THE ASTROPHYSICAL JOURNAL, 217:L29–L33, 1977 October 1

DISCOVERY OF A 7.68 SECOND X-RAY PERIODICITY IN 3U 1626−67*

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Received 1977 June 1; accepted 1977 July 13

ABSTRACT

SAS-3 observations of the X-ray source 3U 1626−67 have revealed the presence of a stable $7^{s}.68$ pulse period. This source was selected for study because of its hard X-ray spectrum. The compilation of source spectra used in the selection process is also presented. Pulse arrival times are analyzed for effects of possible binary orbital motion. Upper limits to the projected orbital radius were obtained which tend to exclude orbital periods in the range $0^{d}.5 \lesssim P_{\rm orb} \lesssim 35^{d}$. Binary systems with either a very long orbit ($\gtrsim 175^{d}$) or a very short orbit ($\lesssim 0^{d}.3$) are most probable.
Subject heading: X-rays: sources

I. INTRODUCTION

All of the ~11 known X-ray pulsars have hard energy spectra with substantial flux above 10 keV (Rappaport and Joss 1977*a* and references therein; McClintock *et al.* 1977; Huckel *et al.* 1977; Davison 1977; Becker *et al.* 1977). As a guide to selecting sources for study which might exhibit pulsed X-ray emission, we have compiled a list of sources with hard X-ray spectra. The list, given in Table 1, was prepared from the MIT OSO-7 X-ray source catalog (Markert *et al.* 1977). A spectral hardness ratio, relating the flux above ~15 keV to the flux below ~10 keV, was calculated for each source. All the sources with a significant flux above 15 keV were then ranked according to spectral hardness; known extragalactic sources were excluded.

The 17 "hardest" X-ray sources, listed in Table 1, include eight previously known X-ray pulsars and the binary systems Cyg X-3, Cyg X-1, and 3U 1700−37. There is clearly a strong correlation between spectral hardness and X-ray pulsars/X-ray binaries. A compilation of the spectra of X-ray sources by Jones (1977) also indicates a similar correlation. Three X-ray pulsars that do not appear in Table 1 are highly variable or transient sources (A1118−61, A0535+26, and A1540−53; Ives, Sanford, and Bell Burnell 1975; Rosenberg *et al.* 1975; Davison 1977; Becker *et al.* 1977) that were discovered by the *Ariel 5* satellite, launched after the OSO-7 observations were made.

The source 3U 1626−67 was chosen from Table 1 for study with the SAS-3 satellite because it has the hardest spectrum among those sources with sufficient intensity to permit a significant search for pulsations. Other sources in Table 1 such as 3U 1700−37, 3U 1822−37, and 3U 2030+40 have also been studied and, thus far, have not been found to be pulsing. The detailed results for these sources will be presented elsewhere.

* This work was supported in part by the National Aeronautics and Space Administration under contract NAS5-11450.

† Alfred P. Sloan Research Fellow.

II. OBSERVATIONS

The source 3U 1626−67 was observed during the intervals 1977 March 24.4–26.0 and 1977 April 1.7–3.8, 5.8–6.5, and 24.2–25.2. For most of the observations SAS-3 was operated in the pointed mode so that 3U 1626−67 was nearly centered in the $1^{\circ}.7$ (FWHM) field of view of the horizontal tube detecter (Buff *et al.* 1977; Lewin *et al.* 1976) during each satellite orbit, excluding a brief ~800 s Earth occultation. Raw counting rate data, representing the energy interval 1.5–12 keV, are shown in Figure 1 for 15 satellite orbits. The average count rate was about 3 times that expected from the *Uhuru* and OSO-7 catalogs (Giacconi *et al.* 1974; Markert *et al.* 1977). The source intensity is also highly variable by factors of ~3 on time scales from ~100 s to ~300 s.

The spectral data obtained with the horizontal tube detector in the energy range ~1.5–30 keV indicate that the energy spectrum is extremely hard (i.e., spectral index $\alpha = 0.3 \pm 0.4$). This is consistent with the spectrum observed in the OSO-7 data (Table 1). The integrated flux in this energy band corresponds to a luminosity of $\sim 2 \times 10^{35}\, d^2$ ergs s^{-1}, where d is the source distance in kiloparsecs.

III. PERIODIC PULSATION

Fourier analysis of the data shown in Figure 1 (but in finer time bins) revealed a stable pulse period of $7^{s}.680$. The data were then folded modulo the best-fit pulse period which was determined by the iterative procedure described in McClintock *et al.* (1977). The resultant pulse profiles from the March 24.4–26.0 observation are shown in Figure 2 for five energy intervals between 1.5 and 30 keV.

The 3–6 keV and 6–12 keV pulse profiles show about 7% of the power pulsed in a broad maximum with a 40% duty cycle. The broad pulse contains a statistically significant secondary minimum. The 1.5–3 keV profile is nearly featureless except for a small minimum that coincides with the secondary minimum of the 3–6 keV

TABLE 1

GALACTIC X-RAY SOURCES RANKED ACCORDING TO SPECTRAL HARDNESS*

No.	Source	l^{II}	b^{II}	R=KR/AR	KR†	AR†	X-Ray‡ Pulse Period (s)	Binary‡ Period (d)
1.......	3U 0449+66	143.6	+14.4	3.28	0.26±0.06	0.08±0.04	...	....
2.......	MX 0600+46	166.4	+11.9	0.91	0.21±0.06	0.24±0.05	...	....
3.......	3U 1223−62	300.1	− 0.1	0.71	0.98±0.13	1.39±0.14	696	∼23§
4.......	*3U 1626−67*	321.8	−13.1	0.67	0.89±0.13	1.32±0.11	7.68	≳175 or <0.3
5.......	3U 0900−40	263.1	+ 3.9	0.56	1.50±0.15	2.67±0.15	283	8.97
6.......	3U 0918−55	275.9	− 3.9	0.52	0.36±0.11	0.70±0.09	...	...
7.......	3U 1653+35	58.3	+38.1	0.48	0.76±0.13	1.57±0.12	1.24	1.70
8.......	3U 1258−61	304.1	+ 1.2	0.41	1.23±0.13	3.00±0.17	272‖	≳15‖
9.......	3U 1700−37	347.8	+ 2.2	0.36	1.71±0.24	4.70±0.63	...	3.41
10......	3U 1956+35	71.3	+ 3.1	0.31	7.86±0.35	25.07±0.81	...	5.60
11......	3U 1728−24	1.9	+ 4.8	0.31	2.11±0.17	6.83±0.33	120	...
12......	3U 0115−73#	300.7	−43.6	0.30	0.42±0.09	1.38±0.10	0.715	3.89
13......	3U 1822−37	356.8	−11.3	0.26	0.42±0.09	1.63±0.10	...	...
14......	3U 2030+40	79.8	+ 0.7	0.25	1.91±0.16	7.54±0.31	...	0.20
15......	MX 1608−52	331.0	− 0.8	0.22	0.82±0.23	3.71±0.35	...	...
16......	3U 1118−60	292.1	+ 0.4	0.17	0.69±0.15	3.49±0.21	4.84	2.08
17......	3U 0352+30	163.1	−17.1	0.17	0.33±0.09	1.90±0.11	835	...

* The spectra of many of the galactic X-ray sources have been obtained from OSO-7 data (Markert *et al.* 1977). We define spectral hardness, R, as the ratio of counting rate in the krypton detector (15–40 keV) to that in the argon detector (3–10 keV). All sources with $R \gtrsim 0.15$, and with a significant detection ($>3\,\sigma$) in the krypton detector, are listed.

† Counts s^{-1} in the OSO-7 argon (AR) and krypton (KR) detectors (Clark *et al.* 1973).

‡ For references see Blumenthal and Tucker 1974; Tananbaum and Hutchings 1974; Joss and Rappaport 1976; Rappaport and Joss 1977*a*.

§ Hammerschlag-Hensberge *et al.* 1976.

‖ McClintock *et al.* 1977.

\# The extragalactic source SMC X-1 is included for comparison.

pulse profile. At higher energies ($\gtrsim$12 keV) the pulsed fraction increases to ∼15%, while the pulse shape changes dramatically, and the phase of maximum intensity shifts by ∼180°. This complex dependence of the pulse shape on energy is seen in most of the longer period X-ray pulsars ($P > 100$ s; cf. Rappaport and Joss 1977*a*).

It is important to ascertain that the observed pulse period is not due to a beating effect between some other shorter pulse period and the sampling interval of the satellite in the normal operating mode (0.83 s). Therefore, an additional measurement of the pulse profile in the 1.5–12 keV range was made with SAS-3 in the fast timing mode (8 ms resolution; see Primini *et al.* 1976). The pulse profile obtained in this mode, though of less statistical precision, confirmed the existence of the 7^{s}68 period and the basic pulse shape shown in Figures 2*b* and 2*c*. We note that 3U 1626−67 is the first X-ray pulsar with a period that falls in the "gap" between Cen X-3 and A0535+26 (Rappaport and Joss 1977*a*).

Data from 50 satellite orbits were used to search for effects of possible binary orbital motion and changes in the intrinsic pulse period. Because the source intensity and the pulsed fraction are small, data from typically two to four consecutive satellite orbits were folded modulo the apparent pulse period to determine a "pulse arrival time." An improved arrival time was then obtained by cross-correlating a master pulse template, constructed from all the data, with the individual pulse profiles. This technique is described by Rappaport *et al.* (1976), Primini, Rappaport, and Joss (1977), and McClintock *et al.* (1977). In all, 21 pulse arrival times were obtained which span a 32 day interval. The best fit to a constant pulse period during the interval 1977 March 24–April 6 (after correcting for the Earth's motion about the Sun) is 7^{s}680604 ± 0^{s}000002 (95% confidence).

A function representing trial circular orbits with periods in the range 0^{d}3 to 200^d was fitted to the 21 pulse arrival times. The rate of change of intrinsic pulse period, $\dot{P}$, was also allowed to be a free parameter because such changes are apparently characteristic of the X-ray pulsars (Rappaport and Joss 1977*b*). The method of analysis is discussed in detail by Rappaport *et al.* (1976). Only upper limits to the projected orbital radius, $a_x \sin i$, were found; these are displayed in Figure 3 as a function of the assumed trial orbital period. Also shown, for reference, are contours of constant mass function and the orbital parameter values for four X-ray binaries.

For orbital periods less than ∼0^{d}3, the limit on $a_x \sin i$ is set by the temporal structure exhibited by the pulse profiles. In particular, the 3–6 keV pulse profile (Fig. 2*b*) has the sharpest features, e.g., the secondary minimum at phase 0.39, and the rapid decline after the main pulse at phase 0.56. These features have a time scale of $\sim\frac{1}{2}$ s and thereby ensure that the pulse is not being smeared by an orbital motion of more than ∼1 lt-sec.

For orbital periods in the range 0^{d}5 $\lesssim P_{orb} \lesssim$ 35^d the mass function, as determined from Figure 3, is constrained to have a value $f(M) \lesssim 1 \times 10^{-6}\, M_\odot$. Unless the orbital inclination angle is $\lesssim 8°$ ($\leq$0.01 *a priori*

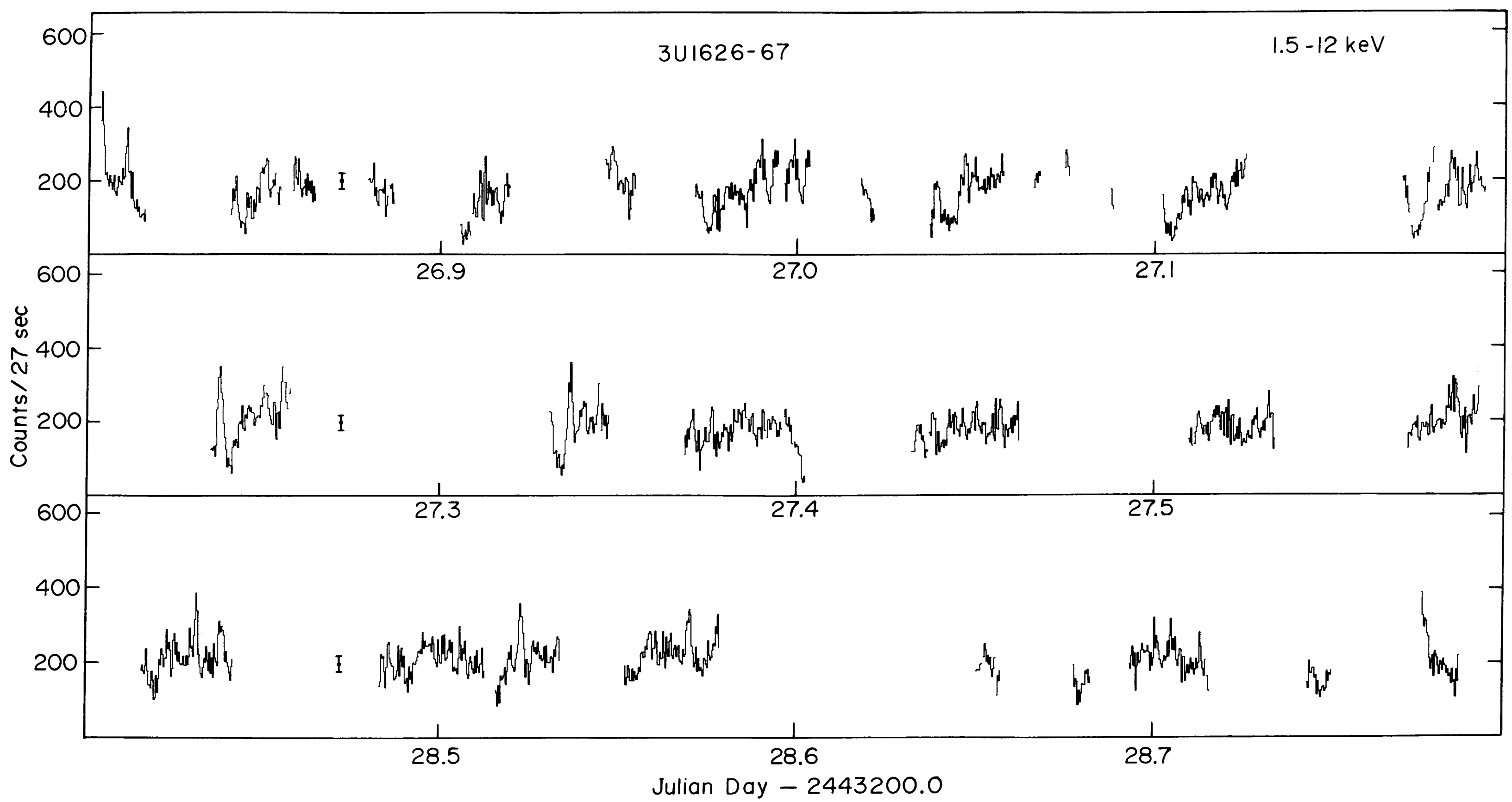

FIG. 1.—Counting rate data for 3U 1626−67 in the energy interval 1.5–12 keV. Data taken during times when the satellite was in Earth occultation or in the South Atlantic Anomaly are not shown. Other gaps in the data result from telemetry dropouts. A nonsource background rate has been subtracted, and typical statistical error bars are indicated.

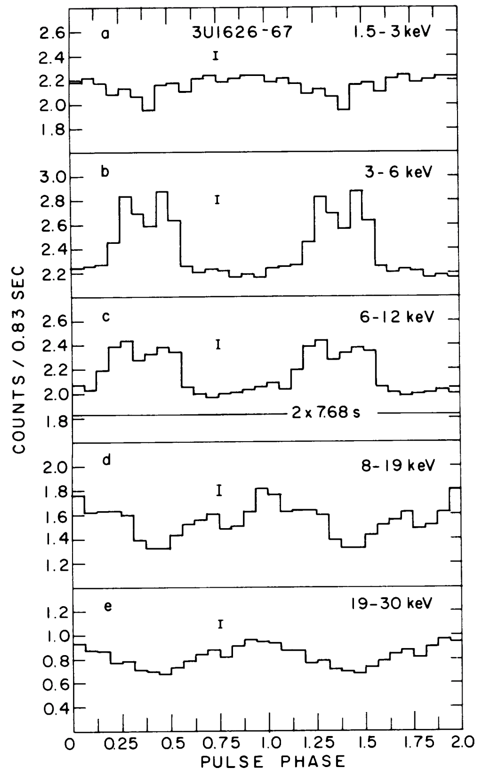

FIG. 2.—Average pulse profiles for five energy intervals, derived from data obtained during 1977 March 24.4–26.0. The data are folded into 16 bins modulo the 7.68 s pulse period and are repeated in a second set of bins. The indicated count rate is for 3U 1626−67, after nonsource background has been subtracted. The mean "effective" energies for the 6–12 keV and 8–19 keV intervals are ~8 keV and ~13 keV, respectively, for a flat energy spectrum.

probability), there is no reasonable combination of masses for the X-ray star and companion star that would yield a mass function this small. We therefore conclude that orbital periods in the range $0^d.5 \lesssim P_{orb} \lesssim 35^d$ are almost certainly excluded. Longer orbital periods are allowed, but a period of greater than $\sim 175^d$ and $a_x \sin i \gtrsim 300$ lt-sec are required for a mass function of $\gtrsim 1\ M_\odot$. For short orbital periods ($P_{orb} \lesssim 0^d.3$) the less stringent limit on $a_x \sin i$ of ~1 lt-sec allows plausible values of $f(M)$ for compact systems involving a low-mass companion star.

IV. DISCUSSION

Three possible models are considered for 3U 1626−67: (1) an isolated neutron star deriving its power from rotational kinetic energy; (2) an isolated neutron star accreting matter from a dense interstellar cloud; and (3) an accreting neutron star in a binary orbit.

The first of these models has at least one serious flaw in addition to the obvious fact that the spectral and temporal characteristics of 3U 1626−67 strongly resemble those of the other X-ray binaries and not those of any of the radio pulsars. When the data are fitted with a function involving a term in $\dot{P}$ but with no orbital parameters, a value of $\dot{P}/P = -(1.7 \pm 0.1) \times 10^{-4}\ \mathrm{yr}^{-1}$ is obtained. The negative sign of $\dot{P}/P$ indicates a spin-up for the neutron star rather than the spin-down required if the energy source is rotational kinetic energy. Thus the first hypothesis is ruled out.

Model 2 is more difficult to exclude. The source luminosity (2×10^{35}–2×10^{37} ergs s^{-1} for $d = 1$–10 kpc) could be produced by the accretion, onto a neutron star, of matter from an interstellar cloud with density $n \sim 10^4$–$10^6\ \mathrm{cm}^{-3}$, radius $\gtrsim 10^{14}$ cm, and $T \sim 10^4$ K (cf. Bondi 1952; Ostriker, Rees, and Silk 1970; Shvartsman

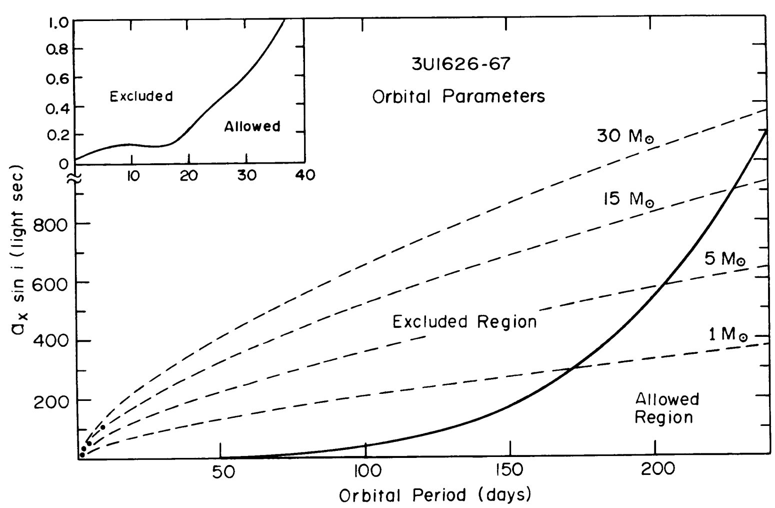

FIG. 3.—Allowed circular orbits for 3U 1626−67 that are consistent with the SAS-3 timing data. The rate of change of intrinsic pulse period, $\dot{P}$, is a free parameter in the orbital fits. The heavy curve represents the upper limits (95% confidence) on $a_x \sin i$ as a function of orbital period. The dashed curves are contours of constant mass function $f(M)$. The four dots represent the orbits of Her X-1 ($P_{orb} = 1^d.70$), Cen X-3 ($2^d.08$), SMC X-1 ($3^d.89$), and 3U 0900−40 ($8^d.96$). The inset near the top of the figure shows the limits on $a_x \sin i$ in more detail for $P_{orb} < 40^d$. For orbital periods less than $\sim 0^d.3$ the upper limit to $a_x \sin i$ is ~1 lt-sec.

1971). An H II region that is ionized by the X-ray source and which has the above parameters could have escaped detection in radio and optical surveys (e.g., Dixon 1970; Sivan 1974). The observed time variability (100–300 s) could result from unsteady accretion through the magnetosphere of the neutron star and need not be attributed to a companion star. The inferred rate of change in the intrinsic pulse period could be induced by accreting matter from the interstellar cloud if the luminosity is $\gtrsim 7 \times 10^{36}$ ergs s^{-1} (Rappaport and Joss 1977*b*), and if the accreting matter has sufficient specific angular momentum.

The above discussion notwithstanding, we believe that 3U 1626−67 is most likely comprised of a neutron star in a binary orbit about a nondegenerate stellar companion. The assumption that the compact object is a neutron star follows by analogy from the interpretation that most, if not all, of the other X-ray pulsars are neutron stars (Rappaport and Joss 1977*b*; Mason 1977).

For the case of a wide binary orbit ($P_{orb} \gtrsim 175^d$ and $a_x \sin i \gtrsim 300$ lt-sec), the stellar companion could be an OB supergiant with a stellar wind that can transfer sufficient matter at distances of the order of $\sim$1 AU. Another possibility is that the companion star is a rapidly rotating Be star (cf. Maraschi, Treves, and van den Heuvel 1976) where a ring of material is being ejected into the equatorial plane of the star. The efficiency of the mass transfer process in this type of binary system has not yet been estimated quantitatively. A third possibility is that the companion star is a red giant which is sufficiently large to overflow its critical potential lobe even for such a wide orbit.

For the case of a compact binary system ($P_{orb} \lesssim 0^d.3$, $a_x \sin i \lesssim 1$ lt-sec), a low mass star in orbit about a neutron star would satisfy all the observational constraints. A detailed discussion of this type of model for 3U 1626−67 will be presented elsewhere (Joss, Avni, and Rappaport 1977).

We are grateful to the SAS-3 group for their assistance in this work and, in particular, J. Nugent for participation in the data analysis. We thank P. Joss for pointing out the possibility that 3U 1626−67 is a compact binary system. We also thank P. Myers and J. Bahcall for helpful discussions. This work was supported in part by the National Aeronautics and Space Administration under contract NAS5-11450.

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