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SAS 3 OBSERVATIONS OF GX 1+4[1]

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ABSTRACT

GX 1+4 is one of the brightest celestial sources of high-energy X-rays. It is a pulsar with a period of ~ 2 minutes (perhaps a multiple of 2 minutes), decreasing at a variable rate which, since 1971, has averaged ~ 2% per year, but which can be larger than 5% per year. This is the largest rate of decrease observed for any pulsar. The rate of decrease appears to be correlated with the luminosity, in support of the idea that the period decrease is produced by accretion torques acting upon a neutron star. We see no evidence for a Doppler shift due to motion of the pulsar in a binary orbit; this is consistent with the results of optical observations which suggest that any orbital period is fairly long (months to years). We have measured the spectrum of GX 1+4 as a function of pulse phase, as well as the phase-averaged total spectrum, and the average spectrum of the pulses alone. The shape of the average pulsed spectrum suggests that the pulsations may be produced by "hot spots" which are a few hundred meters in extent, with temperatures of ~ 10^8 K ($kT \approx 8$ keV).

Subject headings: pulsars — X-rays: sources

I. HISTORY

GX 1+4 was discovered by the MIT Balloon Group in data taken on 1970 October 16 (Lewin, Ricker, and McClintock 1971). They observed variability on a time scale of minutes, and noted that the variations might be periodic with a period of ~ 2.3 minutes. The presence of periodic pulsations was confirmed by the *Copernicus* satellite (White *et al.* 1976). Pulsations have also been observed by *OSO 8* (Becker *et al.* 1976), *HEAO 1* (Doty *et al.* 1978), and an MPI/AIT balloon payload (Kendziorra *et al.* 1980). The period of 4.3 minutes reported by the *Copernicus* group (White *et al.* 1975) was perhaps an alias: the period of ~ 2.2 minutes was beyond the Nyquist frequency of the sampled X-ray data (White *et al.* 1976). An earlier analysis of *SAS 3* data (Doty 1976) yielded a period ~ 1 s too long; this error was the result of incorrectly projecting the phase of the pulsations across the gaps in our "quick-look" data.

Glass and Feast (1973) discovered a bright infrared source with a peculiar spectrum in the *Copernicus* error box for GX 1+4. The unusual nature of this object was confirmed by Davidsen, Malina, and Bowyer (1977). There is little doubt that this object is associated with GX 1+4.

II. OBSERVATIONS

The observations reported here were performed with the *SAS 3 Y*-axis detector system (Lewin *et al.* 1976; Buff *et al.* 1977). Only two of the *Y*-axis detectors were used to collect data: an argon proportional counter covering the energy range ~ 1.2–12 keV, and a xenon proportional counter covering the energy range 8–55 keV. Each counter had a sensitive area of ~ 100 cm^2 and was equipped with a collimator defining a circular field of view of ~ 1°7 FWHM.

Other detectors viewing the *Y*-axis were not used for collecting data, but were used to estimate the satellite aspect relative to X-ray sources of known position when star camera aspect data was unavailable.

We observed GX 1+4 on 1975 October 7–10 and December 25–28 and 1976 February 1–6 and July 4. The 1976 February observation was the longest (~ 5 days), and the data it yielded were of very good quality; most of the results reported here are derived from it.

All observations show strong periodic variability with a period of ~ 2 minutes. In addition, there is significant irregular, nonperiodic variability on time scales of greater than 2.8 minutes (frequencies of < 6 mHz); Fourier power spectra show noise in excess of that expected from counting statistics. There is no evidence in our data for periodic variability with periods of ~ 4 or ~ 6 minutes. The rms difference in the average shape of even and odd numbered pulses is 12 ± 4% of the rms pulse amplitude in the energy range of 8–18 keV, assuming Poisson statistics. Thus, one could argue that there exists evidence (at a 3 σ level of confidence) that the period is ~ 4 minutes. However, the observed excess (nonperiodic) noise at ~ 4 mHz ($P \sim 4.2$ minutes) is sufficient to explain this difference. Therefore, our data do not show sufficient evidence for a ~ 4 minute period. Recently reported results from an MPI/AIT balloon flight in 1978 November (Kendziorra *et al.* 1980) show that they too observe a statistically significant (~ 3.5 σ) difference between even and odd pulses. They suggest that this perhaps indicates a period of ~ 4 minutes. As mentioned above, also recognized by the MPI/AIT group, the observed differences can be the result of the irregular

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variability and do not necessarily represent a coherent pulsation with a ~ 4 minute period. One can, of course, not rule out the possibility that the period is a multiple of ~ 2 minutes, but convincing evidence for that has not been shown to date.

III. PULSE PROFILES

The average pulse profiles (light curves) of GX 1+4 in seven different energy ranges are shown in Figure 1. The horizontal line below each profile represents the measured background level. Two complete cycles are plotted for each curve. Phase 0 is arbitrary, and was chosen to be the peak of the curve (same location at all energies). These curves were derived from the data taken on 1976 February 1–6.

The most prominent feature at low energies is a sharp dip at phase ~ 0.47. At high energies, the pulse profile is dominated by the peak at phase $0 (= 1)$ and a shoulder near phase 0.8. Above 8 keV, the shape of the pulse profile is nearly independent of energy. This suggests that we may be observing emission from a region near the surface of the neutron star at these energies, unaffected by the energy-dependent absorption and scattering phenomena. The shape of the pulse profile cannot be explained by a simple model with hot spots at the magnetic poles of a neutron star with a dipolar magnetic field. The pulse profile lacks the symmetry that would be expected in that case (Rappaport and Joss 1977*a*).

IV. SPECTRA

We have estimated spectral parameters for three different kinds of energy spectra: blackbody (flux $= S_1 E^3/[\exp(E/kT) - 1]$), exponential (flux $= S_0[\exp(-E/kT]$), and power law (flux $= S_1 E^{-\alpha}$). In some of the fits, a model for absorption by cold gas was included (Brown and Gould 1970). Our coarse energy resolution does not allow us to fit the data to more complicated spectra. The overall time-averaged spectrum is fit acceptably by an exponential with $kT = 27 \pm 6$ keV, $N_H = (4.5 \pm 1) \times 10^{22}$ atoms cm^{-2}, and an energy flux of $(8 \pm 2) \times 10^{-9}$ ergs cm^{-2} s^{-1}.

We have applied the techniques of "pulse phase spectroscopy" (see Pravdo *et al.* 1977) to the data in Figure 1. These spectra are time averages for a given phase bin and therefore ignore any spectral variability associated with the observed non-periodic variability of GX 1+4. Figure 2 shows fitted spectral parameters as a function of pulse phase for an exponential spectrum, along with the (derived) total energy flux. Neither a blackbody nor a power law spectrum fits the data at any phase in the pulse profile. Fits to exponential spectra are acceptable at all phases except near the peak of the pulse profile (phase 0 and 1): here, the source spectrum is steeper at high energies than the best exponential fit. Since the fitting procedure tends to overestimate the high-energy flux near phase 0, the total energy flux at this phase is probably overestimated by this procedure. In Figure 2 we show the spectral parameters as a function of phase; the plotted error bars are 1 σ error bars based on counting statistics only; systematic errors resulting from background fluctuations, spacecraft attitude uncertainties, and calibration uncertainties produce additional uncertainties of $\pm 16\%$ in S_0, $\pm 20\%$ in kT and N_H, and $\pm 25\%$ in the total energy flux (90% confidence). The total energy flux curve closely resembles the pulse profiles for the energy channels above 8 keV. This is not surprising; photons with energies above 8 keV account for $\sim 80\%$ of the total energy flux; in addition, at lower photon energies the energy flux is less strongly modulated.

The constancy of the shape of the pulse profile for the four energy channels above 8 keV suggests that, at these energies, the process which modulates the radiation behaves in a manner which is independent of energy. An energy-independent modulation process could allow the separation of the spectrum of the modulated (pulsed) radiation and an unpulsed component. This can be useful because the total emission may be a mixture of radiation produced by different processes at different places in the system. To estimate this "pulsed" spectrum (averaged over all phases of the pulse profile) we have determined the pulse amplitude in each of the four channels of the xenon detector by cross-correlating the light curve for each channel with a template light curve. Only half of the data were added to produce the template; this guarantees that statistical fluctuations in the data will not contribute any systematic offset to our measurement of the pulsed spectrum. The template was normalized so that its average (over all phases) was zero and its rms amplitude was one. The measured amplitudes for the various energy channels were used as input for our spectral fitting procedure. This technique will yield the average spectrum of the modulated radiation even if it is not 100% modulated, as long as the modulation is independent of energy.

The absorption observed in the total spectrum is negligible above 8 keV; if we assume no absorption then only a blackbody fits the pulsed spectrum acceptably, with $kT = 8.5 \pm 1$ keV. The fact that no blackbody fits the data at any phase of the pulse profile, as mentioned earlier, does not exclude that one component of the spectrum, namely the pulsed spectrum alone, averaged over all phases, could be fitted by a blackbody. If we assume that the principal peak in the pulse profile is produced by the "uncovering" of a hot spot on the surface of the neutron star, then the area that this hot spot projects toward the Earth is $\sim 0.2\,(d/10)^2$ km^2; here, d is the distance in kpc to GX 1+4.

This interpretation must be treated with caution: the radiation transport processes near the surface must be quite complicated. We are not directly detecting radiation produced by the impact of accreting matter on the neutron star surface; this process might produce γ-rays rather than X-rays (P. Joss, private communication). Although the shapes of the light curves seen here could be produced by the geometrical modulation of the emission of hot spots (Lambertian surfaces) on a rotating sphere (Doty 1978), the modulation may involve more complicated beaming processes. For a further discussion on this see Rappaport and Joss (1977*a*) and references therein.

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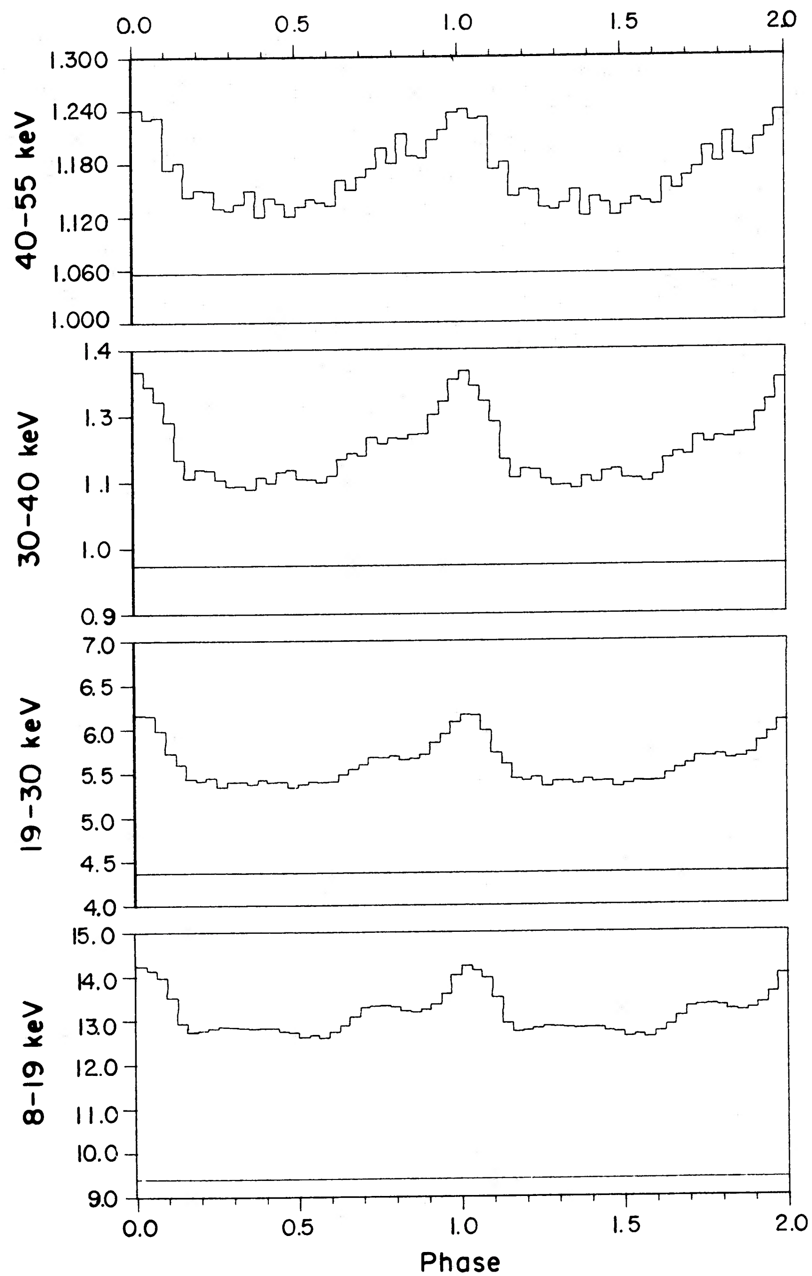

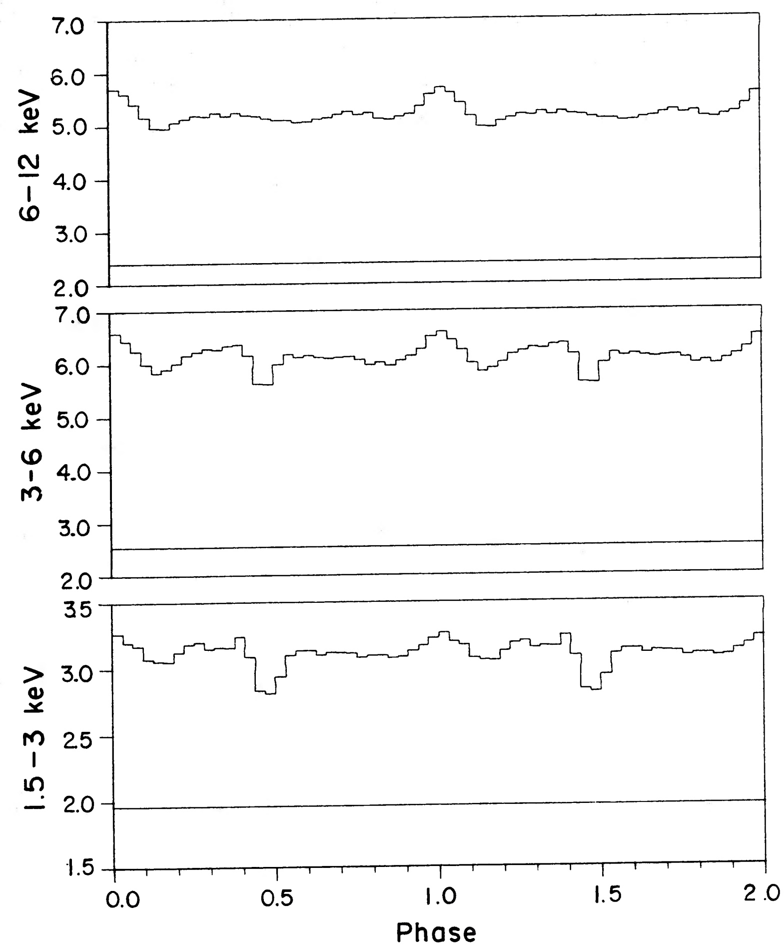

FIG. 1.—Average light curves for GX 1+4 for 7 energy channels. The vertical scale is counts per 0.8 s. The horizontal line across each plot is the background level. Each curve is plotted twice horizontally. The 1 σ errors are $\sim 1\%$ for the ranges 30–40 keV and 40–55 keV; $\sim 0.6\%$ in the range 1.5–3 keV; $\sim 0.4\%$ in the ranges 3–6 keV, 6–12 keV, and 19–30 keV, and $\sim 0.3\%$ in the range 8–19 keV.

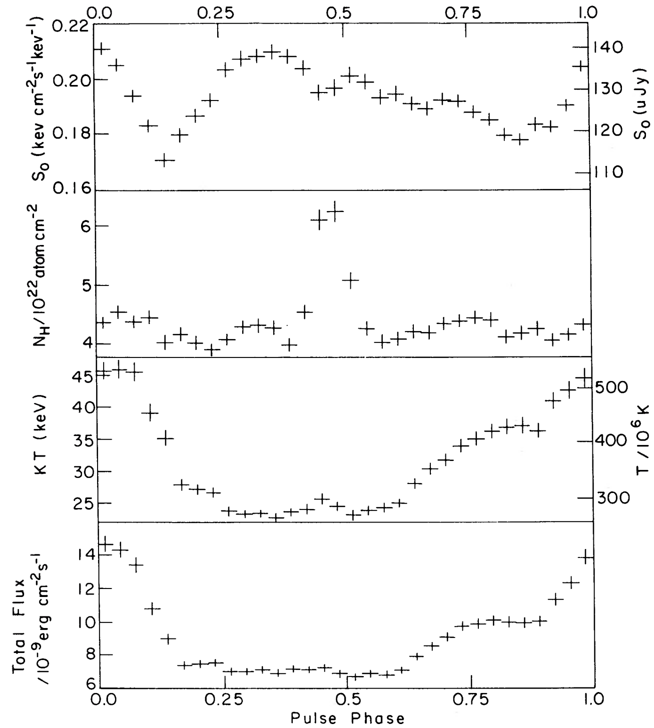

FIG. 2.—Fitted spectral parameters for GX 1+4 as a function of pulse phase. The model spectrum is an exponential: $S(E) = S_0 \exp(-E/kT)f(E, N_H)$, where the function f models absorption by cold gas. The total flux shown at the bottom has been computed by integrating the model spectrum.

If we allow a very large quantity of absorbing gas, an exponential fits the average pulsed spectrum acceptably. The best fit has $kT \approx 34 \pm 10$ keV and $N_H \approx (3.3 \pm 1) \times 10^{24}$ atoms cm^{-2}. The gas must be intrinsic to the pulsing source, as it cuts off only the average pulsed spectrum, not the unpulsed emission.

V. SPIN-UP AND ORBITAL ELEMENTS

Measurements of the phase of the pulsations as a function of time were used to determine the pulse period and its rate of change (see, e.g., Rappaport *et al.* 1976). The phase was determined by cross-correlating measured pulse profiles against a representative profile called the template. The template used was the profile from the xenon counter data of 1976 February 5. If the period is changing at a constant rate, the phase as a function of time will follow a parabola, whose coefficients may be used to find p and $\dot{p}$. The results are shown in Table 1. The periods in Table 1 have been corrected for Doppler shifts due to the motion of the Earth relative to the solar system barycenter. Error bars are 90% confidence limits.

The spin-up rate due to accretion torques on a compact object has been given by Pringle and Rees (1972), Lamb, Pethick, and Pines (1973), and Rappaport and Joss (1977*b*):

$$\frac{\dot{p}}{p} \approx -3 \times 10^{-5} f\left(\frac{p}{1\text{ s}}\right)\left(\frac{L}{10^{37}\text{ ergs s}^{-1}}\right)^{6/7} \text{yr}^{-1}\,.$$

The function f is expected to be ~ 1 for a neutron star, and ~ 0.003 for a white dwarf. Under the assumption that GX 1+4 is at a distance of ~ 10 kpc and that it emits X-rays isotropically, the total X-ray luminosity during the 1976 February observations was $\sim 5 \times 10^{37}$ ergs s^{-1}. This yields a value of ~ 2 for f, suggesting that GX 1+4 is a neutron star.

TABLE 1

SAS 3 OBSERVATIONS OF GX 1+4

Julian Date	Period p (s)		$\dot{p}/p$ (yr^{-1})		Energy Flux (10^{-9} ergs cm^{-2} s^{-1})
2,442,695.7	122.34	±0.06	...		10 ± 5
2,442,773.3	121.367	±0.004	−0.08	±0.04	22 ±10
2,442,812.6	120.6589	±0.0003	−0.0318	±0.0015	8 ± 2
2,442,963.7	120.19	±0.05	...		4.5±1

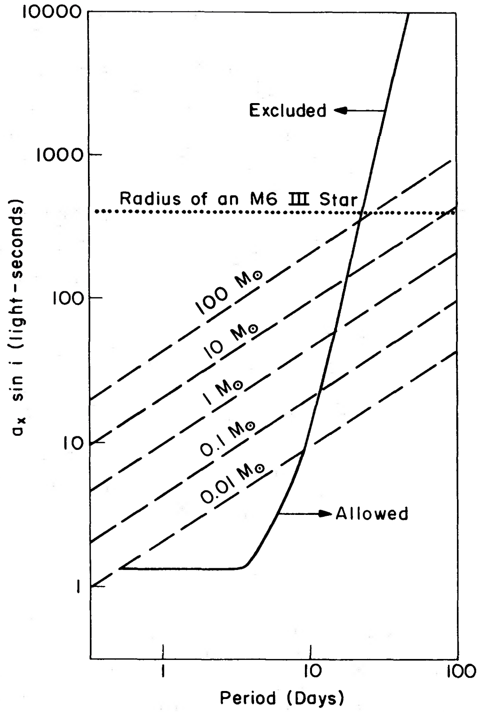

FIG. 3.—Limits for the projected semimajor axis of a hypothetical orbit of GX 1+4 as a function of the assumed orbital period. The dashed lines are loci of constant mass function.

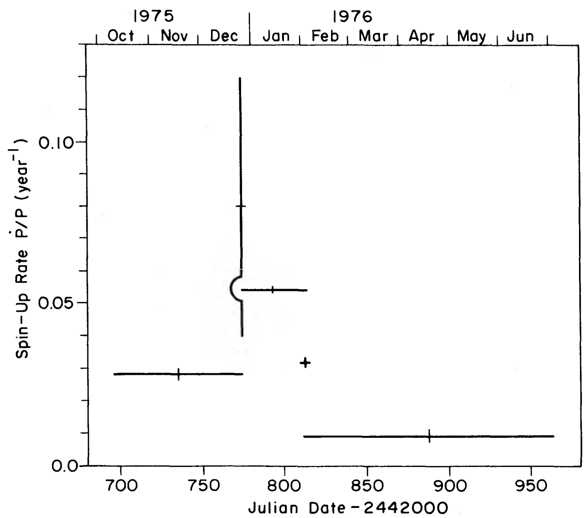

FIG. 5.—Changes in the spin-up rate of GX 1+4. The high values in early 1976 occurred when GX 1+4 was in a state of relatively high luminosity.

We have checked the pulse phases from the 1976 February observations for evidence of possible orbital motion. We have assumed that the orbit is circular, and we have performed a series of least-squares fits, each with the orbital period and $a_x \sin i$ fixed (a_x is the radius of the orbit of the neutron star and i the orbital inclination). The free parameters for these fits were the orbital phase, the pulse phase, the pulse period, and the rate of change of the pulse period. From the behavior of the best χ^2 as $a_x \sin i$ and the orbital period were varied, we deduced upper limits for $a_x \sin i$. The results are plotted in Figure 3. The solid curve is an upper limit (90% confidence) for $a_x \sin i$ as a function of orbital period. The dashed lines are lines of constant mass function, $F(M) = M^3 \sin^3 i/(M + M_x)^2$. The dotted line is the radius of a star of spectral type M6 III, which is the proposed spectral type of the optical counterpart (Davidsen *et al.* 1977). Our results are con-

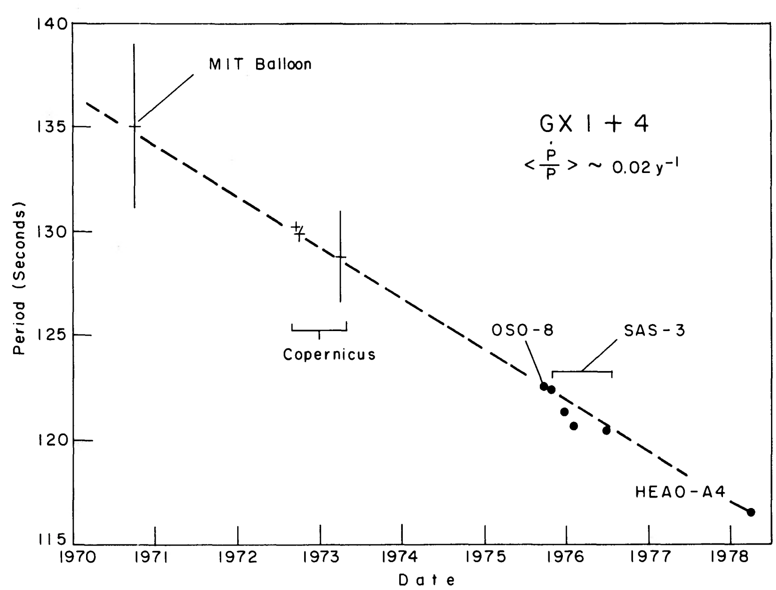

FIG. 4.—The long-term variation of the pulse period of GX 1+4. The dashed line corresponds to a decrease of 2% per year. Included are data points taken or derived from Lewin *et al.* (1971), Becker *et al.* (1976), White *et al.* (1976), and Doty *et al.* (1978). From White *et al.* we chose the alias period of 2.17 minutes.

sistent with the suggestion by Davidsen *et al.* that the orbital period may be several years.

The long term spin-up of GX 1+4 is displayed in Figure 4. The dashed line corresponds to a period change of $\sim 2\%$ per year. The period measurements of 1975 and 1976 do not follow this line exactly. If these deviations were due to an orbital Doppler shift, then the orbital velocity of the pulsar would be in excess of 750 km s^{-1}. Such a large orbital velocity yields orbital elements which are inconsistent with the limit in Figure 3 unless the orbital period is greater than 30 days. Such a combination of long orbital period and large orbital velocity requires an implausibly large mass function of $\gtrsim 10^3\ M_\odot$. We therefore believe that these deviations represent a change in the intrinsic spin-up rate (see Rappaport and Joss 1977*b*, and references therein, for a discussion of similar fluctuations in other pulsars). If we neglect the contribution of orbital Doppler shifts, we can use the data in Table 1 to calculate possible changes in the intrinsic spin-up rate. The results are shown in Figure 5. The spin-up rate appears to have peaked near the end of 1975 and then declined in early 1976. The fluxes in Table 1 show similar behavior.

It thus appears that the luminosity and the spin-up rate are correlated, as the theory reviewed by Rappaport and Joss (1977*b*) predicts.

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Note added in proof.—Recently, two groups (using data from $\sim$20 to $\sim$70 keV) have reported evidence that the true period of GX 1+4 is twice the values assumed previously [Koo and Haymes 1980, *Ap. J.* (*Letters*), **239**, L57; Strickman, Johnson, and Kurfess 1980, *Ap. J.* (*Letters*), **240**, L21]. As discussed in this paper, there is no evidence for that in our data ($\sim$2 to $\sim$55 keV). If the new period is correct, as seems likely, all periods reported by us here should be exactly doubled. Our derived values for $\dot{P}/P$ are unchanged since they are independent of the period.

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