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A 5.57 HR MODULATION IN THE OPTICAL COUNTERPART OF 2S 1822−371

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ABSTRACT

A periodic 5.57 hr modulation has been observed in the optical counterpart of the X-ray source 2S 1822−371. Two alternative periods are consistent with the data: $P = 0^{d}.232114$ and $P = 0^{d}.232191$, with statistical uncertainties of $0^{d}.000015$ in each case. Minimum light occurred at JD 2,444,105.668 ± 0.005. The amplitude of the modulation is about 1 mag, independent of *UBV* color, and no variability exceeding the 2% level other than the 5.57 hr effect is found on time scales down to a few seconds. The light curve of the star can be understood in terms of a highly inclined close binary system which contains a relatively large, luminous accretion disk that is periodically occulted by a companion star and an associated gas stream. On the assumption that the companion is a main-sequence star, the distance of the system is found to be more than 600 pc, based on the absence of color variations commensurate with the 5.57 hr intensity cycle. The corresponding maximum 2–11 keV luminosity of the source is more than 4×10^{34} ergs s^{-1}.

Subject headings: stars: variables — X-rays: binaries

I. INTRODUCTION

The variable galactic X-ray sources (e.g., Bradt, Doxsey, and Jernigan 1979) can be loosely classified on the basis of their observed properties to be of two types. Those belonging to the first type generally have hard X-ray spectra, pulsed X-ray emission, and are found in binary association with relatively normal early-type stars that dominate the optical emission of the system. These sources have been shown fairly conclusively to be magnetized neutron stars that are accreting material from their binary companion. There are also related systems such as Cyg X-1 in which the accreting body may be a black hole and not a neutron star. The second group contains the remaining sources that do not exhibit such easily interpretable characteristics and are consequently not well understood. This group may eventually be resolved into more than one fundamentally different type of source, but presently they can be observationally classified as showing some or all of the following characteristics: soft, variable X-ray spectra; no X-ray pulsations; and relatively faint, blue optical emission whose spectrum is dominated by emission lines, particularly He II λ4686 and the C III–N III λ4640 blend. Many of these systems also show X-ray and optical bursts.

Recent detailed optical studies of some members of this second group have uncovered evidence for periodic behavior that suggests that they too are binary systems (Gottlieb, Wright, and Liller 1975; Thorstensen *et al.* 1979; Middleditch *et al.* 1980). In this *Letter*, we report another example of such a system, 2S 1822−371 (Griffiths *et al.* 1978). It is shown that this star exhibits a regular and morphologically stable modulation in its optical light with an amplitude of ~1 mag and a period of 5.57 hr.

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II. OBSERVATIONS

The optical counterpart of 2S 1822−371 (Griffiths *et al.* 1978) was observed photometrically with the 1.5 m telescope at CTIO on 1979 June 20. The unfiltered light from the star was measured using an S20 photocathode. A second photomultiplier tube was attached to the offset guider in place of the eyepiece and was used to monitor simultaneously a nearby star for comparison. Data were taken at a time resolution of 10 ms for the first 34 minutes of the 1 hr 45 minute observation; thereafter, because of a computer failure, only 50 s temporal resolution was available. The data from this run are plotted in Figure 1 integrated in 50 s intervals and clearly show that the optical emission of 2S 1822−371 is variable by a factor of ~2 on a time scale of about an hour.

To determine whether this variability was periodic, we obtained a series of photographs of the star using the 26 inch (66 cm) Yale-Columbia refractor at the Mount Stromlo Observatory. A total of 36 good exposures of 20 minutes duration were made between 1979 July and October on sensitized IIA-O plates. No filter was used, but the combined response of the emulsion and the telescope corresponds closely to a photoelectric *B* magnitude. The images of 2S 1822−371 plus 13 comparison stars were measured using the Mount Stromlo Iris photometer, while the magnitudes of four of the comparison stars were calibrated photoelectrically with the 30 inch (76 cm) telescope at Mount Stromlo. This procedure provides magnitude estimates

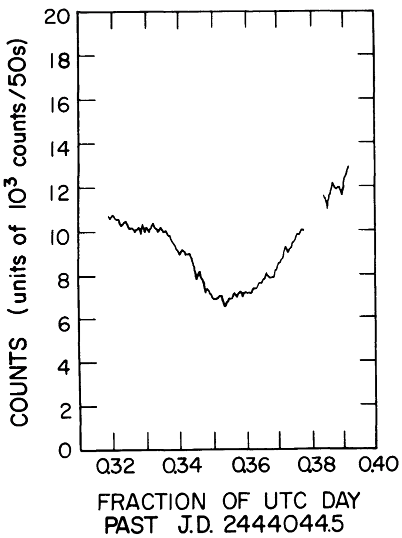

FIG. 1.—Photometric observation of 2S 1822−371 made in white light on the 1.5 m telescope at CTIO on 1979 June 20. The data have been accumulated in 50 s intervals, and the effects of small (<3%) changes in atmospheric transparency have been corrected by reference to data on a comparison star taken simultaneously with a second data channel, after an ~20% contribution from background light in both channels has been removed.

for 2S 1822−371 which are probably accurate to $0^{\mathrm{m}}05$, and certainly to $0^{\mathrm{m}}1$.

After only a few nights of photographic photometry, it became clear that the variability of 2S 1822−371 was indeed periodic with a period close to 5.57 hr (Seitzer *et al.* 1979). All 36 photographic measurements of 2S 1822−371 are plotted in Figure 2 folded on the best-fit period derived below ($5^{\mathrm{h}}5707$). The B magnitude of the star varies between $15^{\mathrm{m}}4$ and $16^{\mathrm{m}}4$, while the scatter in the folded light curve is consistent with the expected accuracy of the data, indicating that the modulation is morphologically stable. The light curve is flat-topped, with an asymmetric minimum that has a relatively slow decline and a steep rise. The width of the minimum at half-light is ~0.3 of a cycle.

Further photoelectric photometry of 2S 1822−371 was obtained with the CTIO 1.5 m telescope in 1979 August. The comparison channel was unavailable at this time, so a sequence of ~15 minute runs were made on the star using a B filter, interspersed with short U- and V-band observations and measurements of a standard star and the background sky brightness. The data have been reduced to the standard UBV system, and the B-band data are plotted in the lower panel of Figure 3. Data taken on August 19-20 and 20-21 have been combined to give complete coverage of the 5.57 hr cycle.

The data taken at CTIO in August confirm the asymmetry of the modulation found photographically and further indicate that the minimum can be described by two components: a broad, shallow ($\Delta m \approx 0.3$) feature that begins at phase ~0.66, superposed on a second, narrower minimum centered at phase 0.0 (by definition). The star recovers its maximum flux at phase ~0.17. The shoulder in the light curve at phase ~0.91 is clearly present in the June data (Fig. 1), confirming that this is a recurrent feature of the light curve. There also appears to be a shallow ($\Delta m \approx 0.07$) secondary minimum lasting for about 20% of the cycle and centered at phase 0.5.

The UBV measurements made in 1979 August at CTIO yield mean colors for 2S 1822−371 of $B - V = -0.006 \pm 0.007$ and $U - B = -1.01 \pm 0.01$. There is an additional systematic uncertainty of $0^{\mathrm{m}}008$ and $0^{\mathrm{m}}02$, respectively, in transforming to the standard color system. The $B - V$ and $U - B$ colors of 2S 1822−371 as a function of phase in the 5.57 hr cycle are illustrated in the top two panels of Figure 3. There is no detectable change in these colors as a function of intensity or time, and we can set a 2 σ upper limit of $\Delta(B - V) < 0^{\mathrm{m}}07$ and $\Delta(U - B) < 0^{\mathrm{m}}14$, respectively.

a) *Ephemeris*

The measurements of the heliocentric time of minimum light of 2S 1822−371 obtained from the 1979 data reported in this *Letter* are listed in Table 1. These can be combined to yield a period of $0^{\mathrm{d}}23215 \pm 0^{\mathrm{d}}00004$ with minimum at JD 2,444,105.668 ± 0.005.

Charles, Thorstensen, and Barr (1980) obtained two 15 minute red exposures of 2S 1822−371 in 1978, centered on JD 2,443,628.793 and JD 2,443,629.866, during which the magnitude of the star differed by 0.5 mag (a 6 σ difference). It is likely that the second, fainter measurement was made near minimum light, while the first was made during the relatively flat maximum of the light curve. 2S 1822−371 is 0.5 mag fainter than

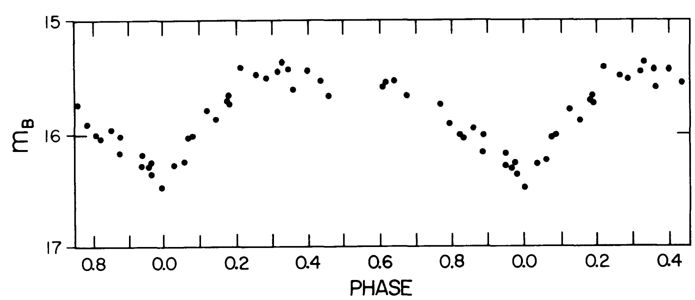

FIG. 2.—Photographic photometry of 2S 1822−371 taken at Mount Stromlo between 1979 July and October folded about the best-fit period derived in the text. Phase is measured from the minimum of the light curve.

maximum at phase ~0.8 and ~0.1 (Fig. 2), which implies that minimum light occurred either at JD 2,443,629.912 or JD 2,443,629.838, with a conservative uncertainty of 0.1 cycles ($0^d.023$) (based on the precision of the photographic photometry and the known gradient of the light curve). This latter information can be used to refine further the period given above. There are two periods that are consistent with both the 1979 data and one or the other of the two alternative epochs for minimum light inferred from the 1978 data. These are $P = 0^d.232114 \pm 0^d.000015$ ($\chi^2 = 2.4$ for 5 d.o.f.) and $P = 0^d.232191 \pm 0^d.000015$ ($\chi^2 = 4.2$ for 5 d.o.f.).

b) *Short Time Scale Variability*

The unfiltered high-time-resolution data taken in 1979 June with the two-channel photometric system have been searched for short time-scale variability in 2S 1822−371. The signal on this star (~2000 ct s^{-1}) was found to vary on a time scale of a few seconds, in excess of the variability expected from statistical processes alone. The excess variability had a rms amplitude of ~2% of the mean count rate. Although the comparison star showed no such excess on a signal of ~14,000 ct s^{-1}, this is treated as an upper limit to the intrinsic variability of 2S 1822−371, since the comparison data were taken through a larger diaphragm and would be less sensitive to variations induced by seeing fluctuations. Fourier analysis of a second (nonphotometric) 5 hr time series taken in 1979 August in white light revealed no statistically significant periodicities in the optical emission of 2S 1822−371 above a level of 0.2% between 0.2 and 50 Hz.

TABLE 1

2S 1822−371: Heliocentric Epochs of Minimum Light

Epoch (JD)	Uncertainty	Cycle Number (relative)	Comments[a]
2,444,044.845	0.006	0	pe
2,444,090.114	0.008	195	pg
2,444,101.028	0.008	242	pg
2,444,105.665	0.006	262	pe
2,444,106.597	0.006	266	pe
2,444,137.935	0.01	401	pg

[a] pe = photoelectric; pg = photographic measurements.

III. DISCUSSION

The 5.57 hr modulation of the light from 2S 1822−371 most probably reflects the orbital motion of the system.

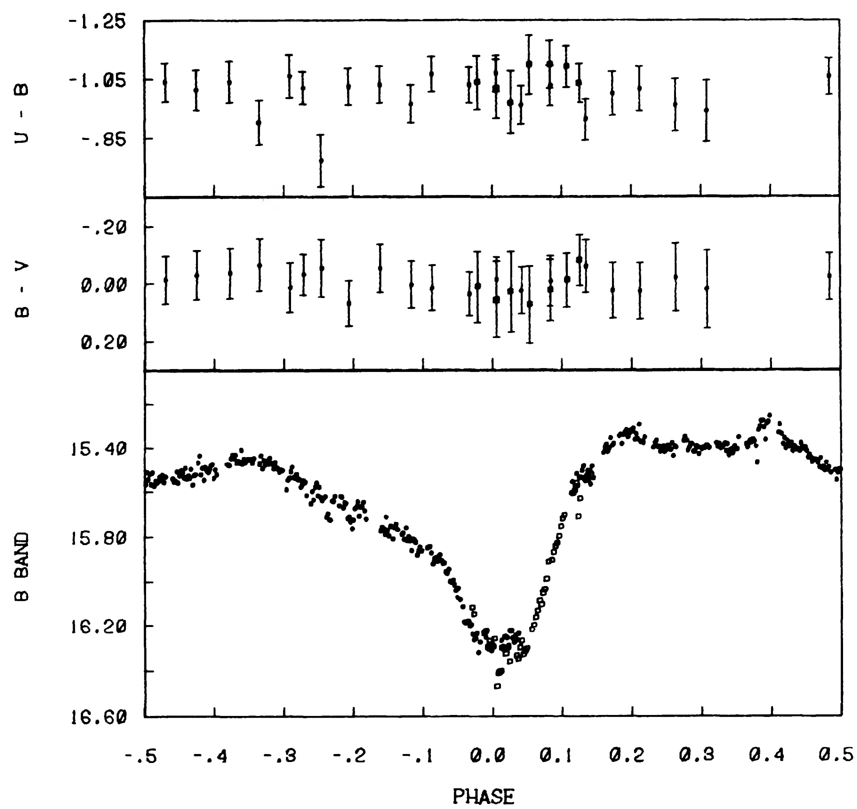

FIG. 3.—Photometry of 2S 1822−371 taken at CTIO on August 19-20 (*filled symbols*) and August 20-21 (*open symbols*) folded on the best-fit period derived in the text. The run on August 19-20 spanned almost exactly one 5.57 hr cycle and began at phase 0.41. The lower panel shows data taken in a B filter, while the upper two panels show the $B - V$ and $U - B$ colors.

Similar orbital periods are found among the cataclysmic variable stars, many of which are also weak X-ray sources (Cordova, Mason, and Nelson 1980). This suggests that 2S 1822−371 may be a related kind of accreting-dwarf binary system, although its optical spectrum (Charles, Thorstensen, and Barr 1980) and the $\sim 2\%$ limit on short time-scale flickering in its optical light set it apart from the cataclysmic variables at least in a phenomenological sense. The lack of rapid variability suggests that the major source of optical emission in 2S 1822−371 is relatively extended and is not likely to be, for example, a localized bright spot on an accretion disk (cf. dwarf novae; Warner 1976) or emission from an accretion column (cf. Am Her; Chiapetti, Tanzi, and Treves 1980).

The optical light curve of 2S 1822−371 is morphologically similar to the periodic 4.8 hr X-ray and infrared modulation of Cyg X-3 (e.g., Mason *et al.* 1976), although the sense of the asymmetry is reversed. The light curve of 2S 1822−371 is, however, significantly different from the more nearly sinusoidal light curve of 4U 2129+47 (Thorstensen *et al.* 1979), which is believed to result from X-ray heating of a companion star. The smaller duty cycle modulation of 2S 1822−371 is more suggestive of occultation of a luminous emission region, for example, an accretion disk, by a companion star.

The lack of detectable color modulation commensurate with the 5.57 hr flux variability imposes constraints on the brightness of any second source of light in the binary system (for instance a companion star) that depend on its color. We assume that the second light source has a constant brightness and that the primary emission is modulated so as to produce the observed variability and compute the maximum allowed contribution of the second source to the V-band flux of 2S 1822−371 at maximum light for a range of secondary source colors. The 2 σ limits on the percentage contribuition of the second source are listed in Table 2 and range from 8% if it has the colors (after reddening) of an M0 star to 16% for the colors of an A0 star.

A further constraint on the system can be obtained if it is assumed that the companion star fills its Roche lobe and obeys the mass-radius relation of a main-sequence star (e.g., Warner 1976; Paczyński 1971). Allowing for uncertainties in the mass-radius relation (cf. Warner 1976; Allen 1973), we find for the companion $0.5\,R_\odot < R_c < 0.7\,R_\odot$ and $0.4\,M_\odot < M_c < 0.8\,M_\odot$ corresponding to main-sequence stars with spectral type in the range $\sim$M2–K0. When combined with the data in Table 2, this implies that the companion star contributes at most 11% of the total V light of the system at maximum light. If the star is not appreciably reddened, the latest spectral type allowed can be combined with the corresponding magnitude limit derived from the lack of color variation to set a lower limit on the distance of the 2S 1822−371 system of $\sim$600 pc. The reddening of the system is unlikely to be severe because of its blue color ($U - B \approx -1.0$) and its galactic latitude ($b = -11°$). Combining a distance limit of 600 pc with the maximum observed X-ray flux of 2S 1822−371 (Bradt, Doxsey, and Jernigan 1979), we find that the maximum X-ray luminosity of the source exceeds $\sim 4 \times 10^{34}$ ergs s^{-1}.

TABLE 2

SECOND LIGHT SOURCE

Reddened Colors		Equivalent Spectral Type (V)	f_v[a] (%) (2 σ)	m_v[b]
$B-V$	$U-B$			
1.45	+1.28	M0	<8	>18.1
0.89	+0.47	K0	<11	>17.8
0.58	+0.05	G0	<13	>17.6
0.27	+0.07	F0	<14	>17.5
0.00	−0.02	A0	<16	>17.4

[a] % of V-band light at maximum contributed by second source of light of indicated color.

[b] Apparent magnitude of second source.

The radius of the companion star together with the semimajor axis of the binary derived from Kepler's third law [$a = 1.58\,(m_T/m_\odot)^{1/3}\,R_\odot$ for $P = 5^h.57$], suggests that the companion star subtends an angle of between 30° and 40° at the X-ray source. This is of the same order as the fractional half-width of the narrow component of the light-curve modulation and suggests that this component may result from occultation by the companion star of an extended luminous disk around the X-ray source in a system with high orbital inclination. The additional light loss observed between orbital phase $\sim$0.66 and $\sim$0.91 may be due to absorption in a gas stream that connects the companion star to the X-ray source or to a thickened sector of the disk where it interacts with the gas stream (cf. Lubow and Shu 1976). If the optical emission region is an accretion disk, then it may be intrinsically luminous and may also reprocess X-radiation incident on it. The ratio L(2–11 keV)/L(3600–6400 Å) for 2S 1822−371 lies in the range 13–65 (corresponding to the minimum and maximum X-ray flux listed by Bradt, Doxsey, and Jernigan 1979), but the blue colors of the star suggest that it may radiate a substantial portion of its energy in the UV. The limits imposed on the intrinsic X-ray luminosity ($L_x > 4 \times 10^{34}$ ergs s^{-1}) do not preclude a degenerate dwarf as the X-ray emitter (Kylafis and Lamb 1979). However, the X-ray luminosity of 2S 1822−371 is significantly greater than that of accreting degenerate dwarfs in cataclysmic variable systems (cf. Cordova, Mason, and Nelson 1980).

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