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THE TRANSIENT PERIODIC X-RAY SOURCE IN TAURUS, A0535+26*

H. BRADT, W. MAYER, J. BUFF, G. W. CLARK, R. DOXSEY, D. HEARN, G. JERNIGAN, P. C. JOSS, B. LAUFER, W. LEWIN, F. LI, T. MATILSKY, J. MCCLINTOCK, F. PRIMINI, S. RAPPAPORT,† AND H. SCHNOPPER‡
Department of Physics and Center for Space Research, Massachusetts Institute of Technology

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ABSTRACT

Light curves of the 104 s periodicity in the transient X-ray source in Taurus (A0535+26) are presented for six energy intervals in the range 1–35 keV for the period 1975 May 30–June 2. The pulse structure ranges from an apparently simple modulation at higher energies to a very complex pattern at lower energies. No Doppler shift is observed in the 104 s pulse period during the three days of observations. This places severe constraints upon possible binary orbital motion. Upper limits on the power at other periodicities are $\lesssim 10$ percent for 2 ms–2 s and $\lesssim 2$ percent for 2 s–2000 s.

Subject heading: X-rays: sources

I. INTRODUCTION

The existence of a class of transient X-ray sources with temporal characteristics resembling those of optical novae is now well established. Two such sources were extensively studied before 1974: Cen X-4 (Evans, Belian, and Conner 1970) and 3U 1543−47 (Matilsky *et al.* 1972; Li, Sprott, and Clark 1976; Belian, Conner and Evans 1973). More recently, several others have been discovered and studied by *Ariel-5* and SAS-3 observers: (1) A1524−61, in Triangulum Australis in 1974 November (Pounds 1974; Kaluzienski *et al.* 1975); (2) A1118−61 in Centaurus in 1974 December (Eyles *et al.* 1975; Ives, Sanford, and Bell-Burnell 1975); (3) A1742−28 near the galactic center in 1975 February (Eyles *et al.* 1975*b*); (4) Aquila X-1 which exhibited a 20-fold increase in X-ray emission in 1975 June (Buff 1975); and (5) A0620−00, extremely bright, in Monoceros in 1975 August (Elvis *et al.* 1975; Matilsky 1975; Doxsey *et al.* 1976).

The Taurus X-ray nova A0535+26, first detected by the *Ariel-5* satellite (Rosenberg *et al.* 1975), began to flare on 1975 April 21 and rose to a maximum intensity of about twice the Crab intensity (3–7 keV) in ~10 days. It was found to have a periodic variation with a modulation depth of at least 25 percent and a probable period of 104.14 ± 0.16 s. Due to the 32 s integrating time of the *Ariel-5* detectors, a 46.1 s period was given as an alternate though less probable period.

The MIT X-ray observatory on the Third Small Astronomy Satellite, SAS-3, launched 1975 May 7, was used to carry out extensive observations of A0535+26 from 1975 May 30 to June 2 (JD 2,442,562.5–2,442,565.7). On June 1, concurrent balloon observations were carried out by Ricker *et al.* (1976). We present here SAS-3 results on the 104 s periodicity, the energy dependence of the pulse shapes, searches for other periods, and the energy spectrum.

II. OBSERVATIONS

The SAS-3 satellite carries tubular collimators (1°.7 FWHM), three crossed slat collimators (one with 1° × ~40° FWHM and two with 0°.5 × ~40° FWHM) as well as modulation collimators and a low-energy concentrator system. The tubular and slat collimators yielded the data discussed here. The detectors are sealed argon-filled and xenon-filled proportional counters of area ~100 cm² each, with a total spectral range of ~1–50 keV. The centers of their fields of view lie along the spacecraft *Y*-axis, i.e., in the azimuthal scan plane.

The source A0535+26 was first observed by SAS-3 with the three slat collimators during the first 3 days after the X-ray detectors were initially turned on, 1975 May 10. The satellite was spinning, and the observations were limited to three transits of the source, each of duration ~15 s, once every 95 minutes.

The May 30–June 2 observations made use of the SAS-3 capability to point the *Y*-axis detectors continuously at a given celestial position. Each orbit yielded about 3000 s of data after Earth occultation and data dropouts were eliminated. Data were taken in the pointed mode with 420, 8, and 1 ms time resolutions for 18, 12, and 10 orbits respectively. The quick-look data now available at MIT comprise the 18 orbits with 420 ms resolution, and one orbit of 1 ms data. We present here data obtained from two proportional counters, one argon-filled (80 cm²) and the other xenon-filled (115 cm²), behind the tubular collimators.

III. TEMPORAL VARIABILITY

The counting-rate data from the first orbit of pointed observations were Fourier analyzed to search for periodicities immediately after the data were received. A large and statistically significant frequency component and several harmonics were evident. These correspond to a primary period of 103.8 ± 0.15 s. The data from each of the 18 orbits with 420 ms timing were then separately folded modulo this apparent period in several spectral bands. For each of the resultant 18 light curves, in the channel with the best signal-to-

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† Alfred P. Sloan Research Fellow.

‡ Present address: Center for Astrophysics, Cambridge, Mass.

noise ratio (8–19 keV), we determined a best fit to the primary period and first harmonic. The minimum in each light curve was thereby determined to ~ ± 1 s.

Trial periods in a range surrounding 104 s were fitted to the times of these 18 minima, which span 3 days of observations. The best-fit heliocentric period is 103.8274 ± 0.0004 s and the rms deviation between the observed and predicted times of minima is 1.5 s. Thus, a constant period satisfactorily fits these data. If we assume a constant rate of change of period, $\dot{P}$, we obtain an upper limit (95% confidence) of $|\dot{P}/P| \leq 0.012$ yr^{-1}. Finally, the data were folded modulo the best-fit period to produce the light curves in Figure 1.

The light curve is relatively simple at high energies ($E > 19$ keV) with minima which reach a depth of 50 percent of the peak amplitude. A sharp dip which is 4 s wide is centered on the broad maximum in the 8–19 keV region and can be seen down to 3 keV. It is much less pronounced at higher and lower energies. During the 3 day observing period, this dip gradually becomes more shallow, and finally disappears.

At lower energies the light curve develops a series of five maxima which are irregularly spaced throughout the 104 s period. The deep minimum in the lower energy light curves appears as a sharp asymmetrically placed notch in the broader minimum at higher energies. The center of this minimum at low energies is shifted in phase by ~5 s from the center of the minimum at higher energies. (Note also this effect in Fig. 1*a*.) These features tend to be persistent; i.e., they are apparent in each of four subsets of the data. On the other hand, nonstatistical fluctuations are noted in individual orbits.

Fourier transforms of the data place limits (3 σ) on other periodic phenomena: fractional power less than 10 percent for periods from 2 ms to 4 s (8–35 keV) and less than 2% for 2 s–2000 s (3–30 keV).

IV. SPECTRUM

The energy spectrum of A0535+26, averaged over the 104 s period, was extremely hard. On 1975 May 12, it had only a slightly higher intensity at 1.5–5 keV than the Crab nebula, whereas it was ~5 times as bright in the 10–35 keV energy channel. During the May 30–June 2 observations, its 1.5–5 keV intensity had decreased by a factor of about 5 and its spectrum had softened somewhat. We find that neither a power law nor an exponential spectrum, with interstellar cutoff terms (Brown and Gould 1970), fitted the data from a May 30 orbit. The best-fit temperature, however, is about 30 keV for the exponential spectrum. Relative to this spectrum, there is an excess at ~15 keV and a steepening above about 20 keV. The latter is consistent with the 18 keV temperature reported by Ricker *et al.* (1976). Spectral data have also been reported by Ricketts *et al.* (1975) for 2–18 keV on June 1.

Spectral fits as a function of phase of the 104 s periodicity have been attempted. They yielded excessively large χ^2 values at certain phases and hence cannot be used to gain physical insight into the spectral variation with phase.

V. DISCUSSION

A model for A0535+26 must be able to account for the following set of observational features: (1) the transient nature of the source, (2) the unusually hard spectrum, (3) the existence of complex pulsations at a stable pulse period of about 104 s, and (4) the lack of variation in pulse period to an accuracy of ~1 s in pulse phase over three days of observations.

The transient character of A0535+26 and the existence of a 10th magnitude peculiar emission-line B star, HDE 245770 (Liller 1975), within the *Ariel-5* ~1 arcmin^2 error region (Rosenberg *et al.* 1975) suggest that A0535+26 is a compact object in a binary system containing HDE 245770. The transient behavior could arise because the primary star suffers episodic mass loss (cf. Fabian, Pringle, and Webbink 1975; Li, Sprott, and Clark 1975), or because the compact object is in a highly eccentric orbit about the companion star, with appreciable mass transfer occurring only near periastron (cf. McCluskey and Kondo 1971; Tsygan 1975; Pacini and Shapiro 1975).

The X-ray pulsations could be caused by the rotation of an accreting neutron star or white dwarf. We note that the compact object in the 3U 0900−40 X-ray/optical binary system is most likely a neutron star (Rappaport and McClintock 1975*a*). This source is similar to A0535+26 in that it is also a slow pulsator (Rappaport and McClintock 1975*b*) and emitter of hard X-rays. The complex temporal and spectral structure of the pulses presumably result from magnetic beaming of, and variable absorption by, the accreting matter.

The observed lack of variability of the pulse period during three days of observations allows us to place constraints on possible binary orbital motion of A0535+26 (cf. Lamb and Lamb 1976). The data were tested for the Doppler effects of assumed circular orbits with a range of orbital periods, P_0, and a range of projected orbital radii, $a \sin i$. For each orbital period tested, an upper limit to $a \sin i$ was set. For orbital periods longer than ~3 days, the largest acceptable values of $a \sin i$ are obtained when the orbital phase at the center of the three-day observation interval is ~0.25 or ~0.75 (phase 0.5 = closest approach to Earth).

The derived upper limits for $a \sin i$ are plotted in Figure 2 (*heavy line*). Contours of equal mass function, $f(M)$, are also shown. Points representing the known orbital parameters for Vela X-1, Her X-1, and Cen X-3 (Rappaport and McClintock 1975*a*; Tananbaum *et al.* 1972; Schreier *et al.* 1972) are plotted for comparison. Note that they all lie above the heavy line, i.e., in the excluded region of the ($a \sin i$, P)-plane for A0535+26. The acceptable region of the plane constrains the A0535+26 system to have one or more of the following characteristics: (1) the companion star has a fairly low mass, (2) the inclination is small, (3) the orbital period is long, or (4) the orbit is highly eccentric. If the identification with the emission-line B star (Liller 1975) is correct, $f(M)$ would be expected to be $\gtrsim 10\ M_\odot$, for $\sin^3 i \sim 1$, and the orbital period would be greater than

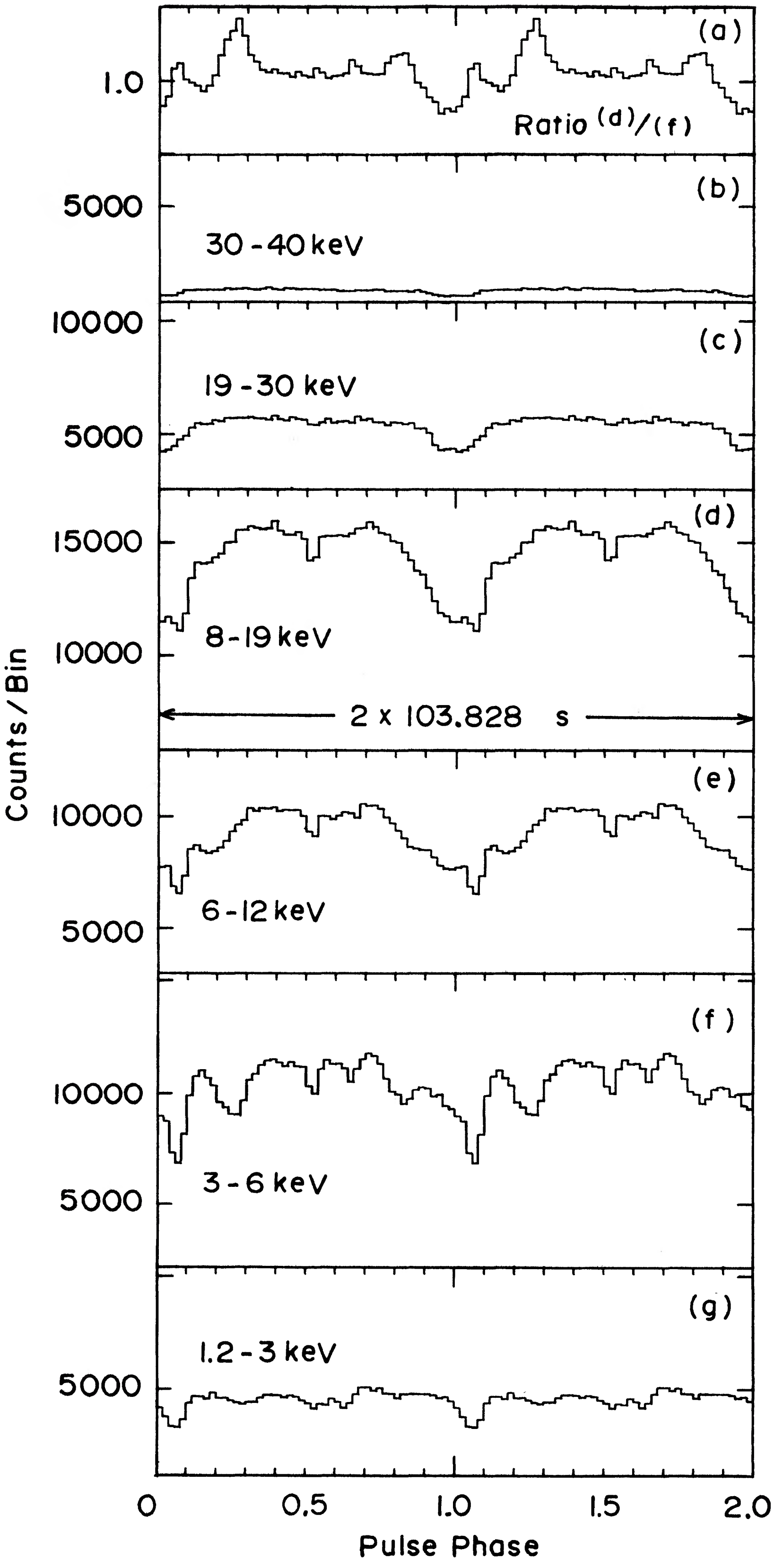

FIG. 1.—X-ray light curves for the sum of the 18 orbits of data folded into 50 bins modulo the pulse period 103.828 s. The folded data are repeated in a second set of 50 bins. The abscissa is drawn at the background level. The ordinate scale factor is the same in each plot. Statistical error bars (~±100 counts per bin) are too small to be shown. The ratio of the 8–19 keV and 3–6 keV light curves is presented in Fig. 1*a*. The observations span the period May 30–June 2 (JD 2,442,562.5–2,442,565.7). See Ricker *et al.* (1976) for light curves which extend to ~100 keV.

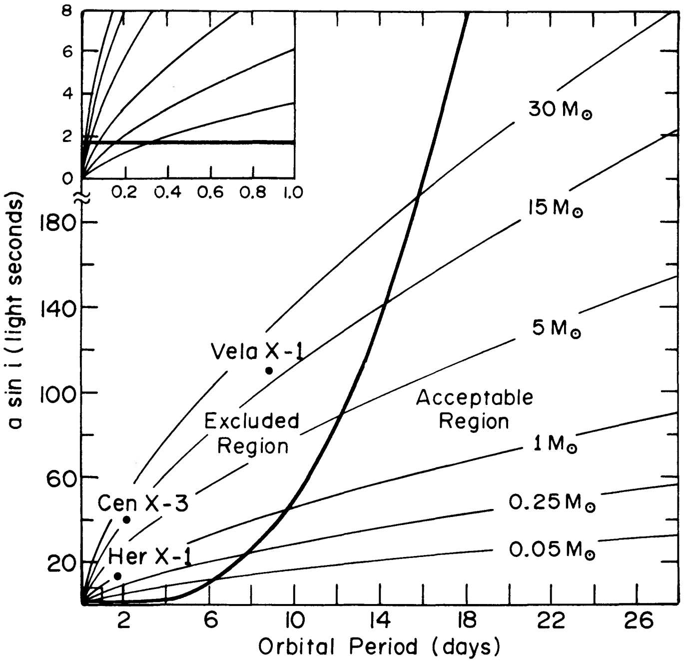

FIG. 2.—Upper limits (*heavy curve*; 95% confidence) on values of $a \sin i$ and the mass function for A0535+26 as a function of orbital period. The limits are calculated for circular orbits and would be larger for eccentric orbits. The lighter curves are contours of constant mass function $f(M)$. Note that the three known pulsing binaries Her X-1, Cen X-3, and Vela X-1 lie in the excluded region for A0535+26. The inset at the top of the figure is a 10× blowup of the region marked by a rectangle at the lower left.

$\sim$14 days. If instead we postulate moderately short orbital periods (1–4 days), then acceptable values of the mass function are very small, i.e. $f(M) \leq 0.008\ M_\odot$. For very short orbital periods, i.e., $P_0 \lesssim 4^{\rm h}$, the limits on $f(M)$ become substantially larger. A similar calculation for eccentric orbits would yield higher limits for $a \sin i$ and $f(M)$ than those indicated in Figure 2.

It is possible that the pulse period is the wobble period of a rapidly rotating neutron star (Brecher 1975) with a rotation period of $\lesssim$1 s (see Pines and Shaham 1972). However, we find no evidence in the X-ray data for such short periodicities.

Finally, the 104 s period may be an orbital period rather than a rotation or pulsation period. In this case, the binary companion must be a compact object that undergoes episodic mass loss. Gravitational radiation from the binary system would cause the orbit to decay, and this in turn could drive the mass transfer (cf. Pringle and Webbink 1975; Pacini and Shapiro 1975).

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H. Schnopper: Center for Astrophysics, 60 Garden St., Cambridge, MA 02138