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EVIDENCE FOR THE BINARY NATURE OF A0535+26*

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ABSTRACT

The transient X-ray source A0535+26 was observed extensively with the SAS-3 satellite on two occasions (1975 May 30–June 2 and November 7–14). Sufficient timing data on the 104 s periodicity were obtained to indicate that the pulse period was changing during both of the observations. We cannot completely exclude the possibility that these period changes are intrinsic to the compact star (e.g., due to accretion torques). However, we demonstrate that all of the SAS-3 timing data can be explained by orbital motion of the X-ray star about a companion. Constraints are then placed on the orbital elements of the system. The results indicate a model for this source that consists of a neutron star in a long-period orbit ($P \gtrsim 17$ days) about an OB star with a variable stellar wind.
Subject headings: stars: binaries — X-rays: sources — X-rays: variable

I. INTRODUCTION

Nearly a dozen transient X-ray sources, with characteristic luminosity-variation time scales on the order of weeks, have now been discovered. In general, when a transient source is discovered, its light curve and energy spectrum can be observed for only a few weeks or months. With such limited information it has been difficult to draw definite conclusions concerning the nature of these objects and their relation to the more permanent features in the X-ray sky. In particular, there has been no compelling evidence that they are binary systems (with the exception of A0620−00; Eachus, Wright and Liller 1976), although this is, perhaps, the most plausible assumption.

In the case of the transient source A0535+26 (Rosenberg *et al.* 1975; Bradt *et al.* 1976; Ricker *et al.* 1976), the 1–6 keV X-ray flux reached a peak intensity of roughly twice that of the Crab nebula on 1975 May 1 and was found to be pulsing with a 104 s periodicity. The only other transient source found to be pulsing was A1118−61, with a 405 s period (Eyles *et al.* 1975), but the source faded before detailed information about the object could be obtained. In contrast, A0535+26 was studied extensively by both the *Ariel-5* and SAS-3 satellites, and considerable information on the pulse shapes over a wide range of energies is available. However, no change in pulse period was originally detected during three days of continuous observations in 1975 May and June (Bradt *et al.* 1976, hereafter referred to as Paper I). This result indicated that if the source is in a binary system, then the orbital period probably is relatively long. A tentative identification of this source with HDE 245770, a 9th magnitude peculiar emission-line B star, was made by Liller (1975), based on the location of the star within the 1′ *Ariel-5* error box (Rosenberg *et al.* 1975). Preliminary searches for photometric optical variability which might indicate the binary nature of the system have, thus far, been unsuccessful (Stier and Liller 1976).

A0535+26 was monitored extensively with the *Ariel-5* satellite (Pounds 1976) until its intensity decreased to below the detectable level of $\sim 7 \times 10^{-3}$ that of the Crab Nebula on about 1975 September 20. These long-term monitoring observations did not include further determinations of the pulse period.

On 1975 November 7, A0535+26 brightened again (Joss 1975), thereby yielding another opportunity to search for variations in the pulse period. The source attained about 10 percent of its previous peak luminosity and was observed with SAS-3 over an interval of 7 days before becoming too faint for further X-ray observations. In this *Letter* we present the results of these observations, which, when combined with the earlier May/June data, yield evidence for binary orbital motion. These results should complement optical studies of HDE 245770 in attempts to confirm the optical identification and determine the orbital elements of the system.

II. OBSERVATIONS

A0535+26 was observed with SAS-3 to brighten to an intensity of about one-fifth that of the Crab Nebula on 1975 November 7.5 (UT) (Joss 1975). It remained detectable ($\gtrsim 1/20$ Crab intensity) and was observed until 1975 November 14.5 (UT). During this observation another source was concurrently studied with the rotation modulation collimators, which view along the Z-axis (spin axis) of the satellite. The Z-axis was therefore held near the position of this other source, which fixed the elevation of A0535+26 at 20° above the satellite rotation equator. In this configuration we obtained useful data on A0535+26 only from the proportional counter behind the center slat collimator (see Paper I). The energy channels for this detector are 1.3–5 keV, 5–10 keV, and 8–35 keV.

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The energy interval in which the pulse profiles had the best-defined shape for the purpose of accurate timing was the 1.3–5 keV interval. The pulse profiles in various energy intervals during the May/June observations are shown in Figure 1 of Paper I. The pulse profiles observed in November are consistent with those of the earlier observations, within the limited statistical accuracy of the November observations.

The November observations, reported here, yielded 24 orbits of usable data from which we determined the arrival times of the 104 s pulses.

III. ANALYSIS AND RESULTS

The present data from each SAS-3 orbit were folded modulo the apparent pulse period of 103.8 s. The time of the center of the prominent minimum (Fig. 1 of Paper I) could then be estimated to within an uncertainty of ~ 1 s.

The arrival times of the 18 minima from the May/June data and the 24 minima from the November data are plotted in Figure 1, relative to the arrival times expected for the best-fit constant pulse period for each of the two sets of data. The Doppler effect due to the orbital motion of the Earth has been taken into account. The May/June data have been reanalyzed using the lower energy channels (1.2–6 keV) rather than the higher energy channels that were used in Paper I. In the reanalysis, pulse profiles from individual satellite orbits were cross-correlated against a master pulse template, which substantially improved the accuracy of the arrival-time determinations. The best-fit periods for the two sets of data differ by only 1 part in 5000, which would correspond to a constant spinup rate of $\dot{P}/P \approx -0.4 \times 10^{-3}$ yr^{-1}, where P is the observed pulse period. (We shall assume here that the 104 s periodicity is a manifestation of the rotation period of a compact star; see § IV.)

For each set of data, a quadratic term was added to the fit to represent a changing pulse period (Fig. 1). For the May/June and November data the minimum values of χ^2, χ^2_{min}, are reduced by factors of 2.8 and 17, respectively, with the addition of the quadratic term. The corresponding spin-up rates for the two observations are $\dot{P}/P \approx (-5.7 \pm 1.1) \times 10^{-3}$ yr^{-1} (1 σ) and $(-11.0 \pm 0.6) \times 10^{-3}$ yr^{-1} (1 σ), respectively. The values for $|\dot{P}/P|$ are $\sim$15–25 times larger than the average value of $|\dot{P}/P|$ inferred for the interval of roughly 6 months between the observations. It is therefore clear that the period changes cannot be the result of a continuous and constant change in the intrinsic pulse period of the X-ray star. On the other hand, these changes in period could result naturally from orbital motion of the X-ray star about a companion. We shall return later to the question of whether some or all of the observed changes in period could be the result of changes in the intrinsic pulse period of the X-ray star.

The two sets of data can be combined to search for allowed circular orbits if we tentatively assume a constant intrinsic pulse period. A minimum χ^2 fit was made to the data with six free parameters: orbital period (P_{orb}), orbital amplitude ($a_x \sin i$), orbital phase, pulse period, and a zero point of pulse phase for each of the two data sets (since the number of pulses between these data sets is not uniquely determined).

The results of this fit are shown in Figure 2. Acceptable orbital periods range from 17^d to 156^d in discrete intervals. The existence of separate "islands" of acceptable values in the (P_{orb}, $a_x \sin i$)-plane arises from the fact that the sum of the time intervals spanned by the two data sets is considerably less than one orbital period. The (P_{orb}, $a_x \sin i$)-plane (Fig. 2) is not continued beyond orbital periods of 100 days. For periods longer than this, acceptable values of the mass function $f(M)$ exceed 100 $M_\odot$, which is not physically plausible. Only orbital periods near 77^d and 52^d yield mass functions that are appropriate to a system containing a B star (whose mass is most likely $\gtrsim$10 $M_\odot$) and with $\sin i \gtrsim 0.8$.

To help choose among the several possible orbital periods, we have employed one additional SAS-3 observation of A0535+26 that took place on 1975 July 26 but was unfortunately of low statistical quality. The arrival times of five minima during a 4-hour interval were obtained. The heliocentric pulse period derived from these observations is $103^s.790 \pm 0^s.007$ (1 σ). These data reduce the likelihood of the possible orbital periods of $\sim$17.5, 19.5, 26, 31, and 52 days derived from the May/June and November data (Fig. 2), because the parameters for these orbits predict a significantly different pulse period for 1975 July 26 from that observed.

In view of the tentative identification of A0535+26 with HDE 245770, all possible orbital periods less than $\sim$35 days, with corresponding mass functions less than 1 $M_\odot$, are rendered less probable than those with larger mass functions. The most likely remaining orbital periods are therefore $39^d \pm 0^d.5$ and $77^d \pm 1^d$, with corresponding mass functions $f(M) \sim 1\ M_\odot$ and $f(M) \gtrsim 8\ M_\odot$, respectively.

As noted above, the values of $|\dot{P}/P|$ for the individual observations are substantially larger than the average value inferred from the net change in pulse period over a $\sim$6-month interval. This was cited as evidence for orbital motion. A difficulty with this argument is that if the X-ray pulsations are produced by accretion onto a rotating compact star, then the rate of change of the intrinsic period will very likely be approximately proportional to the X-ray luminosity (see, e.g., Lamb, Pethick and Pines 1973). This probable correlation, coupled with the possibility that the average luminosity between June and November was very small, suggests that the intrinsic spin-up rate could have been considerably larger while the source was being observed than during the interim. There was not sufficient monitoring of A0535+26 between June and November by either the SAS-3 or *Ariel-5* satellites (Pounds 1976) to rule out this possibility. Moreover, Rosenberg *et al.* (1975) and Skinner (1976) reported that on 1975 April 28 the apparent pulse period of the

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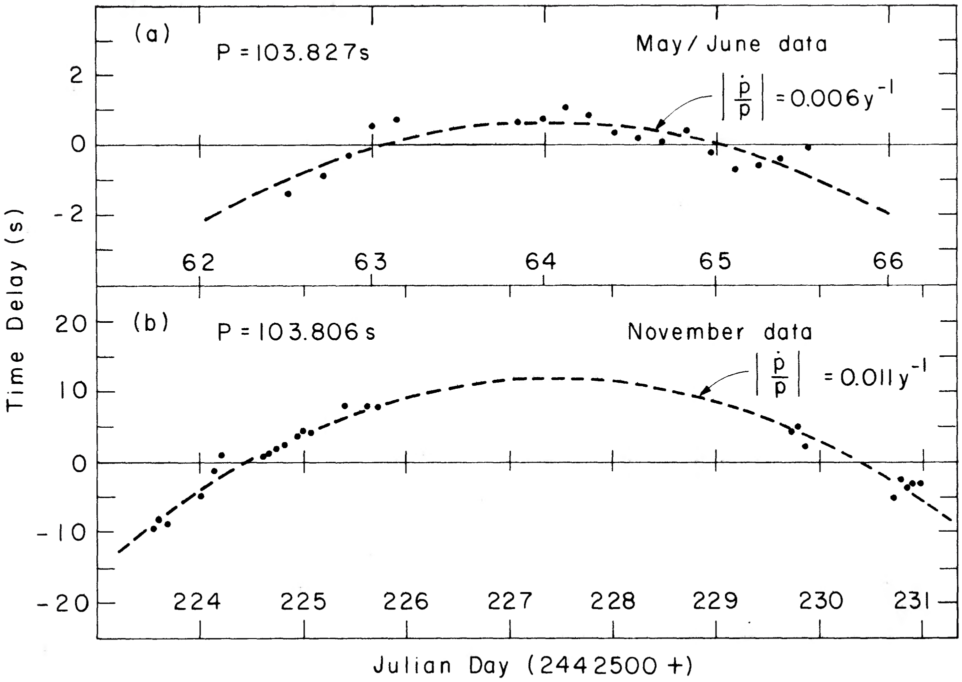

FIG. 1.—Delays in arrival time of the 104 s pulses relative to delays expected for the best-fit constant pulse period. The dashed curves are best-fit parabolae to the delays. Note the differences in scales for the two sets of data. The scatter of points about the quadratic curves exhibit rms jitters of 0.4 and 1.2 s for the May/June and November data, respectively. This result reflects the higher statistical quality of the May/June data.

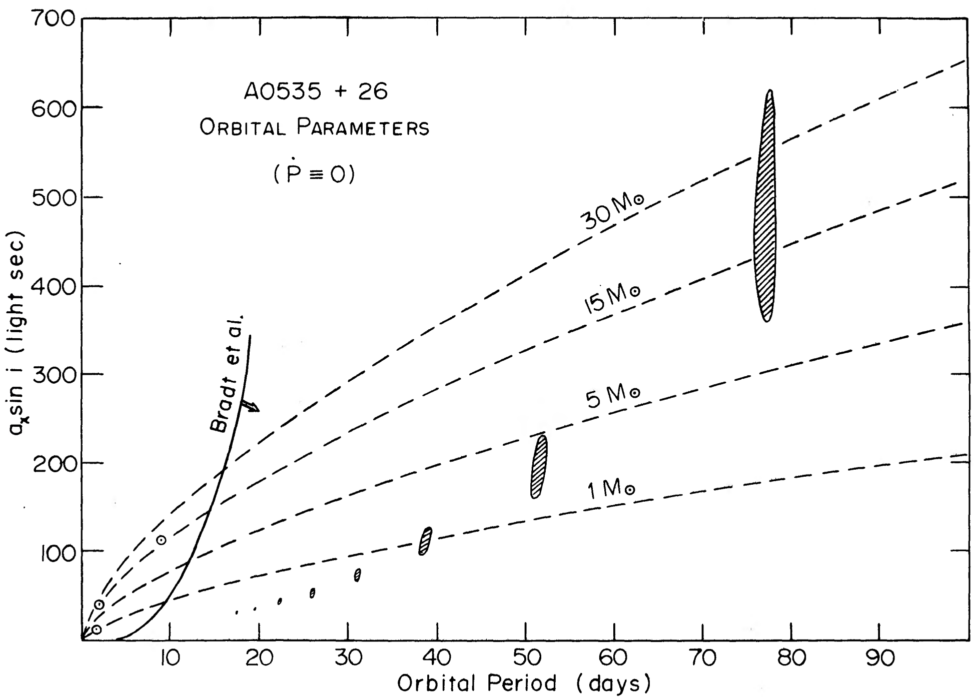

FIG. 2.—Allowed circular orbits for A0535+26 that are consistent with the SAS-3 timing data and the assumption of no changes in intrinsic pulse period. Each error contour contains a 95% confidence region under the assumption that the true orbital period is near the local best-fit value. *Dashed curves*, contours of constant mass function. The lower left portion of the figure is taken from Paper I and indicates the upper limits on a_x sin i inferred from the May/June data alone. The encircled points represent the orbits of Her X-1 (P_{orb} = 1^d70), Cen X-3 (2^d08), and 3U 0900−40 (8^d97).

source was $104^s.17 \pm 0^s.1$. The large change in pulse period between this observation and the May/June SAS-3 observation is not consistent with Doppler effects due to any of the allowed orbits shown in Figure 2 but is consistent with a large intrinsic spin-up when the source was near its maximum luminosity. (For a more complete discussion of the importance of accretion torques in slow X-ray pulsars, see Fabian and Pringle 1976.)

There is, however, another fact that supports the view that the observed values of $\dot{P}$ in May/June and November are not primarily due to an intrinsic accretion-driven spinup. The luminosity in May/June was 2–3 times higher than in November whereas the value of $|\dot{P}/P|$ was $\sim$2 times lower than in November. This is opposite to the effect that one would expect if the observed spin-ups were intrinsic and driven by accretion.

Although we believe that an intrinsic spin-up probably does not account for most of the observed magnitude of $\dot{P}$ in June and November, we did test for the effect that a constant intrinsic spin-up (or spin-down), $\dot{P}_{\rm int}/P$, would have on the allowed orbits shown in Figure 2. The "islands" of acceptable orbital periods and radii are shifted in the ($P_{\rm orb}$, $a_{\rm x}\sin i$)-plane as the assumed value of $|\dot{P}_{\rm int}/P|$ is increased. For values of $|\dot{P}_{\rm int}/P|$ up to $\sim 2 \times 10^{-3}$ yr^{-1}, acceptable fits to the data corresponding to $f(M) < 100\ M_\odot$ can be found. For example, the "island" centered at $P_{\rm orb} \simeq 39$ days and $a_{\rm x}\sin i \approx 106 \pm 15$ lt-sec is shifted in period by $-1^d.5$ and $+5^d$ for $\dot{P}_{\rm int}/P = -1$ and $+1 \times 10^{-3}$ yr^{-1}, respectively, while the best-fit values of $a_{\rm x}\sin i$ increase by factors of 2.0 and 1.3, respectively.

We have also tested for the effects of possible orbital eccentricity e on the allowed orbits in Figure 2. We find that eccentricities close to unity can be accommodated. When eccentric orbits are fitted, the best-fit values of $a_{\rm x}\sin i$ change but the best-fit values of $P_{\rm orb}$ do not change appreciably. For example, when an orbit with $e = 0.9$ is considered for the "island" centered at $P_{\rm orb} \approx 39$ days, the best fit value of $a_{\rm x}\sin i$ increases to 250 lt-sec. We have not investigated in detail the possibility that completely new acceptable "islands" appear when eccentric orbits (with or without a constant $\dot{P}_{\rm int}/P$) are considered.

IV. DISCUSSION AND SUMMARY

The pulse profiles of A0535+26 between 1 and 30 keV (Fig. 1 of Paper I) are remarkably similar to those of 3U 0900−40 (McClintock *et al.* 1976), and McClintock *et al.* argue that the X-ray star in 3U 0900−40 is very probably a neutron star. It therefore seems likely that the X-ray star in A0535+26 is also a rotating, magnetized neutron star that is accreting mass from a binary stellar companion.

A0535+26 has several characteristics that are typical of previously studied "transient sources." It had not been reported in previous high-sensitivity sky surveys[1] (Giacconi *et al.* 1974; Markert *et al.* 1976). It underwent a rapid rise from below the detectability limit of *Ariel-5* to a peak brightness of roughly twice that of the Crab nebula in $\sim$10 days. The rapid rise was followed by an exponential-type decay with a time constant of $\sim$10 days. Five months after the onset of X-ray activity, the source was below the *Ariel-5* sensitivity threshold. Unlike previous "transients," A0535+26 brightened again $\sim$6 months after its original discovery and was observed to be pulsing, as before, with a period that had changed by about 1 part in 5000.

We have shown that all of the SAS-3 timing data for A0535+26 are consistent with a long-period orbit in the range $17^d \lesssim P_{\rm orb} \lesssim 77^d$. If the orbital eccentricity and intrinsic spin-up (or spin-down) rate are small ($e \lesssim 0.1$ and $|\dot{P}_{\rm int}/P| \lesssim 10^{-4}$ yr^{-1}), then the regions of acceptable values of $P_{\rm orb}$ and $a_{\rm x}\sin i$ are essentially as shown in Figure 2. For larger values of e and $|\dot{P}_{\rm int}/P|$, orbits with other values of $P_{\rm orb}$ and $a_{\rm x}\sin i$ are allowable.

We have found that if a circular orbit and no changes in intrinsic pulse period are assumed, the most likely values for the orbital elements are those within the "islands" centered at $P_{\rm orb} \approx 39^d$ and 77^d in Figure 2. Moreover, if the tentative identification of the source with a B star (Liller 1975) is correct and if the mass of this star is $\gtrsim 10\ M_\odot$, then the allowable values of $a_{\rm x}$ for both of these "islands" are $\gtrsim 200$ lt-sec (i.e., sin i must be less than ~ 0.5 if $P_{\rm orb} \approx 39^d$). This result together with the sporadic X-ray behavior, leads us to conclude that the most plausible model for this system consists of a compact object in a relatively wide orbit about an OB star with a variable stellar wind (cf. Fabian 1975; Fabian, Pringle, and Webbink 1975). Because of the greater distance from the primary to the neutron star (i.e., $\gtrsim 200$ lt-sec versus $\lesssim 100$ lt-sec for Her X-1, Cen X-3, and 3U 0900−40), the X-ray luminosity can be small and even undetectable except during occasional episodes of enhanced stellar wind from the OB star.

Given the present evidence on A0535+26, it is plausible to conjecture that other transients with comparatively hard spectra and comparatively low intrinsic luminosities are compact objects undergoing accretion in relatively wide binary systems wherein the companion stars have variable stellar winds. In contrast, the more luminous transients with softer spectra may be close binaries powered by variable critical-lobe overflow (see, e.g., Avni, Fabian, and Pringle 1975; Li, Sprott, and Clark 1976).

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[1] There is recent evidence that A0535+26 was present at a very weak level in previously unanalyzed *Uhuru* data (Forman, Jones, and Tananbaum 1976).

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