THE ASTROPHYSICAL JOURNAL, 324:851–858, 1988 January 15

SAS 3 AND *EINSTEIN* OBSERVATIONS OF THE 11 MINUTE ORBITAL PERIOD OF THE GLOBULAR CLUSTER X-RAY SOURCE 4U 1820−30

EDWARD H. MORGAN AND RONALD A. REMILLARD
Center for Space Research, Massachusetts Institute of Technology

AND

MICHAEL R. GARCIA
Center for Astrophysics
Received 1987 February 12; accepted 1987 July 8

ABSTRACT

We confirm the 685 s modulation of the X-ray intensity of 4U 1820−30, a bright X-ray source in the globular cluster NGC 6624. A unique period is determined from 15 observations made with *SAS 3* during 1976 and 1977. The amplitude of the modulation (peak-to-peak) is seen to vary between 1% and 5% in the energy range of 1–6 keV, and the average modulation amplitude is 2.6%. In each case, the X-ray source was in a high-luminosity, non-bursting state, and we find no correlation between the modulation amplitude and the source luminosity. The period determined by combining the *SAS 3* epochs with those from *EXOSAT* and the *Einstein Observatory* is 685.011836(32) s. The upper limit (3 σ) on the period derivative is $-0.09 < \dot{P} < 0.18$ ms yr^{-1}, which implies $-1.3 < \dot{P}/P < 2.7 \times 10^{-7}$ yr^{-1}. This result lowers the upper limit on $\dot{P}$ by five orders of magnitude (as reported by Stella, Priedhorsky, and White in 1987) and strengthens their interpretation that the modulation represents the orbital period of the binary system. If the neutron star is accreting matter from a small degenerate helium dwarf ($M_c \approx 0.07\ M_\odot$) that is overflowing its Roche lobe, we expect $\dot{P}/P > 1.2 \times 10^{-7}$ yr^{-1}. The cause of the X-ray modulation is not uniquely determined, but comparisons with other X-ray light curves favors the partial obscuration of an extended X-ray source by a bulge in the accretion disk.

Subject headings: clusters: globular — X-rays: binaries

I. INTRODUCTION

The recent discovery of a 685 s modulation in the X-ray source 4U 1820−30 (Priedhorsky, Stella, and White 1986; Stella, Priedhorsky, and White 1987; Morgan and Remillard 1986; Garcia, Grindlay, and Burg 1986; Morgan *et al.* 1986) has been interpreted as evidence of the orbital period of the X-ray binary system. As such, it is the shortest orbital period known. The X-ray source is near the center of the globular cluster NGC 6624 (Jernigan and Clark 1979; Hertz and Grindlay 1983). Its X-ray emission is the most luminous among the globular cluster sources in the Galaxy (Bradt and McClintock 1983; Hertz and Grindlay 1983). The globular cluster X-ray sources are believed to be low-mass X-ray binaries (LMXB; i.e., a binary composed of a late-type star and an accreting neutron star or black hole). Globular cluster sources exhibit X-ray spectra, luminosities, and X-ray bursts that are all very similar to that observed in other LMXB and the fact that they are members of a globular cluster implies that the companion is a low mass star. The X-ray modulation of 4U 1820−30 provides the first evidence of an orbital period for a globular cluster X-ray source.

4U 1820−30 is one of the first sources in which X-ray bursts were detected (Grindlay *et al.* 1976; Belian, Conner, and Evans 1976). It is a burst source only when it is in the low state ($L_x \leq 2 \times 10^{37}$ ergs s^{-1}; Clark *et al.* 1977). However, the X-ray luminosity is more frequently within the range of 3–9 $\times 10^{37}$ ergs s^{-1}. The X-ray bursts signify that the accreting, compact object is a weakly magnetized neutron star (e.g., Lewin and Joss 1981).

Detached binary systems will naturally evolve toward shorter periods as angular momentum is lost through magnetic braking or gravitational radiation. Accretion occurs when the orbital separation shrinks to the point where the companion star fills its Roche lobe. However, Paczyński and Sienkiewicz (1981) and Rappaport, Joss, and Webbink (1982) show that a binary system containing a compact object and a hydrogen-rich main-sequence star cannot evolve into a system with an orbital period less than ~70 minutes. The minimum separation is reached soon after the companion star loses enough mass that its internal nuclear burning ceases. Thereafter the star becomes degenerate and its radius expands in response to mass loss; the orbital period will increase as accretion continues. If the companion star is initially hydrogen depleted, the minimum period may be as low as ~30 minutes (Nelson, Rappaport, and Joss 1986). Savonije, de Kool, and van den Heuvel (1986) show that the minimum period is as short as ~10 minutes if the companion is a helium-burning star.

The latter scenario cannot be applied directly to the case of 4U 1820−30, since the helium-burning secondary requires a young, massive progenitor which would not be available in a globular cluster. An alternate class of models is a binary system formed by capture. Verbunt (1987) has proposed that 4U 1820−30 could have been formed by a direct collision between a neutron star and a red giant. The giant's envelope would be lost as the neutron star spirals in, and the resulting short-period binary would consist of the neutron star and the giant's degenerate core. The evolution of the binary system could force the companion star to fill its Roche lobe and supply the accretion flow. Bailyn and Grindlay (1987) have proposed another collision model and tidal capture mechanism for the formation of 4U 1820−30. In this scenario a close encounter between a neutron star and a main sequence star may dissipate enough energy through tidal interaction to bind the pair. The later evolution of the companion star off the main sequence leads to a common envelope that could cause the system to evolve into a close binary. Collision models may also explain the high incidence of X-ray binaries in globular clusters, compared to the Galaxy as a whole (Clark 1975), since the space density of stars in the cores of globular clusters is so high.

The X-ray phenomenology of 4U 1820−30 also includes variability on timescales other than the 11 minute period. Observations by *EXOSAT* show that the source exhibits quasi periodic oscillations (QPO; Stella, White, and Priedhorsky 1987). Most current models of QPO behavior assume a rapidly rotating neutron star (e.g., Alpar and Shaham 1985; Boyle, Fabian, and Guilbert 1986). In addition, the source exhibited aperiodic variability on one occasion (Stella, Kahn, and Grindlay 1984), with an autocorrelation time scale of 17 s. Finally, Priedhorsky and Terrell (1984) find evidence of a 176 day X-ray period, which they attribute to the behavior of an accretion disk—via either quasi-periodic instability or precession effects. Each of these three types of X-ray phenomena has been observed in other LMXB.

II. OBSERVATIONS

Extensive pointed observations of 4U 1820−30 were made with the *SAS 3* satellite during 1975–1977, when X-ray bursts were first being investigated. In addition, 12 observations of this source were made with the *Einstein Observatory*; however, only the two observations listed in Table 1 show clear evidence of the 685 s modulation. A journal of the observations is presented in Table 1. Most of the data are taken from the horizontal tube collimator ("HTC"; Buff *et al.* 1976). The HTC provides three energy channels, roughly 1–3, 3–6, and 6–12 keV and has a circular field of view of 1°7 FWHM. In our timing analysis, we use the sum of the first two energy channels (i.e. 1–6 keV) to maximize the ratio of signal to noise. In some observations the X-ray source was not in the field of view of the HTC, and we use data from the center slat detector ("CSL"; field of view of 1° × 16° FWHM) in the energy range of 1–6 keV. Observations were also made with the *Einstein* MPC (see Grindlay *et al.* 1980 for a description of the instrument) on 1979 April 4 and 7. The MPC covers the 1–20 keV band with 8 energy channels.

All of the observation times are converted from Universal Time to heliocentric time (Landolt and Blondeau 1972) to provide a "stationary" reference frame in which coherent, short-period modulations may be measured. The search for periodic modulations is then performed in two ways. First, we compute power density spectra from the fast Fourier transforms (FFT) of detrended data for each observation. Second, we also search for periodicities by computing a χ^2 fit using a sine-cosine series in ω, 2ω, 3ω, etc., for a wide range of the trial frequencies (ω). The second method is used extensively when we combine the observations listed in Table 1.

The observations were frequently interrupted by Earth occultations and by the satellite's passage through the South Atlantic anomaly. In addition, some early observations were planned with an alternating sequence of pointing targets. The raw data contain very significant, low-frequency variations (10%–100%) due to changes in the source intensity and instrumental transmission, since there were drifts and oscillations in the pointing orientation of the satellite. A standard procedure for computing FFTs is to fill the data gaps with the mean value of the intensity. This will cause distortions in the power density spectrum. In order to detect the small-amplitude modulations of 4U 1820−30, we remove all variability with time scales longer than 1 hr. In an observation of length T_{obs} this "detrending" procedure is accomplished by subtracting an N-term Fourier fit from the raw data, excluding gaps, where $N = 2T_{obs}/(1 \text{ hr})$, and the lowest frequency term is $1/(2T_{obs})$. The longer observations were broken into segments lasting no more than 30 hr, to minimize the number of Fourier terms needed to properly model the long-term variability.

The X-ray spectral parameters of the source are obtained from the three HTC energy channels and also two channels of the xenon tube collimator ("XTC"; 1°7 FWHM; 8–18 and 18–27 keV). The counting rates in the five energy channels are fit by a spectral model assuming optically thin, thermal emission with absorption by cold matter along the line of sight. Specifically the assumed photon number spectrum is

$$\frac{dN}{dE} = N_0 e^{-N_{\rm H}\sigma(E)} e^{-E/kT} E^{-1} . \quad (1)$$

The free parameters are the normalization (N_0), the column density ($N_{\rm H}$) and the temperature (T), while $\sigma(E)$ is the cross section for absorption given by Brown and Gould (1970). Since the CSL observations provide only a single energy channel below 6 keV, we fix the column density at a value consistent with that implied by measurements at 21 cm ($\sim 2 \times 10^{21}$ cm^{-2}; Haberl *et al.* 1987). The data from the eight MPC channels of the *Einstein Observatory* were fitted to this same spectrum.

III. RESULTS

a) Determination of the X-ray Period

We detect the 685 s X-ray periodicity in the Fourier transforms of detrended data from 15 of the 20 *SAS 3* observations (see Table 1). The data are binned in 13.3 s time intervals. The significance of any given term in the Fourier transform is obtained from an evaluation of the expectation value, $Ne^{-P'/\langle P\rangle}$. This indicates the statistical (i.e., chance) probability of detecting any power spectrum value as large as P', where $\langle P\rangle$ is the mean value in a power spectrum and N is the number of Fourier terms examined. The observed values of $P'/\langle P\rangle$ are presented in the fifth column of Table 1. The most significant individual detection is in 1977 February, where $P'/\langle P\rangle = 28.7$, while five of the observations (observations 1, 2, 6, 9, and 10 in Table 1) show $P'/\langle P\rangle < 3.0$. All of the 15 detections are consistent with a period of 685 ± 2 s.

In the sixth column of Table 1 we present the period obtained by combining observations taken within a 14 day interval. The results are consistent with a single modulation period that is changing by less than 0.5 s yr^{-1}. We test the coherence of these modulations by computing the minimum χ^2 values, as a function of trial period, for a single sinusoidal fit to all of the 15 detrended data sets that exhibit the 685 s modulation. The χ^2 minima are shown in Figure 1. All of the χ^2 dips in this figure represent aliases of the true period. Only the deepest χ^2 minimum represents a period that produces a consistent phase for every detected modulation. This unique period is 685.0124 (5) s.

The χ^2 values (29,870 degrees of freedom) are systematically inflated by changes in the modulation amplitude in the detrended data. This is due to variations in both the collimator transmission and the percentage modulation of the source itself (see Table 1). Therefore, we are unable to strictly interpret the significances of the χ^2 minima or compare different minima by applying a F-test. The error bar in Figure 1 is an empirical

TABLE 1

OBSERVATIONS OF 4U 1820−30

Observation Number	Date (UT)	Length[a] (hr: minutes)	Detector	$\frac{P'}{\langle P \rangle}$	Period (s)	X-Ray Modulation[b]: Amplitude (%)	X-Ray Modulation[b]: Epoch (JD-2440000)	Average X-Ray Spectrum[c]: Luminosity (10^{37} erg/s)	Average X-Ray Spectrum[c]: Temp (keV)	Average X-Ray Spectrum[c]: N_H 10^{21}
1.........	1975 Sep 17.3	6:21	ALL	0.9	...	0.3 ± 1.0	...	1.5 ± 0.3	1.3 ± 2.0	0.0 ± 2.3
2.........	1976 Jan 23.8	14:57	HTC	1.4		1.5 ± 0.7	...	5.6 ± 0.4	6.1 ± 0.5	3.3 ± 2.1
3.........	1976 Jan 24.5	28:23	HTC	9.9	684.8 ± 0.2	2.8 ± 0.4	2802.56568(46)	6.5 ± 0.7	6.9 ± 0.5	8.4 ± 2.2
4.........	1976 Jan 25.7	25:11	HTC	25.8		2.6 ± 0.3	2803.72229(44)	7.0 ± 0.5	7.0 ± 0.4	8.9 ± 1.9
5.........	1976 Jan 28.8	12:58	CSL	14.5		2.2 ± 0.4	2806.63996(47)	8.0 ± 0.5	8.7 ± 0.5	...
6.........	1976 Mar 27.5	10:09	HTC	1.5		1.1 ± 0.5	...	4.1 ± 0.2	6.2 ± 0.5	0.8 ± 2.6
7.........	1976 Mar 29.2	8:32	HTC	6.1		3.3 ± 0.8	2866.91922(83)	5.6 ± 0.6	9.2 ± 1.3	0.6 ± 2.8
8.........	1976 Mar 29.9	14:57	HTC	3.1		3.5 ± 1.0	2867.66509(48)	5.0 ± 0.8	6.0 ± 1.2	1.7 ± 4.2
9.........	1976 Mar 30.5	2:55	HTC	0.3		2.4 ± 1.0	...	4.8 ± 0.3	7.2 ± 0.7	2.8 ± 2.5
10.........	1976 Apr 1.2	9:57	HTC	1.7	685.05 ± 0.1	1.4 ± 0.8	...	5.3 ± 0.6	6.8 ± 0.6	5.4 ± 2.3
11.........	1976 Apr 4.4	6:43	CSL	5.7		2.3 ± 0.7	2873.05520(48)	6.0 ± 0.5	6.5 ± 0.4	...
12.........	1976 Apr 6.0	15:35	CSL	3.6		2.2 ± 0.6	2874.90424(30)	4.3 ± 0.2	5.4 ± 0.4	...
13.........	1976 Apr 7.0	19:01	CSL	8.4		2.0 ± 0.4	2876.00545(48)	5.5 ± 0.4	5.9 ± 0.4	...
14.........	1976 Apr 7.9	18:15	HTC	20.0		2.9 ± 0.4	2876.80663(40)	4.7 ± 0.4	6.9 ± 0.6	0.2 ± 2.3
15.........	1976 Apr 8.7	22:14	CSL	6.2		1.5 ± 0.4	2877.65519(38)	5.0 ± 0.4	6.3 ± 0.4	...
16.........	1976 Aug 27.7	23:16	HTC	18.2	684.9 ± 1.1	2.6 ± 0.4	3018.63737(36)	5.2 ± 0.3	7.3 ± 0.6	2.7 ± 2.3
17.........	1976 Sep 27.9	23:26	HTC	26.0	685.0 ± 0.4	4.4 ± 0.4	3049.89878(26)	3.8 ± 0.3	7.0 ± 0.8	0.0 ± 3.2
18.........	1976 Oct 1.2	16:20	HTC	8.5		2.9 ± 0.5	3053.03834(67)	3.0 ± 0.2	5.7 ± 0.8	0.0 ± 3.3
19.........	1977 Feb 2	18:06	HTC	28.7	685.2 ± 1.7	3.0 ± 0.4	3196.93086(40)	3.7 ± 0.3	6.5 ± 0.8	0.0 ± 3.0
20.........	1977 Sep 19.5	5.38	HTC	13.2	683.0 ± 3.5	4.7 ± 0.6	3406.10546(27)	3.5 ± 0.2	6.3 ± 0.8	0.0 ± 3.0
21.........	1979 Apr 4.7	4:51	MPC	...	684.9 ± 0.12	3.0 ± 0.4	...	3.1 ± 0.1	6.3 ± 0.4	0.0 ± 1.0
22.........	1979 Apr 7.5	4:49	MPC	14.2		4.5 ± 0.5	3969.202446(48)	2.9 ± 0.1	6.4 ± 0.4	0.0 ± 0.9

[a] The actual exposure times are ~50% of the indicated observation lengths.

[b] The peak-to-peak amplitudes and epochs were calculated assuming a period of 685.011836 s.

[c] The spectrum was fitted by a thermal bremsstrahlung model of the form

$$\frac{dN}{dE} = N_0 e^{-N_H \sigma(E)} e^{-E/kT} E^{-1} .$$

The CSL observations do not provide sufficient spectral resolution at low energy, so we have assumed an N_H of 2×10^{21} cm^{-2}. The quoted luminosities are for the energy range of 1–25 keV and assume a distance of 6.4 kpc.

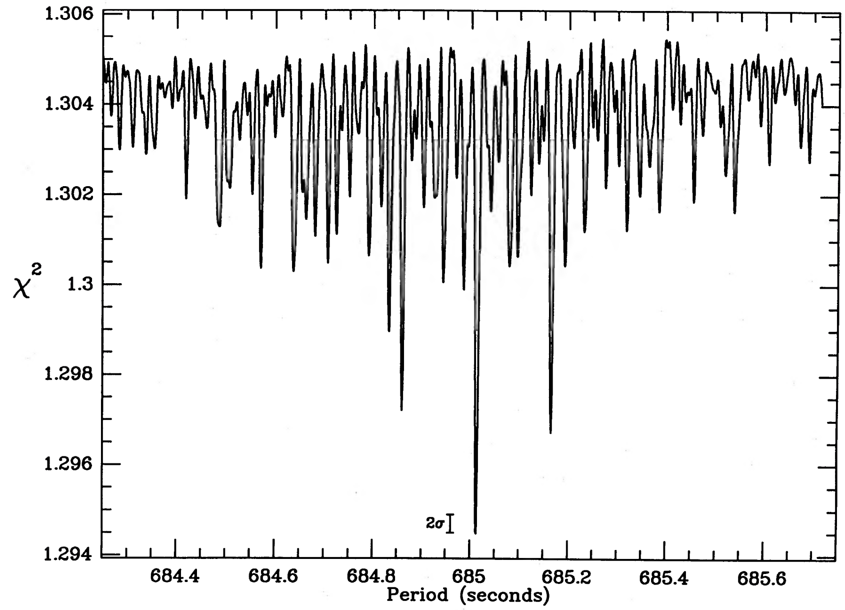

FIG. 1.—The minimum, reduced χ^2 values for a model consisting of a sinusoidal modulation plus a constant, plotted as a function of the trial period (29,870 degrees of freedom). The deepest minimum is at 685.0124(5) s, and this is the only period that accounts for a consistent modulation phase for all of the *SAS 3* observations. The minima are fully resolved, despite their narrow appearance on the plot.

estimate from the examination of the χ^2 variations over a large range of trial frequencies that are well separated from the complex alias pattern that dominates the plotted results.

The epochs given in Table 1 were calculated by fitting the smoothed data, folded about the period 685.0124 s, to a template. The template consisted of the fundamental and first two harmonics of the best χ^2 fit for the entire *SAS 3* data set. The errors in the phases were calculated by varying the phase of the template until χ^2 increased by an amount equivalent to a 2 σ fluctuation, as determined by the empirical estimate described in the preceding paragraph. The epoch and error of the *Einstein* observation were calculated in a similar way with a single sinusoid template.

The *EXOSAT* observations (Stella, Priedhorsky, and White 1987) that provided the original discovery of the 685 s period were not sufficient to determine a period with uncertainty less than 2 s. However, the result obtained with *SAS 3* and *Einstein* can be uniquely combined with the phases of the four *EXOSAT* light curves, thereby enlarging the observation baseline to 9.7 yr. Combining all of the heliocentric epochs of the modulation maxima, *we derive a refined period of 685.011836* (*32*) s, a departure of only 1.1 σ from the result determined from *SAS 3* data alone. In Figure 2 we plot the phase of maximum intensity (assuming the refined period) for each observation by *SAS 3*, *Einstein*, and *EXOSAT*. The phase alignment clearly indicates the coherence of the modulations. There is no evidence of curvature in Figure 2, which would represent a time derivative of the period. By fitting a parabolic

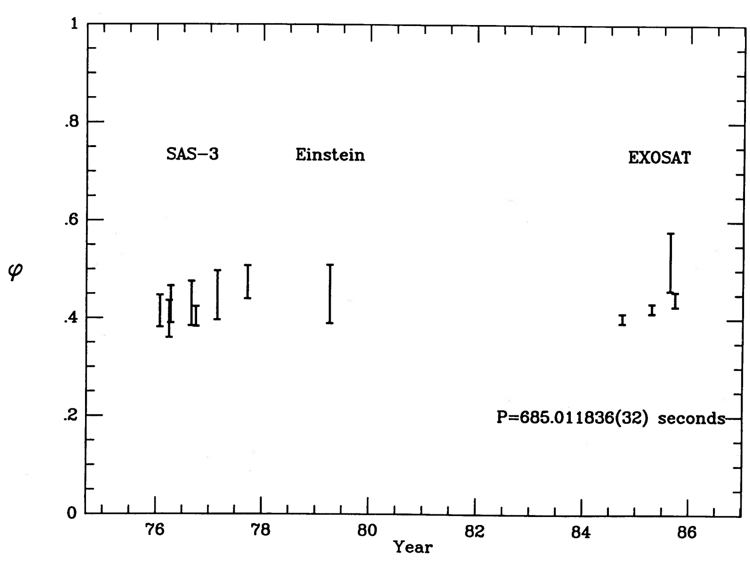

FIG. 2.—The phases of the maximum intensity for each of the observations that contain the 685 s X-ray modulation, assuming a period of 685.011836 s. The *SAS 3* data were grouped together when the observations were made within 1 wk. A constant $\dot{P}/P$ is a parabolic curve on this plot.

curve to these phase measurements, we find upper limits of $-0.09 < \dot{P} < 0.18$ ms yr^{-1} with a confidence level of 3 σ.

b) Folded Light Curves and Correlations

We investigated the energy dependence of the X-ray modulation for the 10 observations in which the modulation was detected by the HTC. The detrended data from the three HTC energy channels were folded separately at the period of 685.011836 s, and the results are shown in Figure 3. The X-ray modulation is seen to be independent of photon energy, in agreement with the results of Stella, Priedhorsky, and White (1987). In the energy range of 1–3 keV (HTC channel "A") the average modulation amplitude (peak-to-peak, percentage of the mean intensity is 2.14% $\pm$ 0.15%, while the same quantity is 1.86% $\pm$ 0.16% in the energy range of 3–6 keV (HTC channel "B") and 2.37% $\pm$ 0.44% in the range of 6–12 keV (HTC channel "C"). In addition, the *Einstein* observations show no evidence for spectral variation over the phase of the modulation (Garcia 1987).

There is no simple relation between the amplitude of the modulation and the intensity of the X-ray emission. The X-ray modulation is not detected during the single observation (observation 1) in which the source luminosity was less than 2.5×10^{37} ergs s^{-1}. However, the average modulation of 2.6%

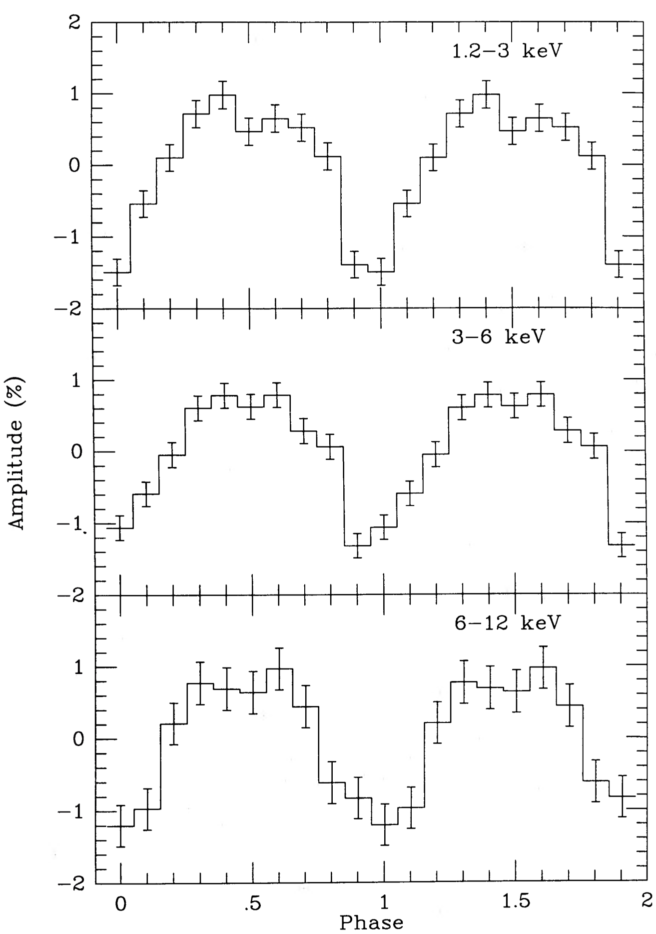

FIG. 3.—The folded light curves from *SAS 3* are shown in three separate energy channels of the HTC detector. The data consist of 10 detrended, HTC observations that exhibit the 685 s modulation. The results are consistent with an energy-independent modulation.

would have been detected. For the observations of 4U 1820−30 at higher luminosity, we tested the correlation between the modulation amplitude (%) and the source luminosity by calculating the linear correlation coefficient. The value of 0.322 for 17 degrees of freedom indicates that these quantities are not correlated; there is a 71% chance that any random sample would produce this result. We have also searched for correlations between the modulation amplitude and both the source temperature and column density; no such correlations were found.

c) X-Ray Variations on Short Time Scales

The *SAS 3* observations were subdivided into intervals of 4 and 8 hrs, and the subdivisions were individually folded at the X-ray period to test whether the modulation amplitude changes at this time scale. We find no evidence for rapid variations in the modulation amplitude. The shortest time scale for a significant change in the modulation amplitude of 4U 1820−30, as seen by *SAS 3*, occurs between observations 16 and 17, where the amplitude increases by 1.80% $\pm$ 0.56% during an interval of 30 days.

The detrended data were also analyzed for aperiodic variability. We calculated the variances at bin sizes of 13.3, 26.6, and 133.0 s for each observation. We also computed autocorrelation functions and conducted a more detailed search for excess variance at timescales between 0.42 s and 10 minute for the three observations in which the source count rate was highest (observations 5, 16, and 18 in Table 1). None of the results indicates source flickering at these short time scales. The upper limits for continual, rapid variability (3 σ; rms values) are 3.2% of the source flux at a time scale of 2.5 s and 1.6% at 13.3 s. Observations of 4U 1820−30 with the MPC detector of the *Einstein Observatory* by Stella, Kahn, and Grindlay (1984) show 3–10 keV flickering with an rms amplitude 4% at 2.56 s bin size and an autocorrelation time scale of 17 s. Since the latter results are within the detection threshold of the *SAS 3* observations with the highest count rates, we conclude that the rapid variations at the level seen in the MPC observations are not a persistent feature in the X-ray emission of 4U 1820−30.

Finally, for each HTC observation we computed an X-ray hardness ratio, using the energy channels with sensitivities in the range of 3–6 and 1–3 keV. The hardness ratio was plotted with a time resolution of 13.3 s to search for significant peaks that are characteristic of absorption events. Cominsky, Simmons, and Bowyer (1985) detected an absorption event in 1977 September during a single scan of 4U 1820−30 with the low energy detectors of the *HEAO 1* A-2 experiment. However, there were no absorption events during 121 hr of exposure time with the HTC detector of *SAS 3*. A reduction by a factor of 2 in the 1–3 keV band, as seen by Cominsky *et al.*, would have been detected in the HTC hardness ratio as a 4.5 σ event in a single 13.3 s data point.

IV. DISCUSSION

a) The Interpretation of P and $\dot{P}$

Our upper limit on $-1.3 < \dot{P}/P < 2.7 \times 10^{-7}$ yr^{-1} rules out the possibility that the modulation represents the rotation period of the neutron star. The average X-ray luminosity of 5×10^{37} ergs s^{-1} requires a mass accretion rate of at least 8.5×10^{-9} $M_{\odot}$ yr^{-1} which is obtained if the neutron star (1.4 $M_{\odot}$, 10 km radius) converts one-half of the available gravitational potential energy of the infalling matter into X-ray emission. If mass transfer occurs via Roche lobe overflow, then this rate of accretion onto a neutron star would cause a rotation period to change at a rate that is five orders of magnitude larger than our upper limit (Joss and Rappaport 1984). If mass transfer occurs via a stellar wind, the changes in the rotation period of the neutron star will depend on the wind structure and velocity. Massive X-ray binaries such as 4U 0900−40 have exhibited both spin-up and spin-down episodes attributed to the accretion of an inhomogeneous, high-velocity stellar wind (Nagase *et al.* 1981). The additional number of phase measures provided by *SAS 3* reduces the possibility that random spin changes occur in the case of 4U 1820−30 (see Fig. 2). Furthermore, Stella, Priedhorsky, and White (1987) argue that there is no basis for hypothesizing accretion via a high-velocity, inhomogeneous wind in the case of 4U 1820−30. The location in a globular cluster restricts the companion star to late spectral types, and the only late-type stars producing substantial stellar winds are Mira variables. Since the wind velocity from these stars would be less than the orbital velocity of the neutron star, even if the binary separation were several hundred solar radii, accretion from a low-velocity wind would cause large, monotonic changes in the rotation period the neutron star. The conclusion of Stella, Priedhorsky, and White, that the X-ray modulation of 4U 1820−30 represents the orbital period of the binary system, is supported by the highly restrictive limits on $\dot{P}$ obtained from *SAS 3*.

If we assume Roche lobe overflow, then the radius of the secondary (R_2) must be equal to the mean radius of the Roche lobe (R_L) given by Kopal (1959),

$$R_L \approx \frac{2a}{3^{4/3}}(1+q)^{-1/3}\,, \tag{2}$$

where q is the ratio of the mass of the neutron star to the mass of the secondary (M_2), and a is the separation between the two stars. If we combine this with Kepler's third law and a mass-radius relation of the form $R_2 = \alpha M_2{}^{\beta}$, we deduce the orbital period in terms of the mass of the secondary,

$$P_{\rm orb} = \frac{9\pi}{(2G)^{1/2}}\alpha^{3/2}M_2{}^{(3\beta-1)/2} = 3.19\times 10^4\alpha^{3/2}\left(\frac{M_2}{M_\odot}\right)^{(3\beta-1)/2}\ {\rm s}\,. \tag{3}$$

For a completely degenerate white dwarf supported by Fermi pressure, $\beta = -\frac{1}{3}$. If the star is composed of helium and/or carbon/oxygen, then $\alpha = 0.0126$ (solar units; Chandrasekhar 1939). In the case of 4U 1820−30, the period of 685 s implies $M_2 = 0.07\ M_\odot$ and $R_2 = 0.03\ R_\odot$. This mass is sufficiently low that Coulomb interactions begin to become important as a secondary source of internal pressure, forcing a modification of the mass/radius relation (Zapolsky and Salpeter 1969). Calculations of Zapolsky and Salpeter models by Vila (1971) show that in the mass range $\sim 0.07\ M_\odot$ in the case of a zero temperature star, $\beta = -0.26$ and $\alpha = 0.0137$. These parameters yield a slightly lower value for M_2 of $0.06\ M_\odot$. For a star with nonzero temperature, the radius will be larger than that of a Zapolsky and Salpeter model.

The change in the period may be expressed in terms of the mass loss by taking the time derivative of equation (3),

$$\frac{\dot{P}_{\rm orb}}{P_{\rm orb}} = \frac{3\beta-1}{2}\frac{\dot{M}_2}{M_2}\,. \tag{4}$$

There are two estimates of $\dot{M}_2$ that are of interest in the evaluation of the observed limit on $\dot{P}/P$. The first is the lower limit for the accretion rate, based on the observed X-ray luminosity, described in the first paragraph of this section. This value of $\dot{M}_2$ ($8.5\times10^{-9}\ M_\odot\ {\rm yr}^{-1}$) may be combined with equations (3) and (4) to give a lower limit on the expected change in the orbital period:

$$\frac{\dot{P}_{\rm orb}}{P_{\rm orb}} \geq 1.2\times10^{-7}\left(\frac{M_2}{0.07\ M_\odot}\right)^{-1}\ {\rm yr}^{-1}\,. \tag{5}$$

This limit, which assumes no significant mass loss from the binary system ($\dot{M}_1 = -\dot{M}_2$), is only slightly below our observational 3 σ upper limit. Since the period change is the second derivative of the phase measurements, the upper limit will scale as the time baseline squared. Thus, we expect that X-ray measurements of 4U 1820−30 by *Ginga* in 1987 will detect the rate of change in the orbital period.

Second, theoretical calculations for the evolution of binary systems *predict* $\dot{M}_2$ if the angular momentum losses are due to gravitational radiation and if the internal state of the secondary star can be specified precisely (Rappaport, Joss, and Webbink 1982). The latter depends on the star's mass, composition, the degree of degeneracy (related to α, β above), and the capure efficiency for mass lost from the secondary. Thus, the measurement of $\dot{P}$ may eventually serve as a diagnostic of the internal conditions of the secondary star in the case of 4U 1820−30. Rappaport *et al.* (1987) discuss the present evolutionary status of 4U 1820−30 and the observational constraints that are placed on the physical parameters of the binary system.

b) *The Nature of the X-Ray Modulation*

The folded X-ray light curves appear energy-independent, and the variations occupy a broad range in the orbital phase. These same characteristics are qualitatively exhibited in the X-ray light curves of several other LMXB, although a variety of physical conditions are invoked to explain their periodic behavior. We discuss two scenarios by which broad, energy-independent modulations in the X-ray light curve of 4U 1820−30 may be produced: (1) an extended X-ray source may be partially obscured by an optically thick bulge in the accretion disk, or (2) a pointlike X-ray source may appear diminished due to electron scattering when viewed through an ionized bulge in the accretion disk. While both are possible, further comparisons favor the former choice.

Observations of 4U 1822−37, 4U 2129−47 and Cyg X-3 show periodic X-ray modulations that have been interpreted as partial eclipses of a spatially extended X-ray source (White *et al.* 1981; McClintock *et al.* 1982; Molnar 1985). These studies conclude that the extended appearance is due to scattering in an ionized corona that surrounds the accretion disk. The partial eclipses have been explained as the obscuration of a portion of the extended X-ray source by either the companion star or a bulge in the accretion disk that remains stationary with respect to the binary stars. In the case of 4U 1822−37, there are two adjacent partial eclipses per orbital cycle, and the broader dip that occurs before the inferior conjunction of the companion star is attributed to a bulge in the accretion disk (White and Holt 1982). The orbital phase of the broad dip is consistent with the hypothesis that the bulge occurs at the impact zone between the accretion stream and the edge of the accretion disk.

There are other LMXB, e.g., 4U 1755−33, MXB 1659−29, 4U 1915−05, and EXO 0748−676, that display periodic variations with an assortment of *sharp* features, such as eclipses or short–time scale dips that are attributed to the passage of material along the line of sight (Parmar *et al.* 1985; Cominsky and Wood 1984; Walter *et al.* 1982; Parmar *et al.* 1986). The periodicity in the X-ray light curve may again be caused by blobs or filaments associated with the accretion stream or a bulge in the accretion disk. For example, the X-ray light curves of EXO 0748−676 appear to be a point-source version of 4U 1822−37 (Parmar *et al.* 1986). The X-ray dips are observed within a broad envelope that precedes a brief, total eclipse presumed to be caused by the companion star; however, the short time scales of the events imply that the X-ray emitting region must be very small compared to the companion star or an accretion disk bulge.

The absence of X-ray spectral variation during intensity dips conveys important information about the conditions of the intervening material. Photoionization will cause the spectrum to "harden," i.e., the dip will be greater at lower X-ray energies. However, the X-ray dips may be observed without spectral hardening if the obscuring material has a very high ionization temperature or if the gas is moderately ionized and the abundances are severely metal deficient (e.g., Parmar *et al.* 1985).

Compared to these other X-ray binaries, 4U 1820−30 is extremely compact and very luminous. The binary separation is 0.2 $R_\odot$, the secondary radius is only 0.03 $R_\odot$, and the accretion disk is estimated to have a radius $\sim$0.1 $R_\odot$, since its maximum size is about 0.6 times the binary separation (Paczyński 1977). The degenerate companion is also very small, occupying an angle that is only 0.05 of the binary period. However, an accretion disk bulge may subtend a much larger angle, since the accretion rate is high and the impact zone between the disk and accretion stream is usually close to the neutron star. Since the X-ray modulation is not confined to small phase interval (see Fig. 3), an accretion disk bulge is highly favored as the origin of intervening material that would cause the periodic modulations in the X-ray flux of 4U 1820−30 (see also Stella, Priedhorsky and White 1987).

As outlined earlier, the remaining questions are whether or not 4U 1820−30 is an extended X-ray source and whether there are self-consistent conditions by which an accretion disk bulge could produce the X-ray modulation. Simulations of a simplified accretion disk corona were computed by Fabian, Guilbert, and Ross (1982). They indicate that the X-ray spectrum and light curve of 4U 1822−37 are roughly consistent with a model in which a central X-ray source with a luminosity of 10^{37} ergs s^{-1} or higher evaporates a hot corona from the inner accretion disk (see also Begelman and McKee 1983). Most of the coronal gas is confined to a sphere of radius less than $10^8\ L_x/10^{37}$ cm, and a low-density corona may extend the size of the scattering region to 10^{10} cm. Extrapolation of these results to 4U 1820−30 allows for a substantial corona, since the average X-ray emission is about 5×10^{37} ergs s^{-1}. The compact accretion disk is still much larger than the expected dimension (10^9 cm) of the high-density corona. A wide range of inclination angles and bulge thicknesses could accommodate the observed $\sim$3% modulation, excluding only very high or very low inclination angles. The bulge would be opaque to all X-ray emission if the Thompson optical depth is large ($\tau > 3$). If the thickness of the disk bulge along the line of sight is estimated to be 0.3 times the radius of the accretion disk (White and Holt 1982), then the average bulge density (n) must be greater than 2×10^{15} cm^{-3} to be optically thick. The ionization parameters, $\xi = L/(nr^2)$ must then be less than 500 ergs cm s^{-1} (see Hatchett, Buff, and McCray 1976 and references therein) implying that the gas in the bulge is only partially ionized.

Do the observed X-ray bursts from 4U 1820−30 rule out the possibility of an extended corona? During the low-liminosity state, X-ray bursts are clearly seen with rise times that are less than 0.25 s (Haberl *et al.* 1987). Since the size of the scattering corona may be as large as the maximum radius of the accretion disk ($\sim$0.1 $R_\odot$), the degradation of event time scales due to scattering could be as large as 0.5 s. However, the 685 s modulation has not been observed when the source is in this low-luminosity, bursting state. It is possible that the blast of energy and particles during an X-ray burst might temporarily disrupt the disk corona, explaining both the disappearance of X-ray modulations and the sharp rise times observed during burst activity. The burst recurrence rate for 4U 1820−30 is only $\sim$3 hr (Vacca, Lewin, and Paradijs 1986; Harberl *et al.* 1987), which may be much less than the time scale for the formation of a corona with substantial scattering optical depth. As the source luminosity descends into a bursting state, it is possible that only the first burst would show a longer rise time due to the effects of scattering in the disk corona.

On the other hand, none of the observations require an extended X-ray source, and it is possible that a point like X-ray source is being viewed through a bubble of ionized gas during the X-ray modulation minima. In this case, the bulge transmits 97% of the X-ray emission. The $\sim$3% X-ray modulation implies an electron density, $n \approx 2 \times 10^{13}$ cm^{-3}, and an ionization parameter $\xi \approx 4 \times 10^4$, which self-consistently implies a fully ionized gas in the disk bulge.

In summary of the discussion given above, there are two physical models that may produce the X-ray light curves of 4U 1820−30: (1) the X-rays emerge from an extended surface of radius $\sim$0.1 R_0 caused by scattering in a hot corona, and the modulation is observed when a thick, partially ionized bulge in the accretion disk periodically obscures a small patch of the X-ray surface; or (2) the X-ray source is periodically viewed through an optically thin bulge of ionized gas. As mentioned above, we prefer the former explanation for two reasons:

First, in the previous cases in which the X-ray light curve has been interpreted as viewing a pointlike X-ray source through clouds or filaments associated with the accretion disk (regardless of whether absorption or scattering is indicated), the X-ray minima have exhibited large-amplitude, short–time scale features, implying that the impact zone produces thick, filamentary structures. In the case of 4U 1820−30, the minima are very broad and shallow, and a search for short–time scale dips or increased variance during minimum phases shows no evidence that the minima are composed of numerous events with short time scales. On the other hand, the light curves of the extended X-ray sources show variations that are generally smooth and broad in phase angle, similar to that observed in the case of 4U 1820−30.

Second, Cominsky, Simmons, and Bowyer (1985) reported the sudden appearance of a thick, absorbing blob, observed in a scan of 4U 1820−30 with the *HEAO 1* A-2 experiment. Since the satellite was operating in a scanning mode, the duration of the absorption event is not well constrained ($< \sim$2 hr) and does not exclude the possibility of an extended X-ray source. The phase of this event was only 0.06 cycles after the X-ray modulation minimum, implying that the material was associated with the disk bulge. Although we do not see similar events in the *SAS 3* observations, we note that the modulation amplitude was observed to be greatest during 1977 September, and the *SAS 3* observations were made only 8 days earlier. This absorption event is easier to understand in the context of a thick, warm disk bulge (the extended source model), compared with the thin, highly ionized bulge hypothesized in the alternative model.

We thank Saul Rappaport for discussions of binary system evolution and for many helpful remarks. Useful information or comments were also provided by L. Stella, W. Priedhorsky, N. White, A. Levine, M. Urry, P. Joss, H. Bradt, and J. McClintock. We also thank Dean Dellinger for assisting in the data analysis. This work was supported in part by NASA grant NASW 442. R. R. acknowledges partial support from NASA grant NAG8-496. M. G. acknowledges partial support from NASA grant NAS8-3075.

REFERENCES

Alpar, M. A., and Shaham, J. 1985, *Nature*, **316**, 239.
Bailyn, C. D., and Grindlay, J. E. 1987, preprint.
Belian, R. D., Conner, J. P., and Evans, W. D. 1976, *Ap. J. (Letters)*, **206**, L135.
Begelman, M. C., and McKee, C. F. 1983, *Ap. J.*, **271**, 89.
Boyle, C. B., Fabian, A. C., and Guilbert, P. W. 1986, *Nature*, **319**, 648.
Bradt, H. V. D., and McClintock, J. E. 1983, *Ann. Rev. Astr. Ap.*, **21**, 13.
Brown, R. L. and Gould, R. J. 1970, *Phys. Rev. D.*, **1**, 2252.
Buff, J., *et al.* 1977, *Ap. J.*, **212**, 768.
Chandrasekhar, S. 1939, *An Introduction to the Study of Stellar Structure* (Chicago: University of Chicago Press, and New York: Dover).
Clark, G. W. 1975, *Ap. J. (Letters)*, **199**, L143.
Clark, G. W., Li, F. K., Canizares, C., Hayakawa, S., Jernigan, G., and Lewin, W. H. G. 1977, *M.N.R.A.S.*, **179**, 651.
Cominsky, L., and Wood, K. 1984, *Ap. J.*, **283**, 765.
Cominsky, L., Simmons, J., and Bowyer, S. 1985, *Ap. J.*, **298**, 581.
Fabian, A. C., Guilbert, P. W., and Ross, R. R. 1982, *M.N.R.A.S.*, **199**, 1045.
Garcia, M. R. 1987, Ph.D. thesis, Harvard University.
Garcia, M., Grindlay, J., and Burg, R. 1986, *IAU Circ.*, 4259.
Grindlay, J. E., Gursky, H., Schnopper, H., Parignault, D. R., Heise, J., Brinkman, A. C., and Schrijver, J. 1976, *Ap. J. (Letters)*, **205**, L127.
Haberl, F., Stella, L., White, N., Priedhorsky, W. C., and Gottwald, M. 1987, *Ap. J.*, **314**, 266.
Hatchett, S., Buff, J., and McCray, R. 1976, *Ap. J.*, **206**, 847.
Hertz, P., and Grindlay, J. E. 1983, *Ap. J.*, **275**, 105.
Jernigan, J. G., and Clark, G. W. 1979, *Ap. J. (Letters)*, **231**, L125.
Joss, P. C., and Rappaport, S. 1984, *Ann Rev. Astr. Ap.*, **22**, 537.
Kopal, Z. 1959, *Close Binary Systems* (London: Chapman and Hall).
Landolt, A. U., and Blondeau, K. L. 1972, *Pub. A.S.P.*, **84**, 784.
Lewin, W. H. G., and Joss, P. C. 1981, *Space Sci. Rev.*, **28**, 3.
McClintock, J. E., London, R. A., Bond, H. E., and Grauer, A. D. 1982, *Ap. J.*, **258**, 245.
Molnar, L. A. 1985, Ph.D. thesis, Harvard University.
Morgan, E. H., and Remillard, R. A. 1986, *IAU Circ.*, 4254.
Morgan, E. H., Remillard, R. A., Priedhorsky, W., Stella, L., White, N. E., and Garcia, M. 1986, *IAU Circ.*, 4261.
Negase, F. *et al.* 1981, *Nature*, **290**, 572.
Nelson, L. A., Rappaport, S. A., and Joss, P. C. 1986, *Ap. J.*, **304**, 231.
Paczyński, B. 1977, *Ap. J.*, **216**, 822.
Paczyński, B., and Sienkiewicz, R. 1981, *Ap. J. (Letters)*, **248**, L27.
Parmar, A. N., White, N. E., Giommi, P. and Goftwald, M. 1986, preprint.
Parmar, A. N., White, N. E., Sztajno, M., and Mason, K. O. 1985, *Space Sci. Rev.*, **40**, 213.
Priedhorsky, W., Stella, L., and White, N. E. 1986, *IAU Circ.*, 4247.
Priedhorsky, W., and Terrell, J. 1984, *Ap. J. (Letters)*, **284**, L17.
Rappaport, S., Nelson, L. A., Joss, P. C., and Ma, C.-P. 1987, *Ap. J.*, **322**, 842.
Rappaport, S., Joss, P. C., and Webbink, R. F. 1982, *Ap. J.*, **254**, 616.
Rappaport, S., Joss, P. C., and Webbink, R. F. 1982, *Ap. J.*, **254**, 616.
Savonije, G. J., de Kool, M., and van den Heuvel, E. P. J. 1986, *Astr. Ap.*, **155**, 51.
Stella., L., Kahn, S. M., and Grindlay, J. E. 1984, *Ap. J.*, **282**, 713.
Stella, L., Priedhorsky, W., and White, N. E. 1987, *Ap. J. (Letters)*, **312**, L17.
Stella, L., White, N. E., and Priedhorsky, W. 1987, *Ap. J. (Letters)*, **315**, L49.
Vacca, W. D., Lewin, W. H. G., and van Paradijs, J. 1986, *M.N.R.A.S.*, **220**, 339.
Verbunt, F. 1987, *Ap. J. (Letters)*, **312**, L23.
Vila, S. 1971, *Ap. J.*, **168**, 217.
Walter, F. M., Bowyer, S., Mason, K. O., Clarke, J., Henry, J. P., Halpern, J., and Grindlay, J. 1982, *Ap. J. (Letters)*, **253**, L67.
White, N. E., Becker, R. H., Boldt, E. A., Holt, S. S., Serlemitsos, P. J., and Swank, J. H. 1981, *Ap. J.*, **247**, 994.
White, N. E., and Holt, S. S. 1982, *Ap. J.*, **257**, 318.
Zapolsky, H. S., and Salpeter, E. E. 1969 *Ap. J.*, **158**, 809.

MICHAEL R. GARCIA: Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

EDWARD H. MORGAN: Room 37–422, Massachusetts Institute of Technology, Cambridge, MA 02139

RONALD A. REMILLARD: Room 37–595, Massachusetts Institute of Technology, Cambridge, MA 02139