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DISCOVERY OF A 272 SECOND PERIODIC VARIATION IN THE X-RAY SOURCE GX 304−1*

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ABSTRACT

Observations of GX 304−1 (3U 1258−61) performed with the SAS-3 satellite on 1977 February 15 revealed regular X-ray pulsations with a period of 272 s. Average pulse profiles, derived from 7 days of observation, are presented in four energy intervals covering the range 1–19 keV. The pulses are basically characterized by a single broad peak, and the amount of modulation decreases rapidly with increasing energy. The pulse arrival times are analyzed for effects of possible orbital motion of the X-ray star, and significant constraints are placed on the orbital parameters. For example, if it is established that the companion is an early-type star with $M \gtrsim 5\ M_{\odot}$, then the orbital period is likely to be greater than ∼15 days. Three 100 s flares were observed during which the source intensity rose by a factor of 4 in ∼10 s.
Subject headings: X-rays: bursts — X-rays: sources

I. INTRODUCTION

GX 304−1 (3U 1258−61) was discovered during high-energy X-ray balloon observations in 1967 October (Lewin, Clark, and Smith 1968*a*, *b;* McClintock, Ricker, and Lewin 1971). Several additional observations of this source have shown that the 1–10 keV intensity is variable by at least a factor of 20 and the 20–50 keV intensity is variable by at least a factor of 7 on a time scale of months (Ricker *et al.* 1973; Giacconi *et al.* 1974). GX 304−1 is distinguished by being a member of a class of ∼10 compact X-ray sources which have been detected at energies up to ∼50 keV. The presence of periodicities (∼1–700 s) in the intensities of four of these objects, GX 1+4, GX 301−2, A 0535+26, and Her X-1 (Rappaport and Joss 1977*a*, and references therein; Trümper *et al.* 1977) prompted us to search for a similar temporal behavior in the intensity of GX 304−1.

Observations of GX 304−1 performed with the SAS-3 satellite on 1977 February 15 revealed regular X-ray pulsations with a period of ∼272 s (McClintock *et al.* 1977). We have subsequently learned that Huckle *et al.* (1977) have also observed X-ray pulsations from a ∼30 square degree region of the sky that contains three sources, including GX 304−1. They found evidence for the existence of two periods, 260 s (or possibly 272 s) and 191 s.

II. OBSERVATIONS

Most of the data were obtained with the horizontal tube detector aboard the SAS-3 satellite (Bradt *et al.* 1976). The detector has an effective area of ∼100 cm^2 and seven energy channels from 1 to 50 keV. The detector views out along the equatorial plane of the spacecraft through a 1°.7 FWHM collimator. Supplementary data were also obtained with the right and center slat detectors whose fields of view partially overlap that of the horizontal tube detector (Buff *et al.* 1977). The data were recorded with 0.42 s time resolution.

During these observations the satellite was operated in a pointed mode so that GX 304−1 was centered in the field of view of the detectors (within 0°.3) throughout that portion of each satellite orbit (∼4000 s) when the source was not occulted by the Earth. The results presented here are based on the analysis of the quick-look data obtained during 52 satellite orbits which occurred between 1977 February 14.8–21.8 UT, and six satellite orbits which occurred between February 28.4–28.9.

III. RESULTS

A Fourier analysis of data from the first few hours of observation clearly revealed an intensity modulation with a period of 272 s. Further Fourier analyses of the data from the subsequent 7 days of observation established the presence of a stable pulse period of 272.2 ± 0.1 s. These data, obtained during 52 satellite orbits, were grouped in 16 sets of ∼3 orbits each and folded modulo the apparent pulse period in the 1–12 keV energy interval. (The 1–12 keV data provided the highest signal-to-noise ratio, despite the fact that this source was chosen for study because of its unusually hard spectrum.) The time of the pulse minimum for each of the 272 s pulse profiles was estimated to an accuracy of ±10 s. The best fit to a constant pulse period was determined from these 16 pulse arrival times to an accuracy of ∼1 part in 10^5.

The data from the first 7 days of observation were then folded modulo this apparent pulse period. The resultant pulse profiles for four energy intervals are shown in Figure 1. Their most noteworthy feature, which sets GX 304−1 apart from the other ∼10 known X-ray pulsars, is the near-absence of modulation at

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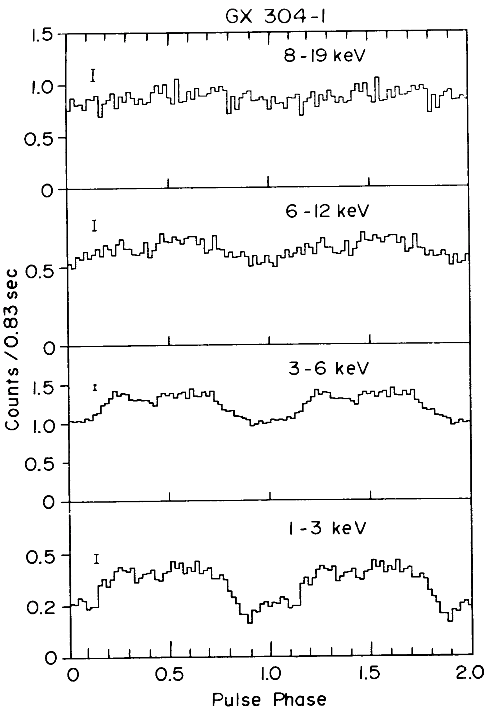

FIG. 1.—Average pulse profiles derived from data that were obtained during 1977 February 14.8–21.8 UT. The data are folded into 50 bins modulo the 272.2 s pulse period and are repeated in a second set of 50 bins. An approximate nonsource background rate, determined during Earth occultation, has been subtracted.

higher energies (>10 keV). The modulation decreases rapidly with increasing energy and is barely discernible in the 8–19 keV data. The pulse profiles are characterized by a single broad peak which has a weak secondary minimum near phase 0.4. The regular appearance of the 1–12 keV pulse profile of GX 304−1 is similar to that of 3U 0352+30 (X Per) and A1118−61 and in extreme contrast to the highly structured profiles of 3U 0900−40 and A0535+26 in this energy range (Rappaport and Joss 1977*a*).

The data shown in Figure 1 were averaged over the 272 s pulse phase, and the 3–19 keV data were fitted to a power-law photon number spectrum of the form

$$dN/dE \propto E^{-\alpha} \text{ photons cm}^{-2}\text{ s}^{-1}\text{ keV}^{-1}.$$

We find $\alpha = 1.5 \pm 0.2$, in agreement with other determinations made at these energies (Tananbaum *et al.* 1975; Huckle *et al.* 1976). The spectrum is relatively hard and there is considerable flux above 10 keV, although this flux is only weakly modulated.

An improved determination of the pulse arrival times, and hence the pulse period, was achieved by cross-correlating a composite 1–12 keV pulse profile with each of the 16 individual pulse profiles. The maximum of the cross-correlation corresponds to a fiducial point on the profile. The heliocentric pulse arrival times thus determined are listed in Table 1. The best-fit constant pulse period is $272^s.267 \pm 0^s.005$ ($2\ \sigma$), with an rms deviation between the predicted and observed arrival times of ~6 s. Two additional arrival times were determined from the observations made during February 28.4–28.9, and these are also listed in Table 1.

The pulse arrival times were analyzed for possible effects of orbital motion of the X-ray star. For each assumed trial orbital period an upper limit was set on the projected orbital radius $a_x \sin i$ (i is the orbital inclination angle). Because of the limited set of pulse arrival times, only circular orbits were tested. The analysis procedure is described in detail by Rappaport *et al.* (1976). The two data points from February 28.4–28.9 were excluded from the fit because the number of pulses in the preceding ~7 day interval could not be determined uniquely, and because effects of changes in the intrinsic pulse period may well be important during this interval (see, e.g., Rappaport and Joss 1977*b*).

The 95% confidence limits on $a_x \sin i$ as a function of orbital period are shown in Figure 2. Orbits similar to those observed for three X-ray binaries with B giant or supergiant companions (SMC X-1, 3U 0900−40, and Cen X-3 [Joss and Rappaport 1976 and references therein]) are excluded for all $i \gtrsim 15°$. A smaller amplitude orbit similar to that of Her X-1 is only marginally excluded by the data. If GX 304−1 is ultimately identified with an early-type companion star with $M \gtrsim 5\ M_\odot$, then the orbital period is likely to be greater than ~15 days.

Three ~100 s flares of emission were detected during the 58 satellite orbits. The raw counting-rate data containing two of the flares which occurred during a single satellite orbit are shown for several energy intervals in

TABLE 1

HELIOCENTRIC ARRIVAL TIMES OF THE 272 SECOND PULSES FROM GX 304−1

Observation Number	Sequential Number of the Pulse	Julian Date (2,443,100+)	Relative Uncertainty (arbitrary units)*
1	0	89.415372	1.8
2	67	89.626653	1.3
3	167	89.941814	1.2
4	872	92.163417	2.5
5	978	92.497362	2.2
6	1092	92.856702	1.6
7	1165	93.086608	1.4
8	1235	93.307293	2.5
9	1395	93.811454	1.2
10	1497	94.132844	1.3
11	1560	94.331398	2.4
12	1624	94.533237	1.3
13	1691	94.744149	1.3
14	1871	95.311494	1.4
15	2075	95.954298	1.5
16	2152	96.197018	1.4
17	4304†	102.978904	1.3
18	4364†	103.168114	2.0

* The arrival times 1 through 16 can be fitted with a constant pulse period with an rms scatter of the residuals of ~6 s. From this we conclude that one unit corresponds to a 1 σ uncertainty of ~4 s.

† The pulse number may be in error because of the ~7 day interval between observations 16 and 17.

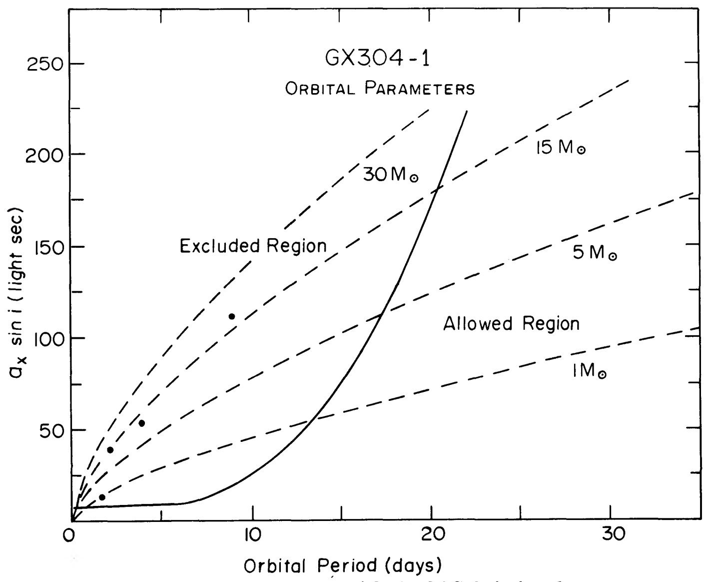

FIG. 2.—Allowed circular orbits for GX 304−1 that are consistent with the SAS-3 timing data. *Heavy curve*, upper limits (95% confidence) on $a_x \sin i$ as a function of orbital period. *Dashed curves*, contours of constant mass function $f(M)$. *Four dots*, the orbits of Her X-1 (P_{orb} = 1ᵈ70), Cen X-3 (P_{orb} = 2ᵈ08), SMC X-1 (P_{orb} = 3ᵈ89), and 3U 0900−40 (P_{orb} = 8ᵈ97).

Figure 3. (The third flare occurred 2.2 days earlier.) During the more prominent flare the source intensity rose in ∼10 s from its average level of ∼0.02 times the intensity of the Crab Nebula to a value of ∼4 times as great. The total duration of the event was ∼100 s. Note that in the 6–12 keV energy range the first flare is apparently masked by an unusually high level of source intensity. The arrows in Figure 3 mark the predicted times of minimum intensity of the 272 s pulsations, which are also discernible in the raw data. The maximum intensity of the flares occurs near pulse phase 0.2 in the 272 s pulsation.

During these observations the field of view of the horizontal tube detector (1°7 FWHM) was centered on the position of GX 304−1 to within 0°2. No other known X-ray sources were within the field of view. We used the data from the right slat and the center slat detectors as described by Hoffman *et al.* (1976) to ascertain that both the flares and the pulsing source originate within an error circle of 20′ radius centered on GX 304−1.

We note the striking similarity in appearance between these flares and the X-ray bursts discussed by Lewin (1976). A significant difference, however, is the ∼10 times longer rise time and slower decay of the GX 304−1 flares. If these flares are the result of the same type of physical process that gives rise to X-ray bursts, then strong evidence will have been provided in favor of models of burst sources involving neutron stars.[1] Additional evidence suggesting that X-ray bursts come from neutron stars has been given by Swank *et al.*

[1] We have assumed that the X-ray star in GX 304−1 is a neutron star because of its similarities to other binary X-ray systems which are believed to contain neutron stars (Rappaport and Joss 1977*b*).

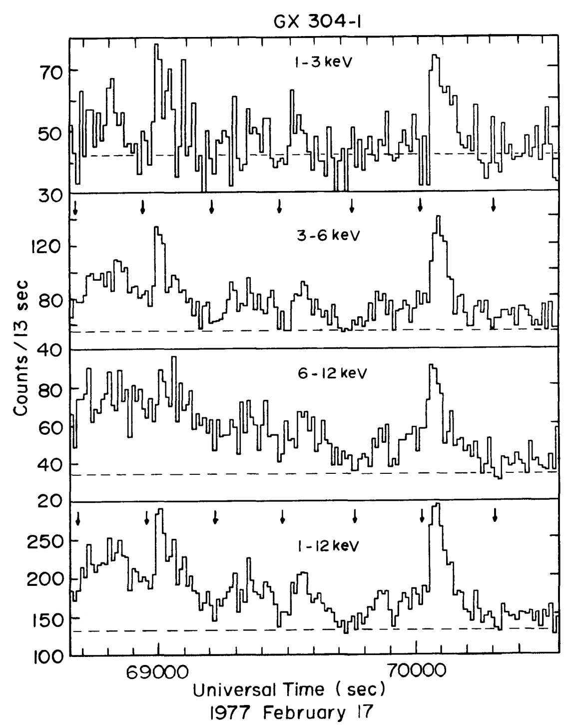

FIG. 3.—Two flares from GX 304−1 shown in several energy intervals. The approximate nonsource background counting rates are indicated by dashed lines. The 272 s pulsation is apparent in the data; the predicted times of minimum intensity are marked by arrows. Note that the peaks of the flares occur near phase 0.2 in the 272 s pulsation. The average nonflare source intensity is ∼0.02 times the intensity of the Crab Nebula (1–12 keV) and the peak flare intensity is ∼4 times as great.

1977. Flares have been observed from Cyg X-1 and LMC X-4 which have a much shorter duration than the flares we have observed from GX 304−1, although the rise times of the GX 304−1 and LMC X-4 flares appear comparable (~10 s) (Canizares and Oda 1977; Epstein *et al.* 1976).

An improved position of GX 304−1 was derived from data obtained during 1975 August 7.9–9.3 UT, with the rotating modulation collimator system on SAS-3. The modulation collimator system and techniques of data analysis are discussed by Doxsey *et al.* (1976) and Schnopper *et al.* (1976). The best position, given by Bradt *et al.* (1977), is

$$\alpha(1950) = 12^{h}58^{m}14^{s}.3\ ,$$
$$\delta(1950) = -61°20'01''\ ,$$

with a 90% confidence error radius of 1′. Mason *et al.* (1977) suggest a Be star, which is ~30″ from this position, as the optical counterpart for GX 304−1.

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REFERENCES

Bradt, H., Apparao, K., Clark, G., Dower, R., Doxsey, R., Jernigan, G., and Walter, F. 1977, in preparation; see also Bradt, H., and Apparao, K. 1977, *IAU Circ.* No. 3054.
Bradt, H., Mayer, W., Buff, J., Clark, G. W., Hearn, D., Doxsey, R., Jernigan, G., Joss, P. C., Laufer, B., Lewin, W., Li, F., Matilsky, T., McClintock, J., Primini, F., Rappaport, S., and Schnopper, H. 1976, *Ap. J.* (*Letters*), **204**, L67.
Buff, J., Jernigan, G., Laufer, B., Bradt, H., Clark, G. W., Lewin, W. H. G., Matilsky, T., Mayer, W., and Primini, F. 1977, *Ap. J.*, **212**, 768.
Canizares, C. R., and Oda, M. 1977, preprint.
Doxsey, R., Jernigan, G., Hearn, D., Bradt, H., Buff, J., Clark, G. W., Delvaille, J., Epstein, A., Joss, P. C., Matilsky, T., Mayer, W., McClintock, J., Rappaport, S., Richardson, J., and Schnopper, H. 1976, *Ap. J.* (*Letters*), **203**, L9.
Epstein, A., Delvaille, J., Helmken, H., Murray, S., Schnopper, H., Doxsey, R., and Primini, R. 1976, preprint.
Giacconi, R., Murray, S., Gursky, H., Kellogg, E., Schreier, E., Matilsky, T., Koch, D., and Tananbaum, H. 1974, *Ap. J. Suppl.*, **27**, 37.
Hoffman, J., Lewin, W., Doty, J., Hearn, D., Clark, G., Jernigan, J., and Li, F. 1976, *Ap. J.* (*Letters*), **210**, L13.
Huckle, H. E., Mason, K. O., White, N. E., Sanford, P. W., Maraschi, L., Tarenghi, M., and Tapia, G. 1977, preprint.
Joss, P. C., and Rappaport, S. 1976, *Nature*, **264**, 219.
Lewin, W. H. G. 1976, *Proc. Eighth Texas Symposium*, in press.
Lewin, W. H. G., Clark, G. W., and Smith, W. B. 1968*a*, *Ap. J.* (*Letters*), **152**, L49.
———. 1968*b*, *Nature*, **219**, 1235.
Mason, K. O., Murdin, P. G., and Visvanathan, N. 1977, *IAU Circ.* No. 3054.
McClintock, J., Li, F., Nugent, J., and Rappaport, S. 1977, *IAU Circ.* No. 3039.
McClintock, J. E., Ricker, G. R., and Lewin, W. H. G. 1971, *Ap. J.* (*Letters*), **166**, L73.
Rappaport, S., and Joss, P. C. 1977*a*, *Nature*, **266**, 123; and references therein.
———. 1977*b*, *Nature*, in press.
Rappaport, S., Joss, P. C., Bradt, H., Clark, G. W., and Jernigan, J. G. 1976, *Ap. J.* (*Letters*), **208**, L119.
Ricker, G. R., McClintock, J. E., Gerassimenko, M., and Lewin, W. H. G. 1973, *Ap. J.*, **184**, 237.
Schnopper, H. W., Delvaille, J. P., Epstein, A., Helmken, H., Murray, S. S., Clark, G., Jernigan, G., and Doxsey, R. 1976, *Ap. J.* (*Letters*), **210**, L75.
Swank, J. H., Becker, R. H., Boldt, E. A., Holt, S. S., Pravdo, S. H., and Serlemitsos, P. J. 1977, *Ap. J.* (*Letters*), **212**, L73.
Tananbaum, H. 1975, *Physics and Astrophysics of Neutron Stars and Black Holes*, (Varenna: Enrico Fermi International School.
Trümper, J., Pietsch, W., Reppin, C., Sacco, B., Kendziorra, E., and Staubert, R. 1977, *Proc. Eighth Texas Symposium*, in press.

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