THE ASTROPHYSICAL JOURNAL, 300:551–556, 1986 January 15

AN ELLIPTICAL BINARY ORBIT MODEL OF GX 1+4

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Received 1985 March 13; accepted 1985 July 12

ABSTRACT

The X-ray source GX 1+4 (4U 1728−24) was observed by the high-energy X-ray spectrometer on *OSO 8* for 5 days from 1978 September 20 to 24. X-rays in the energy range 16–72 keV were analyzed. The pulsar rotation period at 1978 September 21.0 (JD 2,443,772.5) is measured to be 228.508 ± 0.011 s, with a value of $\dot{P}/P = -0.035 \pm 0.007$ yr^{-1}. When these results are combined with the measurements of other observers, evidence is obtained for the rotation period of GX 1+4 being approximately 220 s rather than 110 s, and for an orbital period of GX 1+4 about a companion star of approximately 304 days.

Subject headings: pulsars — X-rays: binaries

I. INTRODUCTION

GX 1+4 (4U 1728−24) was first detected by Lewin, Ricker, and McClintock (1971) with a balloon-borne high-energy X-ray detector. During that observation on 1970 October 17, GX 1+4 was reported to be the most intense hard X-ray source in the Galactic center region of the sky. Its X-ray flux was observed to be modulated with a period $P = 135 \pm 4$ s. Since that time, GX 1+4 has been the subject of repeated observations by many different groups over a broad energy range. The modulation period has been found to be decreasing extremely rapidly, with a mean value of $\dot{P}/P = -0.026$ yr^{-1} (Becker *et al.* 1976) but with large variations ranging from −0.01 to −0.08 yr^{-1} on a time scale of months (Doty, Hoffman, and Lewin 1981). The possibility that the true period of the source is actually twice the period reported by Lewin *et al.* has been suggested by Koo and Haymes (1980); Strickman, Johnson, and Kurfess (1980); and Kendziorra *et al.* (1982). The X-ray intensity, too, has been observed to be highly variable on time scales ranging from minutes to months. Assuming that the source is near the Galactic center at a distance of 10 kpc, the intrinsic X-ray luminosity in the energy range from 20 to 70 keV was observed to vary from 1 to 9×10^{37} ergs s^{-1} in seven months (Doty, Hoffman, and Lewin 1981). On the basis of these X-ray measurements, GX 1+4 is believed to be a rotating magnetic neutron star accreting material from a binary companion identified optically as an M6 III star with a symbiotic spectrum (Davidsen, Malina, and Bowyer 1977).

We present in § II our measurements of the pulse period, pulsar angular acceleration, and luminosity of GX 1+4 obtained with the high-energy X-ray spectrometer on *OSO 8*. We also present the pulsar light curves we observed in different energy ranges and conclude that the period is ∼220 s rather than ∼110 s. In § III we combine our observations with those reported by others and present a history of GX 1+4 as observed in hard X-rays. From the changing period of GX 1+4 we infer a continuous function for $\dot{P}$ that suggests a 304 day periodicity. In § IV we propose that such a 304 day period in the spin-up could be caused by an elliptical orbit of GX 1+4 about its red giant companion.

II. X-RAY OBSERVATIONS

Observations of GX 1+4 were made from 1978 September 20 at 0147 UT to September 25 at 0000 UT with the high-energy X-ray spectrometer on *OSO 8*. The detector has been described in detail by Dennis *et al.* (1977). It consists of an actively shielded CsI(Na) scintillator with a sensitive area of 27.5 cm^2 and a circular field of view of 5° FWHM. For this analysis, X-ray observations in the energy range from 16 to 71 keV are used. The instrument is mounted in the wheel section of the *OSO 8* spacecraft with its axis offset from the (negative) spin axis by 5°. Thus, any source within 10° of this axis is scanned once every wheel rotation, or approximately once every 10 s. The calculated time of arrival of the photon at the barycenter of the solar system was determined for each detected event based on the time of detection (recorded with an accuracy of 312 ms) and the known location of the spacecraft and direction of the source. The procedure is described by Maurer (1979).

X-ray pulsar light curves were accumulated by the method of superposed epochs for each half-day of the observations for three energy ranges: 16–26, 26–41, and 41–71 keV. Observations of GX 1+4 were conducted simultaneously from *OSO 8* at lower energies (see Becker *et al.* 1976). Becker (1979) kindly provided us with a value of P near 114 s, which he obtained at an epoch close to that of our observations. In order to allow us to distinguish between this period and a period twice as long being the true rotation period of the pulsar, we multiplied Becker's value of P by a factor of 2 to obtain an initial estimate of P and binned our data modulo periods near 228 s. Values of P and $\dot{P}$ reported here are those which eliminated any phase drifts of the peaks in the light curves. Phase distributions were derived for each half-day interval and for each energy range. The phase of the peaks in each light curve was taken to be the phase of the second harmonic in the Fourier transform. A second-degree polynomial, fitted to the phases determined in this way as a function of time, was used to modify the initial values of P and $\dot{P}$ to eliminate phase drifts of the peaks in the regenerated light curves. The final set of half-day light curves

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exhibited no statistically significant phase drifts. The phase equation used to obtain the 5 day light curve shown in Figure 1 is (Manchester and Taylor 1977)

$$\phi(t) = \phi_0 + \nu_0 t + \dot{\nu} t^2/2! \,, \tag{1}$$

where $\phi(t)$ is the phase at time t, and t is expressed as the number of seconds since time t_0, arbitrarily taken as JD 2,443, 772.5 (1978 September 21.0). The coefficients of equation (1) are

$$1/P = \nu_0 = 4.3762 \pm 0.0004 \times 10^{-3}\ \mathrm{Hz}\ ,$$
$$-\dot{P}/P^2 = \dot{\nu} = 4.9 \pm 1.0 \times 10^{-12}\ \mathrm{Hz}^2\ .$$

Thus,

$$P = 228.508 \pm 0.022\ \mathrm{s}\ ,$$
$$\dot{P} = -2.55 \pm 0.52 \times 10^{-7}\ ,$$
$$\dot{P}/P = -0.035 \pm 0.007\ \mathrm{yr}^{-1}\ .$$

If GX 1+4 is spinning twice this fast, then

$$P = 114.254 \pm 0.011\ \mathrm{s}\ ,$$
$$\dot{P} = -1.27 \pm 0.26 \times 10^{-7}\ ,$$
$$\dot{P}/P = -0.035 \pm 0.007\ \mathrm{yr}^{-1}\ .$$

These results, when included in a history of GX 1+4, indicate enhanced angular acceleration in mid-1978. This will be discussed in § III.

The light curves derived from all 5 days of data (Fig. 1) were obtained using the phase equation for the period of 228.508 s. The smooth curves in Figure 1 are the result of applying a Gaussian low-pass filter, where the reduction in the amplitude of the Fourier coefficient at 0.02188 Hz (5 cycles/228.508 s) is e^{-1}. This method is justified for intrinsically smooth data under the assumption that the parent population is strongly correlated from bin to bin, with any abrupt differences being only statistical fluctuations. The nonpulsed count rate for each energy range is taken as the minimum in the smooth curve. The area above this nonpulsed count rate represents the pulsed emission.

The photon number spectrum of the pulsed component of GX 1+4 in the energy range from 16 to 71 keV is acceptably represented by a power law. The total flux of GX 1+4 was derived from the same data by Dennis *et al.* (1980). The ratio of the two spectra yields a pulsed fraction (or pulsed-to-total ratio) of 15% ± 3% at 30 keV. Comparison of this value with those previously reported at different energies (Table 1) shows that the pulsed fraction of the radiation from GX 1+4 must increase with increasing energy.

We shall call the two features in the pulsed light curves the preceding pulse (peaking about phase 0.25) and the following pulse (peaking about phase 0.75). Only one pulse occurs in the 41–71 keV light curve (at 3.6 σ significance). This single pulse is in phase with the following pulse at lower energies. This strongly suggests that the true period is 228 s and that we are

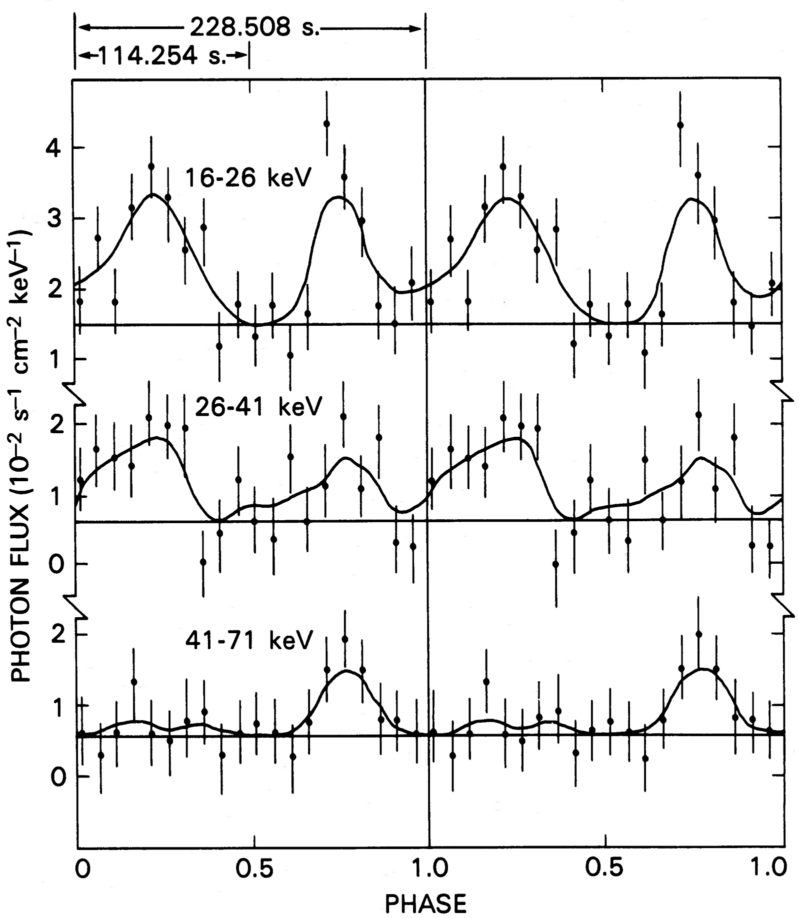

FIG. 1.—Light curves for GX 1+4 binned at a period of 228.508 s. The smooth curve is the result of applying the low-pass filter described in the text. The error bars shown for the individual phase bins are $\pm 1\ \sigma$.

TABLE 1

PULSED FRACTION OF GX 1+4

Energy (keV)	Pulsed Fraction (%)	Reference
2.5–7.5.........	10	White *et al.* 1976
2–20.........	8.7 ± 0.9[a]	Becker *et al.* 1976
	13.6 ± 0.6[b]	Becker *et al.* 1976
17–42.........	<25[c]	Ricker *et al.* 1976
16–71.........	15 ± 3	This work
20–64.........	29 ± 2	Koo and Haymes 1980
22–80.........	52 ± 8	Kendziorra *et al.* 1982

[a] High state.
[b] Low state.
[c] 2 σ upper limit.

seeing both magnetic poles of GX 1+4, with one pole having a harder spectrum (or a higher cutoff energy) than the other. This is the same conclusion previously reached by Koo and Haymes (1980) and Strickman, Johnson, and Kurfess (1980).

III. THE SPIN-UPS OF GX 1+4

We have listed in Table 2 all the reported measurements of the period P and the rate of change of the period $\dot{P}$ of GX 1+4 of which we are aware. To facilitate a direct comparison with the large number of previously published values, we shall adopt for the remainder of this paper the convention that the period of GX 1+4 is half the period P_0 found by us, i.e., $P = \frac{1}{2}P_0$. Note that then $\dot{P} = \frac{1}{2}\dot{P}_0$, but $\dot{P}/P = \dot{P}_0/P_0$. Also listed in Table 2 are inferred values of $\dot{P}$, calculated as the difference in P reported for two adjacent observations divided by the separation in time between them. Unlike the five measured values of $\dot{P}$ given in Table 2, these are *not* direct measurements made by the same instrument over a relatively short time.

The measured values of the period of GX 1+4 show a rapid decrease since 1970 (Fig. 2). A curved line representing steady

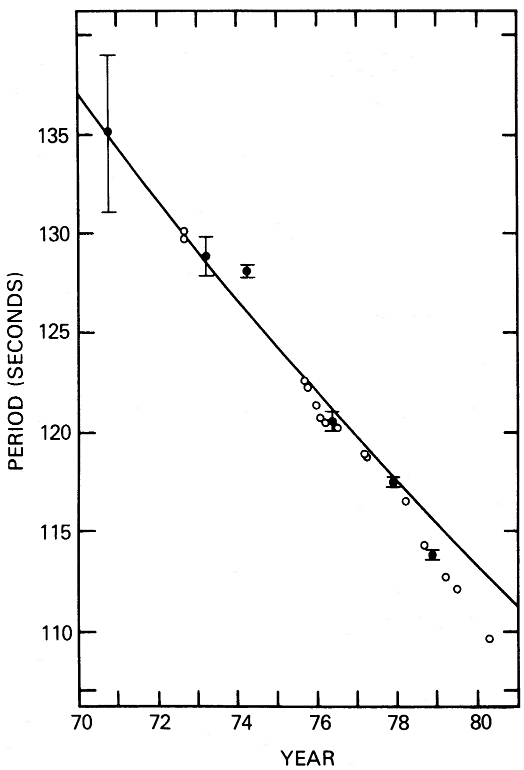

FIG. 2.—Measured values of the period of GX 1+4 plotted vs. time since the discovery of the source in 1970. The curved line represents the decreasing period expected for continuous steady accretion with $\dot{P}/P^2 = -1.55 \times 10^{-4}$ s^{-1} yr^{-1}. Error bars not shown are smaller than the size of the data points shown as open circles.

accretion (constant $\dot{P}/P^2$: Pringle and Rees 1972; Rappaport and Joss 1977) is also shown in Figure 2 to indicate the long-term trend and to delineate episodes of enhanced spin-up. The

TABLE 2

CHANGING PERIOD OF GX 1+4

Observation Date	Observation Date	Julian Date (2,440,000+)	P Half Period (s)	$\dot{P}$ Measured (s yr^{-1})	$\dot{P}$ Inferred (s yr^{-1})	Reference
1970 Oct 16............	1970.79	0875.5	$135 \pm 4.$	...	-2.61 ± 2.10	Lewin *et al.* 1971
1972 Sept 11...........	1972.70	1571.0	130.02 ± 0.06	...	-12.51 ± 7.00	White *et al.* 1976
1972 Sep 18............	1972.72	1578.0	129.78 ± 0.12	...	-1.86 ± 0.30	White *et al.* 1976
1973 Mar 25...........	1973.23	1766.5	128.82 ± 1.0	...	-2.57 ± 0.04	White *et al.* 1976
1974 Apr 2.............	1974.25	2139.9	128.1 ± 0.3	...	...	Koo and Haymes 1980
1975 Sep 16............	1975.71	2671.	122.46 ± 0.03	...	-1.81 ± 1.01	Becker *et al.* 1976
1975 Oct 7–10.........	1975.77	2695.7	122.34 ± 0.06	...	-4.58 ± 0.28	Doty *et al.* 1981
1975 Dec 15–28.......	1975.99	2773.3	121.367 ± 0.004	-9.7 ± 4.9	-6.58 ± 0.04	Doty *et al.* 1981
1976 Feb 1–6..........	1976.09	2812.6	120.6589 ± 0.0003	-3.84 ± 0.18	-1.45 ± 0.03	Doty *et al.* 1981
1976 Mar 17...........	1976.21	2854.	120.493 ± 0.003	...	-1.01 ± 0.17	Becker and White 1980
1976 May 11...........	1976.36	2909.3	120.5 ± 0.5	...	...	Strickman *et al.* 1980
1976 Jul 4..............	1976.51	2963.7	120.19 ± 0.05	...	-1.92 ± 0.07	Doty *et al.* 1981
1977 Mar 12...........	1977.19	3124.	118.873 ± 0.005	...	-1.82 ± 0.08	Becker and White 1980
1977 Apr 12............	1977.28	3245.	118.715 ± 0.005	...	-2.04 ± 0.32	Coe *et al.* 1981
1977 Nov 24...........	1977.90	3471.1	117.45 ± 0.20	...	-2.85 ± 0.66	Strickman *et al.* 1980
1978 Mar 24...........	1978.23	3594.	116.49 ± 0.1	...	-4.58 ± 0.21	Becker and White 1980
1978 Sep 21............	1978.723	3772.50	114.254 ± 0.011	-4.00 ± 0.82	-2.68 ± 1.46	This work
1978 Nov 22–24.......	1978.89	3835.	113.795 ± 0.25	...	-3.45 ± 0.85	Kendziorra *et al.* 1982
1979 Mar 19...........	1979.212	3953.0	112.7 ± 0.1	...	-2.05 ± 0.32	Becker and White 1980
1979 Jul 9..............	1979.52	4063.5	112.076 ± 0.003	-2.91 ± 0.79	-3.08 ± 0.003	Ricketts *et al.* 1982
1980 Apr 18............	1980.30	4347.5	109.668 ± 0.003	-2.52 ± 0.33	...	Ricketts *et al.* 1982

more frequent observations since late 1975 are replotted on a large scale in Figure 3*a* to permit a detailed study of the epochs of enhanced spin-up suggested by Figure 2. The measured instantaneous values of $\dot{P}$ given in Table 2 are plotted in Figure 3*b*, along with the average values of $\dot{P}$ inferred from adjacent measurements of P. The instantaneous values of $\dot{P}$ are shown as open circles with 1 σ error bars. The inferred values represent averages of $\dot{P}$ over an extended time and are shown as horizontal lines which start at the earlier measurement and extend to the later measurement. Again, 1 σ error bars in $\dot{P}$ are indicated.

At least during the event in 1976 when GX 1+4 experienced enhanced spin-up, the change in P reported by Doty, Hoffman, and Lewin (1981) was smooth on a time scale of weeks. The changing period of GX 1+4 from 1975.7 to 1976.5 measured by Doty, Hoffman, and Lewin (1981) can thus be represented by the smooth curve in Figure 3*a* drawn through their reported values of P. We assume that such a smooth variation is a common feature for other, less well measured events. Thus, $\dot{P}$ can also be assumed to be a smooth function on a similar time scale. It is further assumed that the sharp peaks in $\dot{P}$ are not delta functions, since the 1976.04 enhanced spin-up is observed to begin gradually and decay gradually.

Consider now the interval 1976.51–1977.28. At the beginning of this interval, $\dot{P}$ must have had a value of ~ -1.0 s yr^{-1}. The *average* value of $\dot{P}$ during this interval is -1.92 ± 0.07 s yr^{-1} (Table 2). Yet, at the end of this interval, a quite accurate value of $\dot{P} = -1.82 \pm 0.08$ s yr^{-1} can be derived from the observations at 1977.19 (Becker and White 1980) and at 1977.28 (Coe *et al.* 1981). Thus, by the fundamental theorem of calculus, $\dot{P}$ must have exceeded -1.92 s yr^{-1} (in magnitude) at least part of the time during 1976.5–1977.19. An enhanced spin-up is suggested at approximately 1976.9.

An attempt to reconstruct a continous function for $\dot{P}$ has been made for this interval under the following constraints: at 1976.51, $\dot{P} = -1.04$ s yr^{-1} and is decreasing; at 1977.19, $\dot{P} = -1.82$ s yr^{-1}, and $\ddot{P} \approx 0$, i.e., there is an inflection point in the plot of $\dot{P}$ versus time. $\dot{P}$ is a smoothly varying function, and the integral of $\dot{P}$ yields the same change in the period as would the integral of the average $\dot{P}$ (-1.92 s yr^{-1}). Such a smooth function for $\dot{P}$ is plotted in Figure 3*b* between 1976.51 and 1977.19. The plotted function has the minimum value of $\dot{P} = -2.48$ s yr^{-1} to satisfy the above constraints, but the actual value of $\dot{P}$ *could* have been much more negative.

During the interval 1977.28–1978.23, we are plagued with a paucity of observations and large uncertainties in $\dot{P}$. Consequently, the solution for a continuous function is not obvious. However, from 1978.23 to our measurement of $\dot{P}$ at 1978.72, there is little doubt that a large negative value of $\dot{P}$ occurred. The value of $\dot{P}$ during this interval must have been somewhere more negative than the inferred average value of -4.58 ± 0.8 s yr^{-1} for its integral to produce the value of P observed by us at 1978.723. From this consideration, we infer that another spin-up occurred at about 1978.5. Beyond 1978.72, the observations neither require nor rule out epochs of enhanced spin-up.

We summarize by noting that when the smooth $\dot{P}$ curve in Figure 3*b* is integrated numerically, a continuous function for the period P is obtained. This function is plotted in Figure 3*a* as the smooth curve which passes through all the reported values of P (except for the value at 1979 March 19).

We have discussed three epochs when $\dot{P}$ must have reached a maximum in magnitude: 1976.0, 1976.9, and 1978.5. Further

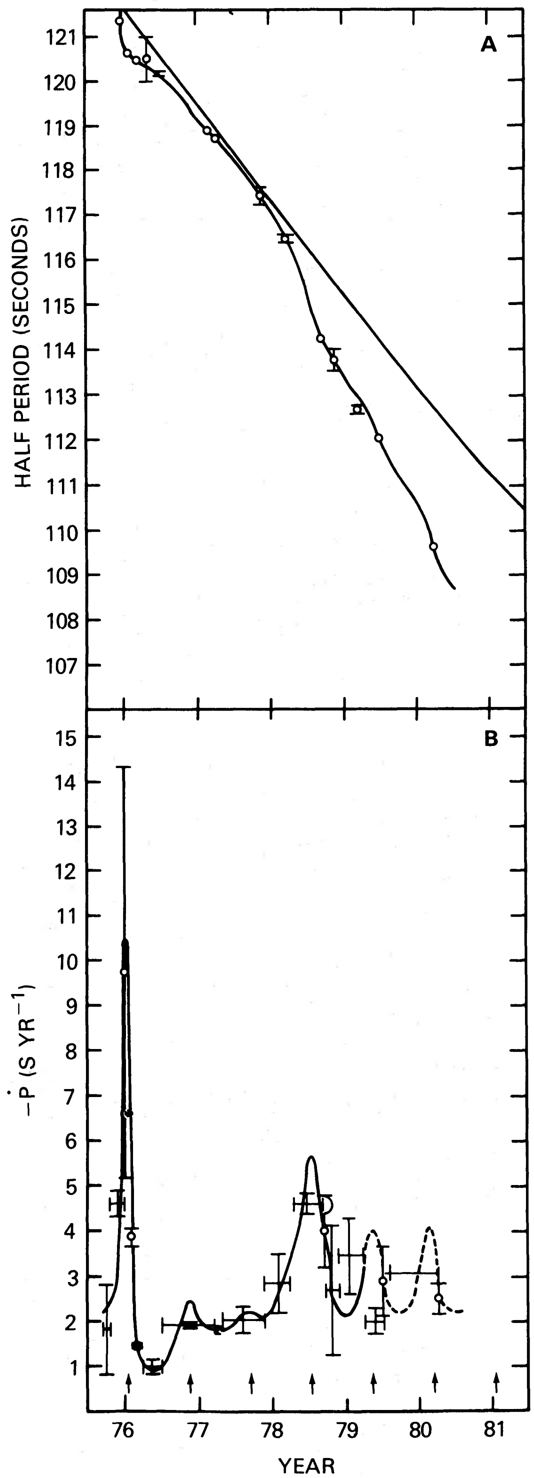

FIG. 3.—(*a*) Same data as Fig. 2 for 1975.5–1980.3. Error bars not shown are smaller than the size of the data points. The smooth curve drawn through the measured values of P is the integral of the corresponding curve through the values of $\dot{P}$ shown in (*b*). (*b*) $\dot{P}$ obtained from the data in (*a*). The measured values of $\dot{P}$ are shown as open circles with vertical ± 1 σ error bars; values of $\dot{P}$ inferred from adjacent measured values of P are shown as vertical ± 1 σ error bars with horizontal lines between the times of the P measurements. The smooth curve shown was derived according to the constraints discussed in the text. The vertical arrows at the bottom indicate the epochs of enhanced spin-up computed from the 304 day orbital ephemeris given in the text.

inspection of Table 2 suggests that $\dot{P}$ must have peaked near the time when the *Copernicus* satellite observed GX 1+4 twice in 1972 September (White *et al.* 1976). The reported values of P, obtained a week apart, permit an inferred value of $\dot{P} = -12.5 \pm 7$ s yr^{-1}. The question which occurs whenever one sees repetitive events of this type is whether there is any periodicity. We find that the following ephemeris can represent the time of occurrence T of the enhanced spin-ups:

$$T = \text{JD } 2{,}441{,}574.5 \pm 304n , \qquad (2)$$

where n is any integer. For the four events discussed above, $n = 0$, 4, 5, and 7 respectively. The epochs of enhanced spin-up which are given by this ephemeris and which occur between 1975.75 and 1981.87 are indicated in Figure 3 as vertical arrows near the bottom of the graph.

The well-defined events at 1972.7, 1976.0, and 1978.5 are separated under this ephemeris by four periods and three periods respectively. The period of 304 days cannot be longer, because no smaller integers divide these two time intervals exactly. Further, the width of the event of 1976.0 precludes the possibility that the period is $\leq 304/2$ days. Thus, 304 days is the only value for the period consistent with the available data. We propose that the enhanced spin-ups are due to the motion of a companion star about GX 1+4 in an elliptical orbit and that the period of this binary is 304 days.

IV. THE ELLIPTICAL BINARY ORBIT MODEL

An optical candidate for the companion star to GX 1+4 was first proposed by Glass and Feast (1973) and discussed further by Davidsen, Malina, and Bowyer (1976, 1977). In the latter reference, the spectral type M6 III is adopted for the star, and its distance is estimated to be 10 kpc, which places the system near the Galactic center. Davidsen *et al.* estimate a characteristic size for the gas distribution in the binary system of $d \approx 6 \times 10^{13}$ cm with a gas density $\rho_G \approx 10^9$ cm^{-3}. These authors also estimate the radius of the M6 giant to be $R_c \approx d/5 = 1.2 \times 10^{13}$ cm. They comment that if this gas is interpreted as a spherically symmetric wind with an assumed velocity of ~ 10 km s^{-1}, the implied mass loss rate is $\sim 10^{-6}\ M_\odot$ yr^{-1}. Davidsen *et al.* also state that if the orbital separation is similar to the size of the gas cloud, then a binary period of the order of years may be expected.

Doty, Hoffman, and Lewin (1981) put a lower limit of 20 days on any orbital period in the system from the lack of observed Doppler shifts in the X-ray pulses. From Figure 3 in Doty *et al.*, $a_x \sin i$ will exceed the typical radius of an M6 III star for orbital periods in excess of 120 days. If we take the mass of GX 1+4 as $M_x \approx 1.5\ M_\odot$ and the mass of the M6 giant as $M_o \approx 1.5\ M_\odot$, then the semimajor axis of a binary orbit with period $T = 304$ days is $a = 1.9 \times 10^{13}$ cm. This value depends only on the cube root of the total mass M; $da/dM = 0.2 \times 10^{13}$ cm $M_\odot{}^{-1}$ for M_x between $M_\odot$ and 3 $M_\odot$.

The eccentricity e of the orbit can be estimated if the X-ray source accretes material solely from a stellar wind, as suggested by Davidsen, Malina, and Bowyer (1977). In this case,

$$\dot{P} \propto \dot{\omega} , \quad \dot{\omega} \propto \dot{M} , \quad \text{and} \quad \dot{M} \propto r^{-2} , \qquad (3)$$

where ω is the angular rotation rate of the pulsar, $\dot{M}$ is its mass accretion rate, and r is the separation from its companion. The first relationship in equation (3) follows from the definition $\omega = 2\pi/P$, the second relationship assumes that the torque on the neutron star is proportional to the mass transfer rate, and the final relationship applies when the material is accreted from a spherically expanding stellar wind and no tidal lobe overflow occurs anywhere in the orbit. Hence, under these conditions, $\dot{P} \propto r^{-2}$. The separations at periastron and apastron in an elliptical orbit are in the ratio of $(1 - e)/(1 + e)$; hence, the ratio of the corresponding values of $\dot{P}$ should be $[(1 + e)/(1 - e)]^2$. If we take $\dot{P}$ from Figure 3*b* as -1.0 s yr^{-1} at 1976.5, when the ephemeris (eq. [2]) predicts the system is at apastron, and take $\dot{P} = -8$ s yr^{-1} at 1976.04 during the preceding periastron, then we derive $e = 0.5$. Later orbits, on the other hand, imply much smaller values of the eccentricity. We adopt $e = 0.25$ as the "best" value of the orbital eccentricity.

Davidsen, Malina, and Bowyer (1977) have inferred that the radius of the M6 giant is of the order of 1.2×10^{13} cm. Because this is more than half the value of the semimajor axis deduced above, we conclude that the inner Lagrangian point will be inside the M6 giant, at least during part of the orbit. Hence, near periastron, tidal lobe overflow would be the mechanism by which mass is transferred. Another striking feature of the curve in Figure 3*a* is that after the deviation of the period from that predicted by the steady accretion model at $\sim$1978.5, the period has never recovered to the value predicted by continuous steady accretion (Ricketts *et al.* 1982).

The elliptical binary orbit model we propose here appears to be consistent with all previous observations of P and $\dot{P}$ of GX 1+4. The specific predictions made by this model which are open to observational test are discussed in the following section.

V. DISCUSSION

We have proposed an elliptical binary orbit for GX 1+4 about an M6 giant primary with a period of 304 days an an eccentricity of $e \approx 0.25$. The combined mass of the system is approximately 3 $M_\odot$. The rotation period of the neutron star is $\sim$220 s.

This model is consistent with the variations in P and $\dot{P}$ observed in GX 1+4. It predicts that future spin-ups should occur at times given by equation (2), i.e., at 1981.03, 1981.86, 1982.69, etc. Observations of the X-ray pulse period over this time span will be extremely valuable in determining the validity of this model. It will be interesting to see whether the deviation after 1978.5 of P from the long-term trend resulting from constant accretion, as shown in Figure 3*a*, will continue. Possible explanations for this deviation include the expansion of the M6 giant primary or the circularization of the orbit by tidal friction such that more time is spent in the tidal lobe overflow mode of mass transfer.

Note added in manuscript.—After the initial submission of this paper, the paper "X-Ray Observations of GX 1+4 with the Monitor Proportional Counter on board the *Einstein Observatory*" by R. F. Elsner, M. C. Weisskopf, K. M. V. Apparao, W. Darbro, B. D. Ramsey, A. C. Williams, J. E. Grindlay, and P. G. Sutherland (*Ap. J.*, **297**, 288, 1985) came to our attention. Elsner *et al.* measured $P = 112.68 \pm 0.03$ s and $\dot{P} = -2.68 \pm 0.10$ s yr^{-1} on JD 2,443,952 ($\equiv$ 1979.21), consistent with our extrapolated curve in Figure 3*b*. Elsner *et al.* also report significant variations in shape from pulse to pulse. Although these authors detect no positive evidence in the 1–21 keV band for the $\sim$4 minute value of the pulse period (as opposed to an $\sim$2 minute value), they cannot exclude a 4 minute value based on their data. The observations we report here did not have count rates sufficiently high to allow us to analyze individual pulses with any statistical accuracy, so we cannot comment on changes in shape from pulse to pulse above 16 keV. The average light curves in our Figure 1, however, strongly support Elsner *et al.*'s interpretation that a 4 minute period of GX 1+4 requires a strong dependence on energy of the flux in the preceding pulse.

The authors thank Dr. N. E. White for several informative and constructive discussions. We also thank Dr. Robert H. Becker and Dr. White for permission to use their unpublished material. This work was sponsored in part by National Aeronautics and Space Administration grant NAS5-25631.

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