1979ApJ...228..893L

THE ASTROPHYSICAL JOURNAL, **228**:893–897, 1979 March 15

A0535+26: REFINED POSITION MEASUREMENT AND NEW PULSE PERIOD DATA*

F. LI, S. RAPPAPORT,† G. W. CLARK, AND J. G. JERNIGAN
Department of Physics and Center for Space Research, Massachusetts Institute of Technology

Received 1978 August 14; accepted 1978 September 13

ABSTRACT

The hard, pulsing, transient X-ray source A0535+26 has been observed with *SAS 3* on three occasions during 1977–1978. These observations have yielded a precise position measurement (20″ error radius) which renders the identification of A0535+26 with the Be star HDE 245770 virtually certain. The pulse phase was tracked for ~9 days in 1978 April and clearly showed both first and second derivatives in the pulse period. An analysis of these new timing data, combined with data from previous observations, leads to the following conclusions: (1) a significant fraction of the observed changes in pulse period is probably intrinsic to the compact X-ray star (e.g., accretion torques on a neutron star), and (2) conservative limits on binary orbital parameters tend to further confirm a long orbital period ($P_{\rm orb} \gtrsim 20$ days).

Subject headings: pulsars — stars: binaries — stars: individual — X-rays: binaries

I. INTRODUCTION

The source A0535+26 is a recurrent transient X-ray pulsar (Rosenberg *et al.* 1975; Bradt *et al.* 1976). Its position was measured to an accuracy of ~40″ with the rotation modulation collimator (RMC) X-ray detectors on the *Ariel 5* satellite. Shortly thereafter, the Be star HDE 245770, which lies within the error region, was proposed as the optical counterpart (see Stier and Liller 1976, and references therein). The 1975 June and November outbursts of A0535+26 were studied extensively with the *SAS 3* X-ray observatory (Bradt *et al.* 1976; Rappaport *et al.* 1976, hereafter Paper I). On the basis of a study of the pulse arrival times, Rappaport *et al.* (Paper I) proposed that A0535+26 belongs to a binary system of relatively long orbital period ($P_{\rm orb} \gtrsim 20$ days). Subsequent to the 1975 outbursts,[1] A0535+26 was observed by *SAS 3* to flare up on three more occasions: 1977 May and December, and 1978 April (Ricker and Primini 1977; Chartres and Li 1977; Clark and Chartres 1978). We report here a refined position for A0535+26 measured during the 1977 December outburst. We also discuss new pulse arrival time data and their implications for binary orbital motion in the system.

II. REFINED POSITION MEASUREMENT

The RMC X-ray detectors on *SAS 3* were used to observe A0535+26 between ~8 h and 20 h (UT) 1977 December 27. Data were obtained with both the $2'.5$ and $4'.5$ (FWHM) RMC detectors (Doxsey *et al.* 1976; Schnopper *et al.* 1976) in each of two different satellite orientations. From these data, four independent measurements of the position of A0535+26 were obtained. The average of these is:

$$\alpha(1950) = 05^{\rm h}35^{\rm m}47^{\rm s}.2\,, \quad \delta(1950) = 26°17'35''\,,$$

with an error-circle radius of 20″ (90% confidence).

Figure 1 is an enlargement of the blue Palomar Observatory Sky Survey (POSS) print of the region near A0535+26 with the *SAS 3* error circle superposed. The area of positional uncertainty has been reduced by a factor of ~4 over the earlier determination (Rosenberg *et al.* 1975). The previously proposed Be star optical counterpart HDE 245770 lies 18″ from the center of the error circle. One much fainter star, near the plate limit of the POSS, may also be present in the error circle.

III. NEW PULSE ARRIVAL TIME DATA

During the 1977 May and 1978 April outbursts, the central slat collimator detector system (Buff *et al.* 1977; Lewin *et al.* 1976) was used to observe A0535+26. Only 3 hours of data were obtained during the 1977 May outburst: $12^{\rm h}$–$15^{\rm h}$ 1977 May 24 (UT). This short data train and the somewhat longer one obtained with the RMC detectors (§ II) were divided into segments of duration equal to ~1 satellite orbit (95 minutes). The data from each segment were then folded modulo a trial pulse period of ~103.8 s to produce a pulse profile. The arrival time of an arbitrary fiducial point on the pulse profile was determined by cross-correlating it with a fixed reference pulse profile (template). The pulse template was produced from one orbit of data with good counting statistics (for details of this procedure, see Rappaport, Joss, and McClintock 1976; Primini, Rappaport, and Joss 1977). The arrival times yield average heliocentric pulse periods of $103^{\rm s}.88 \pm 0^{\rm s}.03$ and $103^{\rm s}.882 \pm 0^{\rm s}.002$ for the 1977 May and December outbursts, respectively.

---

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

† Alfred P. Sloan Research Fellow.

[1] A "flareup" or "outburst" is defined to be an increase in the X-ray intensity of A0535+26 from less than ~1% to greater than 10% of the intensity of the Crab nebula.

1979ApJ...228..893L

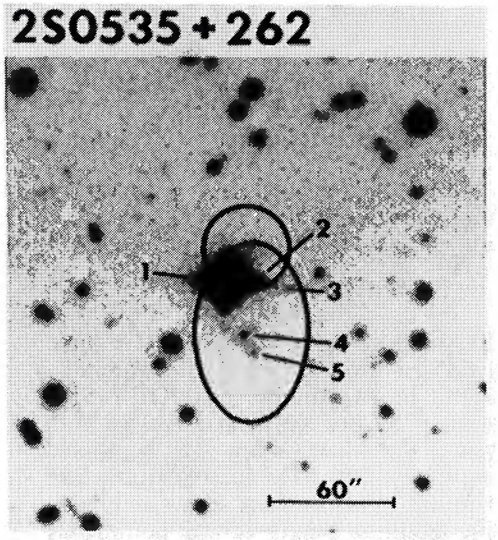

FIG. 1.—Enlargement of the blue Palomar Observatory Sky Survey (© National Geographic Society) print of the region near A0535+26 (2S 0535+262). Stars are numbered for identification purposes. The larger error ellipse represents the *Ariel 5* position measurement (Rosenberg *et al.* 1975), while the smaller circle (20″ radius) is the 90% confidence error region from the present *SAS 3* results. The Be star HDE 245770 (star no. 1) is 18″ from the center of the error circle.

A0535+26 was observed more extensively for a span of ~9 days, beginning 1978 April 16.8 (UT). A total of 45 pulse "arrival times" were obtained in the manner described above. A cursory inspection of these arrival times (Fig. 2) indicates that they cannot be fitted with a constant pulse period. The data trains obtained in the 1977 May and December outbursts are too short to show any similar effect.

We found that the pulse arrival times were well fitted by a polynomial of the form

$$t_n = t_0 + P_0 n + \beta n^2 + \gamma n^3 . \qquad (1)$$

Here t_n is the arrival time of the nth pulse, P_0 is the pulse period (at $n = 0$), β represents the change in pulse period ($\beta \approx \frac{1}{2}P_0\dot{P}$), and γ represents changes in $\dot{P}$ ($\gamma \approx \frac{1}{6}P_0{}^2\ddot{P}$). The cubic term which represents $\ddot{P}$ is required to obtain a satisfactory fit. The function given by equation (1) with the best-fit parameters is plotted in Figure 2 along with the observed pulse arrival times. A similar cubic term does *not* significantly improve the fit to the data described in Paper I (i.e., the best-fit values for $\ddot{P}$ in the 1975 June and November data are consistent with zero). Possible causes for the presence of the cubic term in the 1978 April data will be discussed below.

The pulse period data for A0535+26 during six of the known outbursts are summarized in Table 1 and Figure 3. For three of these observations, the observed rate of change in the pulse period is also given.

IV. REVISED CONSTRAINTS ON ORBITAL PARAMETERS

Rappaport *et al.* (Paper I) have studied the pulse arrival times during the outbursts of A0535+26 in 1975 June and November. They fitted the data primarily with a model having no intrinsic pulse period change (i.e., $\dot{P} = 0$) during either the outbursts or the intervals between outbursts. They obtained "islands" of allowed binary orbital parameters which spanned the range 17 days $\lesssim P_{\rm orb} \lesssim$ 80 days (see Fig. 2 of Paper I). Rappaport *et al.* argued that orbital effects probably dominated the observed pulse period changes ($\dot{P}$) because there was an inverse correlation between X-ray luminosity and the observed magnitude of $\dot{P}$.

We have combined the earlier 1975 pulse arrival-time data for A0535+26 with the new 1978 data for the purpose of reexamining the orbital constraints that were set in Paper I. The total data set is still insufficient to permit the derivation of a unique orbit for the system. In the following paragraphs we explore the consistency of the data with each of several models which serve to constrain the orbital parameters; these models are considered in decreasing order of severity of the restrictions they place on changes in the intrinsic pulse period.

The pulse arrival times obtained during the three extended observations were first fitted to trial circular binary orbits under the assumption that the intrinsic pulse period is always constant (i.e., $\dot{P} = 0$). No orbit of any assumed period and radius was found to fit the

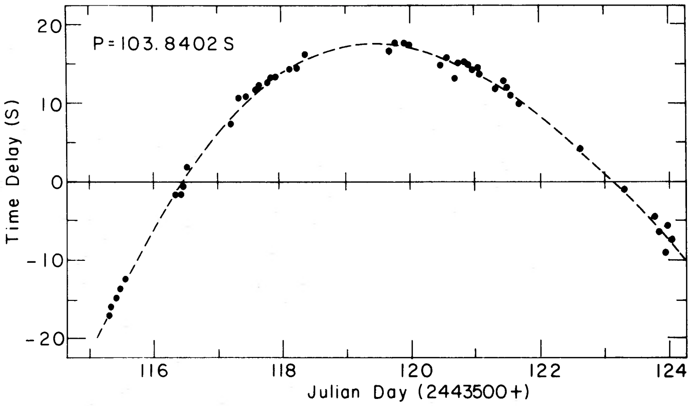

FIG. 2.—A0535+26 pulse arrival-time data from the 1978 April observation. A linear term representing the average pulse period (P_0 = 103.8402 s) has been subtracted from the data. *Dashed curve*, best fit to the data with a polynomial given by eq. (1).

1979ApJ...228..893L

TABLE 1

Pulse Periods for A0535+26

Date	Period (s)*†	$\dot{P}/P$ (yr^{-1})†	I_x/I_{crab}‡	References
1. 1975 April 28	104.17 ± 0.09	...	2	G. K. Skinner 1975
2. 1975 June 1	103.827 ± 0.001	−0.006 ± 0.001	0.5	Paper I
3. 1975 July 26	103.790 ± 0.007	...	< 0.2	Paper I
4. 1975 November 11	103.8061 ± 0.0004	−0.011 ± 0.001	0.2–0.1	Paper I
5. 1977 May 24	103.88 ± 0.03	...	0.5	Present work
6. 1977 December 27	103.882 ± 0.002	...	0.5	Present work
7. 1978 April 21	103.8402 ± 0.0002	−0.0139 ± 0.0002	0.4–0.2	Present work

* Heliocentric pulse period.

† The quoted parameter values are referenced to the temporal center of the observation (first column). Quoted uncertainties are 1 σ error bars.

‡ 2–10 keV intensity referenced to that of the Crab Nebula.

data satisfactorily. We conclude that the simple model adopted in Paper I was too restrictive. Changes in the intrinsic pulse period must have occurred during the 3 years spanning the observations.

According to the conventional model in which X-ray pulsars are accreting neutron stars, the intrinsic pulse periods change as the stars are acted on by accretion torques (see, e.g., Lamb, Pethick, and Pines 1973; Rappaport and Joss 1977). In fact, all pulsars with reliably measured values of $\dot{P}$ are found to be spinning up on the average (i.e., $\langle \dot{P} \rangle < 0$). It is therefore reasonable to assume *a priori* that there is some intrinsic pulse-period change in the case of A0535+26. However, we shall assume initially that the changes in pulse period observed during the outbursts are due largely to the orbital Doppler effect, as is the case, over short intervals, with all the well-measured X-ray binaries. The cumulative effect of a small rate of change in the intrinsic pulse period could, however, result in significant differences between the average intrinsic pulse periods during each outburst.

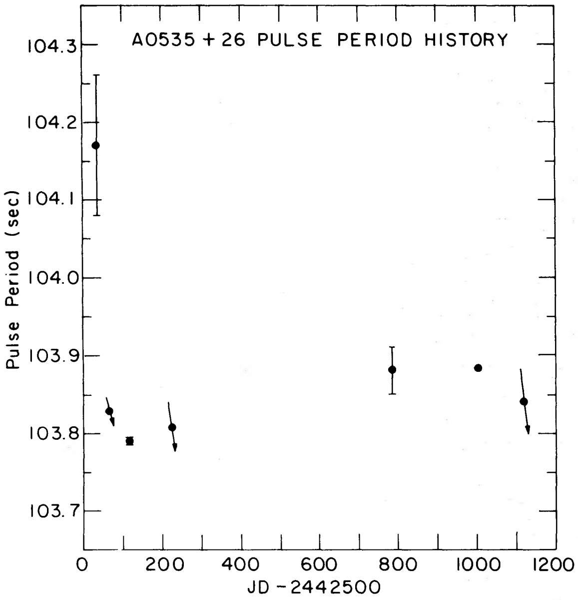

Fig. 3.—A0535+26 pulse period history. *Points with error bars*, pulse periods measured during a single day; *points with downward pointing arrows*, pulse periods measured during the more extended observations. The range of periods covered by the arrow is the total change expected if the rate of change in the pulse period continued at the observed rate for a total of 20 days.

With these considerations in mind, we fitted the following formula to the pulse arrival time data from the three extended observations:

$$t_n = t_{0j} + P_{0j} n + (a_x \sin i \cos \theta)/c\,. \qquad (2)$$

Here t_0 and P_0 have the same meaning as in equation (1), while the subscript j denotes the particular observation (e.g., $j = 2$ denotes the 1975 November data). The last term represents circular orbital motion, where $a_x \sin i$ is the projected orbital radius of the X-ray star, $\theta = 2\pi(t - \tau)/P_{\mathrm{orb}}$, and τ is the time of superior conjunction. In this model, each of the three data sets is allowed to have an independent pulse period and pulse phase to take into account any small pulse-period changes between outbursts. The pulse period is assumed to be constant during the outburst. The observed $\dot{P}$ and $\ddot{P}$ are then to be explained entirely by orbital motion. For this fit to the arrival-time data (eq. [2]), we find a highly restricted set of allowed orbital parameters. These are indicated in Figure 4 by dark vertical lines.

We next considered the possibility that the intrinsic pulse period changes significantly during an outburst. Rappaport and Joss (1977) have estimated, from a model of the accretion torques on X-ray pulsars, that the magnitude of the observed pulse-period change is consistent with that expected from the luminosity of A0535+26 during an outburst (assuming a reasonable distance of ~2 kpc). It is interesting to observe that the three values of $\dot{P}$ measured during outbursts of A0535+26 are all negative (Table 1). This indicates that the observed $\dot{P}$ may indeed be mostly intrinsic since, for an orbit with no correlation between orbital phase and episodes of enhanced emission, there is only one chance in eight of observing three consecutive negative values of $\dot{P}$. Furthermore, the *Ariel 5* pulse period for A0535+26, obtained on 1975 April 28 (Table 1 and Fig. 3), indicates that there was significant spin-up between then and the *SAS 3* observations. We also note that the secular decrease in X-ray luminosity

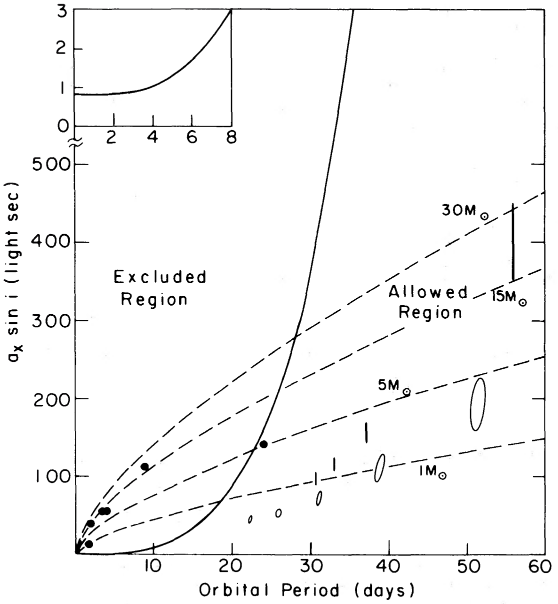

FIG. 4.—Constraints on the orbital parameters of A0535+26. The solid curve that divides the allowed from the excluded region is derived from a fit to the pulse arrival time data with the function given by eq. (3). This model allows for circular orbits and the effects of changes in the intrinsic pulse period. The solid curve also applies for moderately eccentric orbits with periods shorter than ~12 days. (See text for further discussion of eccentric orbits.) *Dark vertical bars*, allowed orbits for a more restrictive model (eq. [2]), where changes in intrinsic pulse period are considered only in the intervals between observations; *dashed curves*, contours of constant mass function; *dots*, orbital parameters for six known X-ray binaries, including 4U 0115+63 (see Rappaport *et al.* 1978 for references); *ellipses*, "islands" of allowed orbital parameters that were obtained in Paper I under the assumption that there were no changes in the intrinsic pulse period during the 1975 June and November observations.

(and in the presumably associated accretion torques) during the course of the nine-day 1978 April observation is sufficient to explain the magnitude and sign of the observed $\ddot{P}$ effect. Taking into account the possibility of substantial intrinsic $\dot{P}$, we believe that the vertical bars in Figure 4 should be interpreted only as indicators of the range of orbital parameters necessary to explain the observed orders of magnitude for $\dot{P}$ and $\ddot{P}$.

In order to allow simultaneously for arbitrarily large values of intrinsic $\dot{P}$ and an orbital Doppler effect, we next fitted the following trial function to the data from the three extended observations:

$$t_n = t_{0j} + P_{0j}n + \beta_j n^2 + \gamma_j n^3 + (a_x \sin i \cos \theta)/c\,. \quad (3)$$

In this expression, the first four terms have the same meaning as in equation (1). The subscript j again denotes the particular observation. The cubic term was omitted for the 1975 June and November data. The last term represents orbital motion and has the same meaning as in equation (2). Use of this formula allows conservative limits to be set on the orbital parameters because the other independent parameters can be adjusted to account for the changes in apparent pulse period without requiring any orbital motion. For each trial orbital period, there are, in effect, 12 free parameters to be fitted to the data from three observations.

Only upper limits to $a_x \sin i$ were found with equation (3) and trial orbital periods in the range 0.1–100 days; these limits are displayed in Figure 4 as a function of orbital period. Also shown, for reference, are contours of constant mass function and the orbital parameters for six X-ray binaries. We emphasize that if the finite value of $\ddot{P}$, derived from the 1978 April data, is actually due to orbital motion, then the orbital parameters must lie in the allowed region of Figure 4.

Only circular orbits have been considered thus far. The addition of a linearized perturbation term to equation (3), to represent the effects of small eccentricities ($e \lesssim 0.3$), yields substantially the same limits on $a_x \sin i$ for orbital periods shorter than ~12 days. For longer orbital periods, the inclusion of an eccentricity term significantly raises the upper limits on $a_x \sin i$. We note, however, that the use of equation (3) to estimate the upper limits to $a_x \sin i$, for both circular and eccentric orbits, is a conservative procedure because the largest fitted values of $a_x \sin i$ correspond to positive values of $\dot{P}$, which are physically implausible when the source is active (luminous) and presumably spinning up. An analysis with all $\dot{P}_j$ restricted to negative values is a difficult nonlinear problem which we have not yet carried out. We have, however, obtained limits on orbital parameters with the negativity requirement imposed on each $\dot{P}_j$ separately, and with small eccentricities allowed as a free parameter; these limits are very similar to those shown in Figure 4.

V. DISCUSSION

The refined position measurement with *SAS 3* makes the identification of A0535+26 with HDE 245770 virtually certain. A reasonable lower limit to the mass of this star is ~5 $M_\odot$ (Hutchings *et al.* 1978). If we assume that the X-rays are emitted by a compact star in orbit about HDE 245770, then the orbital period is almost certainly longer than 1 day. The limits on $a_x \sin i$ and the corresponding limits on the mass function (Fig. 4) then indicate that the orbital period is almost certainly longer than ~15 days. As can be seen from our more restrictive fit to the data (eq. [2] and *solid bars* in Fig. 4), the data are well fitted with orbital periods of 30–55 days. Further constraints on possible orbital periods, based on optical studies of HDE 245770, are given by Hutchings *et al.* (1978).

The observed pulse periods of A0535+26 changed little during the three years of observation, excluding the initial *Ariel 5* measurement (Fig. 3). All of the observed changes that did occur between JD 2,442,560 and JD 2,443,625 could be attributed to orbital Doppler effects if the orbital velocity of the X-ray star were $\gtrsim 150$ km s^{-1}. On the other hand, there are strong arguments (§ IV) which indicate that significant fractions of the changes in pulse period are likely to have been intrinsic to the source (i.e., changes in the rotational period of a neutron star). If this supposition is correct, and if, in addition, A0535+26 had spun up continuously at the rate of 0.01 year^{-1} (Table 1) during the total duration of all of its outbursts (i.e., $\gtrsim 0.2$ year) then this would have led to a net decrease in the pulse period of $\gtrsim 0.2$ s. An orbital velocity of $\gtrsim 300$ km s^{-1} would then be required to explain the near constancy of the observed pulse period by orbital motion which fortuitously canceled the spin-up. By contrast, the largest orbital velocity consistent with the allowed orbital parameters (Fig. 4) and a reasonable mass function $[f(M) \lesssim 15\ M_\odot]$ is ~ 180 km s^{-1}.

The near constancy of the pulse period over three years of observation, despite episodes of apparent spin-up, when the source was active, leads us to speculate that spin-downs (i.e., $\dot{P} > 0$) occur during intervals between outbursts. Spin-downs are possible when the X-ray luminosity (and corresponding accretion rate) is sufficiently low that the Alfvén radius moves out beyond the corotation radius (Lamb, Pethick, and Pines 1973). At these times, A0535+26 would be a "fast rotator" (see Lamb 1977, and references therein; Kundt 1976; Ghosh and Lamb 1978) which loses rather than gains angular momentum. Episodes of spin-down have previously been reported for two of the shorter-period pulsars (Her X-1 and Cen X-3; Giacconi 1974; Fabbiano and Schreier 1977) and also for the longer-period pulsar 4U 0900−40 (Ögelman *et al.* 1977).

Another hard transient source 4U 0115+63 has been studied during its most recent outburst and found to be a 3.6 s pulsar in a 24.3 day orbit (Cominsky *et al.* 1978; Rappaport *et al.* 1978). The available data for A0535+26 are consistent with an orbit similar to that of 4U 0115+63. This strengthens the suggestion by Rappaport *et al.* (1978) that the hard, pulsing transients are binary systems with relatively wide separations, wherein continuous large-scale mass transfer from the primary is inhibited. Outbursts in these transient sources are presumably caused by sudden increases in the spontaneous mass loss from the primary (cf. Rappaport *et al.* 1978) or in the rate of inward transport of material that has accumulated in the accretion disk (Paczyński 1978; see Osaki 1974 for a similar model for dwarf novae). In the former case, the mechanism for the sudden onset of mass loss is not understood. The model involving instabilities in accretion disks suffers from the difficulty that the time scales for the transport of angular momentum in the disks cannot be reliably estimated, and the cause of the instabilities is again unknown.

Simultaneous optical observations during an outburst of a hard transient X-ray source could provide valuable information on the underlying physical processes. In principle, the two models could be distinguished in that the one invoking sudden mass loss predicts changes in the primary that may well be observable. In fact, Bartolini, *et al.* (1978) have reported a "flare-up" in HDE 245770 during the 1977 December outburst. Details of these results and further optical observations are essential for a better understanding of these sources.

The authors are grateful to P. C. Joss, B. Paczyński, and J. Ziólkowski for helpful discussions. We also acknowledge the support of the entire *SAS 3* group during this study.

REFERENCES

Bartolini, C., Guarnieri, A., Piccioni, A., Giangrande, A., and Giovannelli, F. 1978, *IAU Circ.*, No. 3167.
Bradt, H. V. *et al.* 1976, *Ap. J. (Letters)*, **204**, L67.
Buff, J. *et al.* 1977, *Ap. J.*, **212**, 768.
Chartres, M., and Li, F. 1977, *IAU Circ.*, No. 3154.
Clark, G., and Chartres, M. 1978, *IAU Circ.*, No. 3208.
Cominsky, L., Clark, G., Li, F., Mayer, W., and Rappaport, S. 1978, *Nature*, **273**, 367.
Doxsey, R. *et al.* 1976, *Ap. J. (Letters)*, **203**, L9.
Fabbiano, G., and Schreier, E. 1977, *Ap. J.*, **214**, 235.
Ghosh, P., and Lamb, F. K. 1978, *Ap. J. (Letters)*, **223**, L83.
Giacconi, R. 1974, in *IAU Symposium No. 64, Gravitational Radiation and Gravitational Collapse*, ed. C. deWitt-Morette (Dordrecht: Reidel), p. 147.
Hutchings, J. B., Bernard, J. E., Crampton, D., and Cowley, A. P. 1978, *Ap. J.*, **223**, 530.
Kundt, W. 1976, *Phys. Letters*, **57A**, 195.
Lamb, F. 1977, *Ann. NY Acad. Sci.*, **302**, 482.
Lamb, F., Pethick, C., and Pines, D. 1973, *Ap. J.*, **184**, 271.
Lewin, W., Li, F., Hoffman, J., Doty, J., Buff, J., Clark, G., and Rappaport, S. 1976, *M.N.R.A.S.*, **177**, 93P.
Ögelman, H., Beuermann, K. P., Kanback, G., Mayer-Hasselwander, H. A., Capozzi, D., Fiordilino, E., and Molteni, D. 1977, *Astr. Ap.*, **58**, 385.
Osaki, Y. 1974, *Pub. Astr. Soc. Japan*, **26**, 429.
Paczyński, B. 1978, private communication.
Primini, F., Rappaport, S., and Joss, P. C. 1977, *Ap. J.*, **217**, 543.
Rappaport, S., Clark, G., Cominsky, L., Joss, P. C., and Li, F. 1978, submitted to *Ap. J. (Letters)*.
Rappaport, S., and Joss, P. C. 1977, *Nature*, **266**, 683.
Rappaport, S., Joss, P. C., Bradt, H., Clark, G., and Jernigan, J. G. 1976, *Ap. J. (Letters)*, **208**, L119 (Paper I).
Rappaport, S., Joss, P. C., and McClintock, J. 1976, *Ap. J. (Letters)*, **206**, L103.
Ricker, G., and Primini, F. 1977, *IAU Circ.*, No. 3078.
Rosenberg, F. D., Eyles, C. J., Skinner, G. K., and Willmore, A. P. 1975, *Nature*, **256**, 628.
Schnopper, H., Delvaille, J., Epstein, A., Helmken, H., Murray, S., Clark, G., Jernigan, J. G., and Doxsey, R. 1976, *Ap. J. (Letters)*, **210**, L75.
Skinner, G. K. 1975, private communication.
Stier, M., and Liller, W. 1976, *Ap. J.*, **206**, 257.

G. W. Clark, J. G. Jernigan, F. Li, and S. Rappaport: Room 37-535, Massachusetts Institute of Technology, Cambridge, MA 02139