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DISCOVERY OF A 283-SECOND PERIODIC VARIATION IN THE X-RAY SOURCE 3U 0900−40

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ABSTRACT

A 283 s periodic pulsation in the X-ray system 3U 0900−40 has been discovered during observations by the SAS-3 X-ray observatory. Pulse profiles of the 283 s periodicity are presented in five energy intervals covering the range 1–30 keV for the period 1975 July 19.4–23.9. The averaged profile is relatively simple at higher energies and is markedly more complex at lower energies. The peak 1–40 keV intensity observed for the source is 1.2×10^{-8} ergs cm^{-2} s^{-1}, which corresponds to a luminosity of 2.1×10^{36} ergs s^{-1} at a distance of 1.2 kpc. A search for soft X-ray emission ($E < 1$ keV) yielded upper limits of 2×10^{-11} and 5×10^{-11} ergs cm^{-2} s^{-1} in the energy intervals 0.16–0.28 keV and 0.5–0.7 keV, respectively.

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

I. INTRODUCTION

Vela X-1 (3U 0900−40) is one of about eight known binary systems that emit hard (>2 keV) X-rays at luminosities greater than $\sim 10^{36}$ ergs s^{-1}. Two of these, Cen X-3 and Her X-1, exhibit rapid regular pulsations with periods of 4.8 s and 1.24 s, respectively. The arrival times of the pulsations are Doppler-modulated by the orbital motions of the X-ray–emitting objects, which are generally assumed to be rotating neutron stars (see Giacconi *et al.* 1971; Schreier *et al.* 1972; Tananbaum *et al.* 1972). Recently, Lucke *et al.* (1975) have reported the observation of a regular pulsation with period 0.716 s for the binary X-ray source SMC X-1 (3U 0115−73), but no Doppler modulation data are yet available. Several other X-ray sources have been found to have regular pulsations, but with long periods: A1118−61 (405 s; Eyles *et al.* 1975), A0535+26 (104 s; Rosenberg *et al.* 1975; Bradt *et al.* 1976), X Per (835 s; White, Mason and Sanford 1975*b*), GX 1+4 (Lewin, Ricker, and McClintock 1971; White *et al.* 1975*a;* Lewin, Hoffman and Doty 1976), GX 301−2 (697 s; White *et al.* 1975*a;* Hoffman, Lewin, and Doty 1976) and GX 17+2 (1914 s; White *et al.* 1975*a*). To date, none of these other long-period pulsars have been shown to be in a binary system.

Vela X-1 (3U 0900−40), discovered in rocket observations by Chodil *et al.* (1967), was found in OSO-7 satellite observations to be an eclipsing binary with an orbital period of approximately 9 days (Ulmer *et al.* 1972). Refinement of positional data by the *Uhuru* satellite observations led to the identification of its optical counterpart, HD 77581, a B0 supergiant, and to determinations of the mass function for the optical star. Observations with the SAS-3 X-ray satellite on 1975 June 18 revealed regular X-ray pulsations with a period of $\sim$283 s (Rappaport and McClintock 1975) and complex, energy-dependent pulse shapes which are the subject of the present *Letter*. Intensive observations during 1975 June and July determined the Doppler variations of the 283 s period. This provided the basis for an analysis of the system as a double-line "spectroscopic" binary and has led to an estimate of the mass of the X-ray source. These results are presented in the following *Letter* (Rappaport, Joss, and McClintock 1976), hereafter referred to as Paper II.

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II. OBSERVATIONS

Most of the data were obtained with two proportional-counter detectors aboard the SAS-3 satellite. One is an argon-filled detector that has an effective area of 80 cm^2 and three energy channels: 1–3 keV, 3–6 keV, and 6–12 keV. The other is a xenon-filled detector that has an effective area of 115 cm^2 and four energy channels: 8–19 keV, 19–30 keV, 30–39 keV and 39–55 keV. The detectors view out along the equatorial plane of the spacecraft through coaligned 1°.7 FWHM collimators. The data were recorded at 0.42 s time resolution. In addition to the instrumentation described above, we also used the SAS-3 low-energy system (Hearn *et al.* 1975) to search for soft (<1 keV) X-radiation.

During these observations the satellite was operated in a pointed mode so that 3U 0900−40 was nearly centered in the field of view of the detectors throughout the portion of each satellite orbit when the source was not occulted by the Earth. Each satellite orbital period yielded approximately 3000 s of observation time. The results presented here and in Paper II are based on an analysis of the quick-look data obtained during 35 satellite orbits from 1975 June 18.8–24.2 and from 1975 July 19.3–25.3 UT.

The observations began on 1975 June 18 when data recorded during a brief scan over 3U 0900−40 revealed that the source was in a state of high intensity, equal to $\sim$1/3 that of the Crab Nebula (8–19 keV). The satellite was then switched from the scanning mode to the pointed mode of operation (three-axis stabilized). It was immediately evident that the flux was periodic and the pulse period appeared to be $\sim$141 s. However, further study revealed that there were subtle differences between even and odd pulses at higher energies ($E \gtrsim 10$ keV) and gross differences at lower energies (Fig. 1). Hence, the correct period was deduced to be $\sim$283 s.

Here we present the average pulse profiles and time-averaged spectral information that were derived from the eight orbits of data that had the highest signal-to-noise ratio. These data were obtained during 1975 July 19.4–23.9 UT at the observation times given in Table 1 of Paper II.

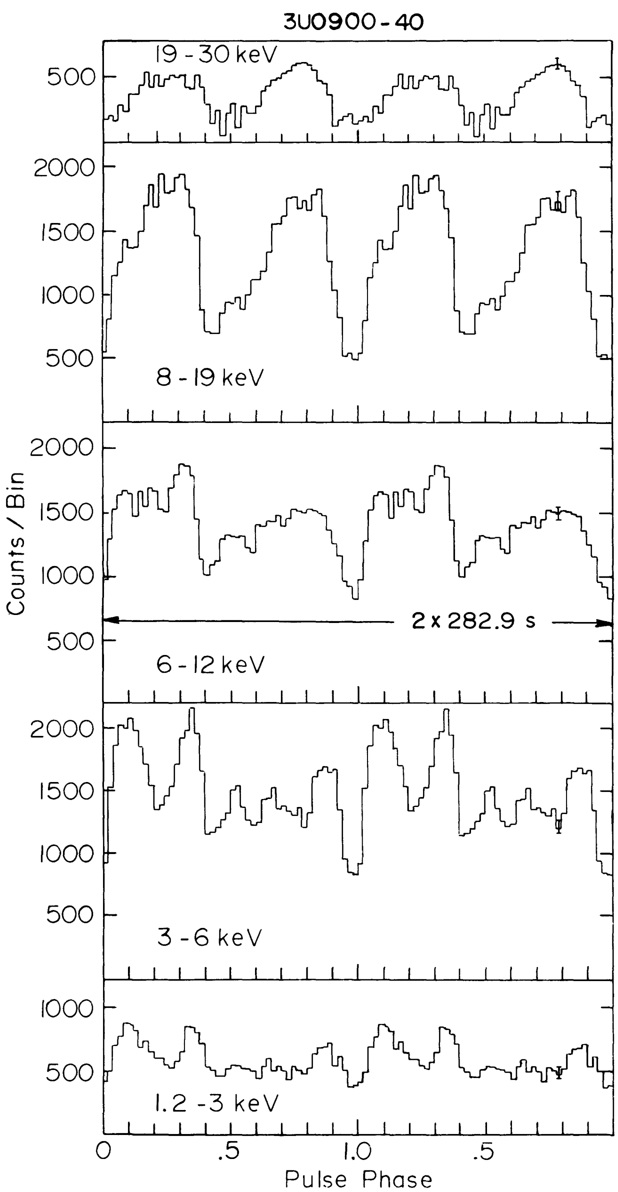

FIG. 1.—Average pulse profiles for eight satellite orbits of data that were obtained during 1975 July 19.4–23.9 (see Paper II, Table 1). The data are folded into 50 bins modulo the pulse period 282^{s}9 and are repeated in a second set of 50 bins. The background counting rate was determined during earth occultation and has been subtracted. A single scale factor was used for the vertical axes. The statistical uncertainties are indicated on each pulse profile near the right boundary of the figure.

III. PULSE PROFILES

We made phase corrections for the orbital motions of the X-ray star and the Earth and folded eight orbits of data modulo the pulse period. The resultant pulse profiles for five energy intervals are shown in Figure 1. Their most striking feature is the strong dependence of their shape on energy. This is also the case for the slowly pulsating source A0535+26 (P = 104 s; Bradt *et al.* 1976; Ricker *et al.* 1976). However, this appears not to be the case for the rapidly pulsating sources Her X-1 (P = 1.24 s; Giacconi 1975) and Cen X-3 (P = 4.8 s; Ulmer 1976) in the energy range 2–20 keV. At energies above $\sim$10 keV the 3U 0900−40 pulse structure is simpler and the modulation depth is greater than at lower energies. Also, the pulse profile at higher energies is composed of two very similar pulses which are separated by nearly half a pulse period. In contrast, the high-energy ($\sim$20–60 keV) light curves of the slowly pulsating source A0535+26 reveal only a single, smooth pulse that has a large ($\sim$80%) duty cycle (Bradt *et al.* 1976; Ricker *et al.* 1976). At lower energies, 3–6 keV, the pulse profiles of 3U 0900−40 and A0535+26 bear a remarkable similarity. Both have a complex and detailed structure which is composed of five maxima (or five dips) per period.

We are presently preparing a set of pulse profiles of 3U 0900−40 from data obtained during 1975 December, about 6 months after the June and July observations discussed here. Our preliminary results indicate that the pulse profiles have changed very little during the course of half a year.

IV. SPECTRAL DATA

The highest intensity of 3U 0900−40 was recorded during observation number 20 (see Paper II, Table 1). To compare the spectrum with the well-known spectrum of the Crab Nebula we divided the orbit-average of the counting rates in each of seven energy intervals by the corresponding counting rates for the Crab Nebula. The resulting ratios (presented in Table 1), which are un-

TABLE 1

INTENSITY OF 3U 0900−40 RELATIVE TO THE CRAB NEBULA

Energy Interval (keV)	(Counting Rate 3U 0900−40)/(Counting Rate Crab)
1.2–3	0.06
3–6	0.12
6–12	0.31
8–19	0.29
19–30	0.31
30–39	0.21
39–55	0.04

certain by less than 10 percent, show that the spectrum of 3U 0900−40 below 40 keV is hard, while above 40 keV it falls off rapidly, in agreement with the work of Ulmer (1975).

Using an assumed distance of 1.2 kpc (Hiltner, Werner, and Osmer 1972; Paper II) and the data given in Table 1, we obtain an orbit-average, 1–40 keV luminosity of 2.1×10^{36} ergs s^{-1}, with an uncertainty of ~20 percent. This is greater than the luminosities that we infer from the data of Ulmer (1975) and Giacconi *et al.* (1974). However, it is probably less than the luminosity of the source during an observation with the *Uhuru* satellite which was reported by Forman *et al.* (1973). Direct comparisons with other experiments are complicated by the different energy intervals of the measurements and the large variations which are observed in the source intensity.

In summary, during 12 days of pointed observations using SAS-3, the luminosity of 3U 0900−40 ranged from $\lesssim 0.2 \times 10^{36}$ ergs s^{-1} to 2.1×10^{36} ergs s^{-1}. The data presented by Forman *et al.* (1973) suggest that on rare occasions the source luminosity may be somewhat greater than 2×10^{36} ergs s^{-1}.

A search was also made for a flux of soft X-rays below 1 keV with the low-energy detectors (Hearn *et al.* 1975), and no evidence for soft X-radiation was found. For each of eight orbits the 3 σ upper limit on the 0.16–0.28 keV flux is 2×10^{-11} ergs cm^{-2} s^{-1}, and on the 0.5–0.7 keV flux is 5×10^{-11} ergs cm^{-2} s^{-1}. The total galactic hydrogen column density in the direction of 3U 0900−40 is $\sim 6 \times 10^{21}$ cm^{-2} (Daltabuit and Meyer 1972). The column density to 3U 0900−40 is likely to be $\gtrsim 0.2$ of this value (cf. Davies 1972; Verschuur 1973), which corresponds to an optical depth $\gtrsim 5$ at 0.25 keV and $\gtrsim 1$ at 0.6 keV. Because of the possibly large optical depth at $\frac{1}{4}$ keV, it is difficult to draw a comparison between the lack of soft radiation from 3U 0900−40 and the large soft flux observed from Her X-1 (Shulman *et al.* 1975; Catura and Acton 1975).

V. DISCUSSION

The existence of X-ray pulsations with a highly stable pulse period rules out the possibility that the X-ray star is a black hole. Moreover, as shown in Paper II, the mass of the X-ray star probably exceeds the maximum stable mass of a white dwarf in the absence of differential rotation (internal rotation periods $\lesssim 10$ s; surface rotation period = 283 s), and such strong differential rotation is unlikely because it would probably induce a dynamical instability (cf. Goldreich and Schubert 1967; Ostriker and Bodenheimer 1968). Finally, the X-ray luminosity of the 3U 0900−40 system is often greater than 10^{36} ergs s^{-1}, which is larger than even the more optimistic predictions for hard X-ray emission from white dwarfs (Fabian, Pringle, and Rees 1976). It is therefore likely that the X-ray source is an accreting neutron star, and we adopt this as a working hypothesis in the following discussion.

The model of the periodically pulsing binary X-ray sources that has gained the widest acceptance invokes the accretion of matter onto the magnetic polar caps of a neutron star (see, e.g., Pringle and Rees 1972; Davidson and Ostriker 1973; Gnedin and Sunyaev 1973; Lamb, Pethick, and Pines 1973). In this model, the magnetic axis of the neutron star is not coaligned with the rotation axis, and the pulses are produced by the beaming of X-rays from the accreting polar caps. Mechanisms that may contribute to the emergent beam pattern include the geometry of the magnetic field, the shape of the surface of the polar cap, cyclotron processes, and anisotropic electron scattering and radiative opacities modified by the intense magnetic field and plasma collective effects within the accreting matter (cf. Pringle and Rees 1972; Baan and Treves 1973; Davidson 1973; Davidson and Ostriker 1973; Gnedin and Sunyaev 1973; Lamb, Pethick, and Pines 1973; Lodenquai *et al.* 1974; Tsuruta and Rees 1974; Tsuruta 1975; Wang 1975).

At higher energies 3U 0900−40 displays two nearly symmetrical and nearly equally spaced maxima (Fig. 1). In the context of the magnetic, rotating neutron star model, this suggests that we may be viewing alternately radiation from the two polar caps of the star. In this connection, we note that in the vicinity of the accretion columns both the vertical and horizontal electron scattering opacities are expected to be only of order unity, due to the relatively low source luminosity (see, e.g., Lamb, Pethick, and Pines 1973). The precise physical interpretation of the pulse profiles, however, is difficult because of their complex temporal and spectral structure which cannot be reproduced by any simple model invoking the effects listed above. In particular, simple models involving an off-axis dipole magnetic field contain geometrical symmetries that lead to temporal symmetries in the X-ray pulses (Doxsey *et al.* 1973; Gnedin and Sunyaev 1973), and such symmetries are broken in the observed pulses, particularly at lower energies.

As noted in § III, the pulse shapes of Her X-1 and Cen X-3 are markedly less energy-dependent than are the pulse shapes of the more slowly pulsating sources, 3U 0900−40 and A0535+26. In Her X-1 and Cen X-3 there is an approximate match at the Alfvén surface between the velocity of the corotating magnetosphere and the Keplerian orbital velocity (Lamb, Pethick, and Pines 1973), but, for a slowly rotating neutron star, the Keplerian orbital velocity will be much larger than the corotation velocity at the Alfvén surface. This suggests that the qualitative difference in the spectral behavior of the pulse shapes may be a consequence of the greater influence of stellar rotation upon the accretion process in the rapidly pulsating systems.

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