.3 × 0°.3 error box which also contains the same IPC source.

In order to clarify the picture in the hard X-ray band ($E > 35$ keV), we have performed an imaging observation of this region of sky, using the French Sigma telescope on board the Soviet *GRANAT* spacecraft, recently launched in the context of the Franco-Soviet Scientific Collaboration.

2. OBSERVATIONS AND DATA ANALYSIS

2.1. *Imaging*

The hard X-ray/soft gamma-ray Sigma telescope is designed to provide sky images in the energy range 35 keV–1.3 MeV, with an angular resolution of 13′ over a wide field of view (4°.7 × 4°.3, at full sensitivity). This is achieved by the use of a coded mask placed at a distance of 250 cm from a NaI position-sensitive detector based on the Anger camera principle. Sigma is carried in a highly eccentric orbit (period = 4 days) by the *GRANAT* spacecraft, which was launched on 1989 December 1. A full description of the Sigma instrument can be found in Paul et al. (1990).

The region of sky containing OAO 1657−415 has been observed for about 29 hr in "spectral-imaging" mode, starting at UT 09:00 on 1990 March 27. Two sets of images are recorded by the instrument in this operating mode: the "fine images," consisting of maps with pixel size of 1′.62 in four wide, contiguous energy bands, and the "spectral images," giving sky pictures in 95 energy channels between 35 keV and 1.3 MeV. The spectral images have a pixel size of 3′.23, and their integration time (about 8 hr, for this observation) is twice that of the fine images.

The recorded images have been "flat-fielded" to remove spatial nonuniformities intrinsic to the detector or due to the background and then deconvolved using standard techniques, as described in Laudet & Roques (1988). In the "fine image" corresponding to the energy range 40–120 keV, a 4.1 σ excess is present at a position coincident with the soft X-ray candidate counterpart of OAO 1657−415 proposed by Parmar et al. (1980). The position of OAO 1657−415, derived from our observation, is R.A. = 254°.246, decl. = −41°.578 (1950), with an associated uncertainty of 4′.

A preliminary analysis of the "spectral images" shows that the source is detected up to about 65 keV, with a statistical significance of about 5 σ in the 35–65 keV range. Its flux relative to the Crab Nebula is of 0.06 and 0.1, in the energy bands 35–52 keV and 52–65 keV, respectively. These flux values correspond to a 35–65 keV luminosity of the order of

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$4 \times 10^{34} \times (d/1 \text{ kpc})^2$ ergs s^{-1}, i.e., a luminosity similar to that measured in 1978 with the *HEAO 1* A-2 instrument (White & Pravdo 1979).

2.2. *Timing Analysis*

The Sigma telescope, when operated in the spectral imaging mode, does not record the arrival time of each detected count. The only data available for a timing analysis are the total number of counts detected in each of the fine image energy bands, integrated over consecutive 4 s intervals. These data have been folded into nine phase bins at trial periods between 37.5 and 38.5 s, with a 0.05 s step. The χ^2 statistic against the hypothesis of a uniform distribution has been computed for each period, taking into account the effective exposure time of each phase bin and correction for the instrumental dead time. A maximum value of the $\chi^2 = 51.1$ (8 d.o.f.) has been found for $P = 37.850$ s, in the data corresponding to the lowest energy band (40–120 keV). A finer scan, from $P = 37.8$ to $P = 37.9$ s with steps of 1 ms, gives the χ^2 versus period curve shown in Figure 1*a*. From the width of the χ^2 peak we estimate an accuracy of about 0.02 s for our period determination. The light curve corresponding to the maximum χ^2 value is shown in Figure 1*b*. No statistically significant evidence of periodicity has been found in the three higher energy bands (120–190 keV, 190–300 keV, and 0.3–1.3 MeV).

Since it is not possible to perform any spatial selection on the counts used for the folding, they also contain the contribution of all the sources within the total (fully and partially coded) field of view. Indeed, two other sources have been detected during this observation: 4U 1700−377 and GX 399−4 (work on them is still in progress and will be reported elsewhere). However, we can ascribe the observed periodicity to OAO 1657−415 for the following reasons. First, both 4U 1700−377 and GX 339−4 were well outside the field of view of all the other instruments which have detected a 38 s periodicity from this region of sky (White & Pravdo 1979; Parmar et al. 1980; Nagase et al. 1984a; Sunyaev et al. 1990). Second, the pulsations were also detectable during an interval of 8 hr in which 4U 1700−377 was not visible in the images, due to its variability. Finally the count rate lower limit derived from the pulsed fraction of Figure 1*b* is in good agreement with that obtained from the imaging data.

TABLE 1

PERIOD HISTORY OF OAO 1657−415

Observation Date	Pulse Period (s)	Satellite
1978 Sep 4	38.218 ± 0.004	*HEAO 1*
1979 Aug 25	38.019 ± 0.009	*Einstein Observatory*
1983 Jul 18–23	37.885 ± 0.001	*Tenma*
1988 Mar 17	37.7505 ± 0.0004	*Ginga*
1990 Mar 27	37.853 ± 0.02	Sigma

In order to search for variations in the pulse frequency during the observation, we have performed the same analysis on the data divided in four intervals. In all the cases, the period was consistent with that determined from the whole data set, within the large errors due to the reduced statistics.

3. DISCUSSION

Since its discovery in 1978, the rotation period of OAO 1657−415 showed a monotonic decrease, on time scales from 200 to 10^3 yr, a behavior exhibited only by a few X-ray pulsars for which several period measurements exist: SMC X-1, LMC X-4, and 4U 1626−67. All the published period measurements for OAO 1657−415, as collected in the review paper by Nagase (1989), are summarized in Table 1.

The period value determined during the Sigma observation, corresponding to $P = 37.853 \pm 0.02$ s at the solar system barycenter, is significantly greater than that observed with the *Ginga* satellite on 1988 March. The connection of our derived period value with a further *Ginga* measurement made on 1989 March 4 ($P = 37.712 \pm 0.003$; Y. Kamata, private communication), implies a spin-down value of at least $3.5 \times 10^{-3}\ \text{yr}^{-1}$.

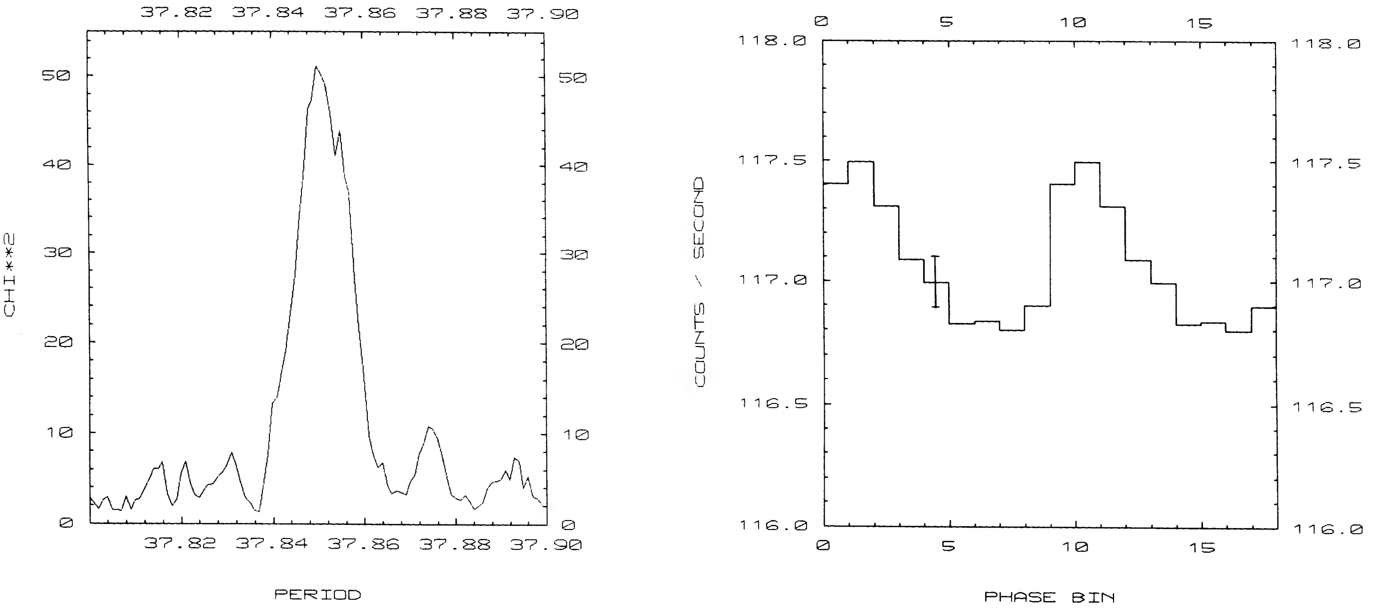

FIG. 1*a*

FIG. 1*b*

FIG. 1.—(*a*) Curve of χ^2 (8 d.o.f.) vs. trial period. (*b*) Light curve corresponding to the maximum of (*a*) ($P = 37.85$ s). The typical 1 σ error bar is shown.

Unfortunately, the lack of an optical identification and of a distance estimate for OAO 1657−415, make it difficult to discuss the observed spin-down in the context of the current models of accretion torques in binary X-ray pulsars.

The Galactic coordinates ($l = 344°$, $b = 0\overset{\circ}{.}3$) and the X-ray flux of OAO 1657−415 are compatible with distances of up to more than 20 kpc. However, the low column density fitted to the *HEAO 1* A-2 spectrum by White & Pravdo (1979) rules against distances greater than a few kiloparsecs. In the following, we will assume $d = 2$ kpc, based on their best fit $N_{\rm H} = 3.6 \times 10^{21}$ cm^{-2}, the relation $A_v = 5.3 \times 10^{-22} N_{\rm H}$ (Bohlin et al. 1978), and the data on A_V versus distance for this region of the Galactic plane (Neckel & Klare 1980).

Due to the limits obtained with the *Tenma* satellite on the orbital Doppler shift of the OAO 1657−415 pulsations, Nagase et al. (1984a) concluded that this source is most likely a low-mass binary system, although they cannot exclude the possibility of a massive system with orbital period of several tens of days or a small inclination. Assuming the low-mass hypothesis, the accretion torque model of Gosh & Lamb (1979) can be applied, since in these systems accretion occurs mainly by Roche lobe overflow and the consequent formation of a disk. The observed change in the period derivative implies that OAO 1657−415 is spinning close to its equilibrium period. The X-ray luminosity in the range 10^{35}–10^{36} ergs s^{-1} then requires a magnetic field of the order of (1–5) $\times 10^{12}$ G. Thus the interpretation of OAO 1657−415 as a fast pulsar does not lead to the high magnetic field problem encountered by other objects with greater luminosity and spin period, such as, e.g., GX 1+4 and Vela X-1 (Makishima et al. 1988; Nagase et al. 1984b). However, two possible problems arise in the application of this model to OAO 1657−415. First, since the spin-down derives from a greater magnetic breaking due to an increase of the magnetospheric radius, it should be related to a decrease in the accretion rate, hence to a lower luminosity. Although a comparison between the fluxes measured with the different satellites is made difficult by the different energy bands, possible systematic errors, and the short time scale variability of the source, there is no evidence that OAO 1657−415 has entered a low-luminosity state correlated with the change in the period derivative. Second, the very short spin-down time scale (300 yr) requires a value of the dimensionless fastness parameter close to the limit of validity of the Gosh & Lamb model, unless the distance of the system is greater than several kiloparsecs.

The hypothesis of a massive binary, in which accretion occurs by stellar wind capture, seems thus more attractive. The observed spin-up and spin-down values can then be explained, e.g., by the model of Börner et al. (1987). In this scenario, a disk can form also in wind-fed systems, due to the interaction between the accreting plasma and the rotating magnetosphere, provided that the magnetospheric radius is close to the corotation radius. When this requirement is applied to OAO 1657−415, a reasonable value for the magnetic field at the surface of the neutron star, $B \sim 10^{12}$ G, is obtained, contrary to the case of Vela X-1, where $B \sim 10^{14}$ G is required (Börner et al. 1987).

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