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ULTRAVIOLET SPECTROPHOTOMETRY OF 2A 1822−371: A BULGE ON THE ACCRETION DISK

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ABSTRACT

The X-ray source 2A 1822−371 has been observed with the *IUE* satellite over an 8 hour period. Long and short wavelength exposures of duration 45 or 60 minutes were alternated in order to resolve the 5.57 hr photometric modulation of the star. The data provide evidence that the shape of the 5.57 hr modulation evolves smoothly with energy between extremes defined by the optical and X-ray curves. The far-UV light curve is more deeply modulated than the X-ray light curve. The combined ultraviolet and the *UBV* band optical data can be fitted with a single blackbody of temperature 2.7×10^4 K, or an optically thick disk model with parameters $T_* = 1.2\times10^5$ K and $R_{\rm out}/R_{\rm in} \sim 30$. A single power-law model does not adequately represent the continuum. There is evidence of absorption due to the 2200 Å interstellar feature whose depth requires a color excess, $E(B-V) \sim 0.1$, with 3 σ upper and lower bounds of 0.29 and 0.01. Emission lines of C IV 1550 Å and N V 1240 Å are detected in the UV spectrum. The work of Mason *et al.* and White *et al.* suggests that the optical and ultraviolet emission arises in an accretion disk, whereas the X-radiation is emitted from a scattering cloud that envelopes a central compact object. In the present paper, the 5.57 hr optical, X-ray and ultraviolet modulation of 2A 1822−371 is interpreted as the result of partial occultation of the emitting region by a companion star and a bulge on the outer accretion disk. X-ray heating of the bulge will probably also contribute to the modulation at optical and ultraviolet wavelengths.

Subject headings: spectrophotometry — stars: individual — ultraviolet: spectra — X-rays: binaries

I. INTRODUCTION

The star 2A 1822−371 has periodic optical and X-ray light curves that distinguish it from any system studied thus far. The unusual features of these light curves are summarized by Mason *et al.* (1980; hereafter M80) and White *et al.* (1981; hereafter W81) and have given rise to an interpretation of the source as an interacting binary system in which the X-rays are emitted from a scattering cloud that envelopes an accreting compact component. The optical emission is produced in a disk of accreting material that surrounds the cloud and central source. The optical and X-ray light curves are very stable and devoid of flickering. The light curves in both bands can be characterized by two modulation components. One is a relatively narrow dip thought to be caused by occultation of the emitting region by an orbiting companion star. A second, broader modulation has been explained in two ways. The first explanation, proposed by M80 on the basis of the optical light curve alone, is that the emitting region is occulted by a gas stream from the companion, or (more likely) by a bulge on the accretion disk where the gas stream collides with it. This model can be extended to include the X-ray light curve (W81). Alternatively, W81 have discussed the possibility that the broad modulation of the X-ray source is caused by beaming of the X-ray emission.

In this paper we report on ultraviolet spectrophotometry of 2A 1822−371 taken around the 5.57 hr cycle with the *IUE* satellite. The pronounced energy dependent modulation found in the ultraviolet enables us to clarify the origin of the various modulation components and to determine a geometry for the system consistent with all the data.

II. OBSERVATIONS

Eight low-resolution spectra of 2A 1822−371 were obtained with the *IUE* satellite on 1980 September 5 at various phases in the 5.57 hr cycle. Spectra were taken alternately in the long (1900–3200 Å; LWR) and short (1200–1900 Å; SWP) wavelength camera using a 10″ × 20″ entrance aperture. The exposure times were either 45 minutes or 60 minutes. A journal of the observations is contained in Table 1, which lists the phase interval

[1]Guest observer on the *IUE* satellite.

TABLE 1

JOURNAL OF OBSERVATIONS

Exposure	Start Time (1980 Sep 5 UT)	Duration (Minutes)	Phase Interval[a]
LWR 8715 ...	$00^h:34^m$	60	0.151–0.332
SWP 10010 ...	$01^h:36^m$	60	0.336–0.513
LWR 8716 ...	$02^h:37^m$	60	0.517–0.698
SWP 10011 ...	$03^h:39^m$	60	0.702–0.883
LWR 8717 ...	$04^h:42^m$	45	0.892–0.026
SWP 10012 ...	$05^h:29^m$	45	0.034–0.168
LWR 8718 ...	$06^h:19^m$	45	0.185–0.319
SWP 10013 ...	$07^h:06^m$	45	0.323–0.461

[a] Calculated from an epoch JD 2,444,105.668 using a period of $0^d.232110$.

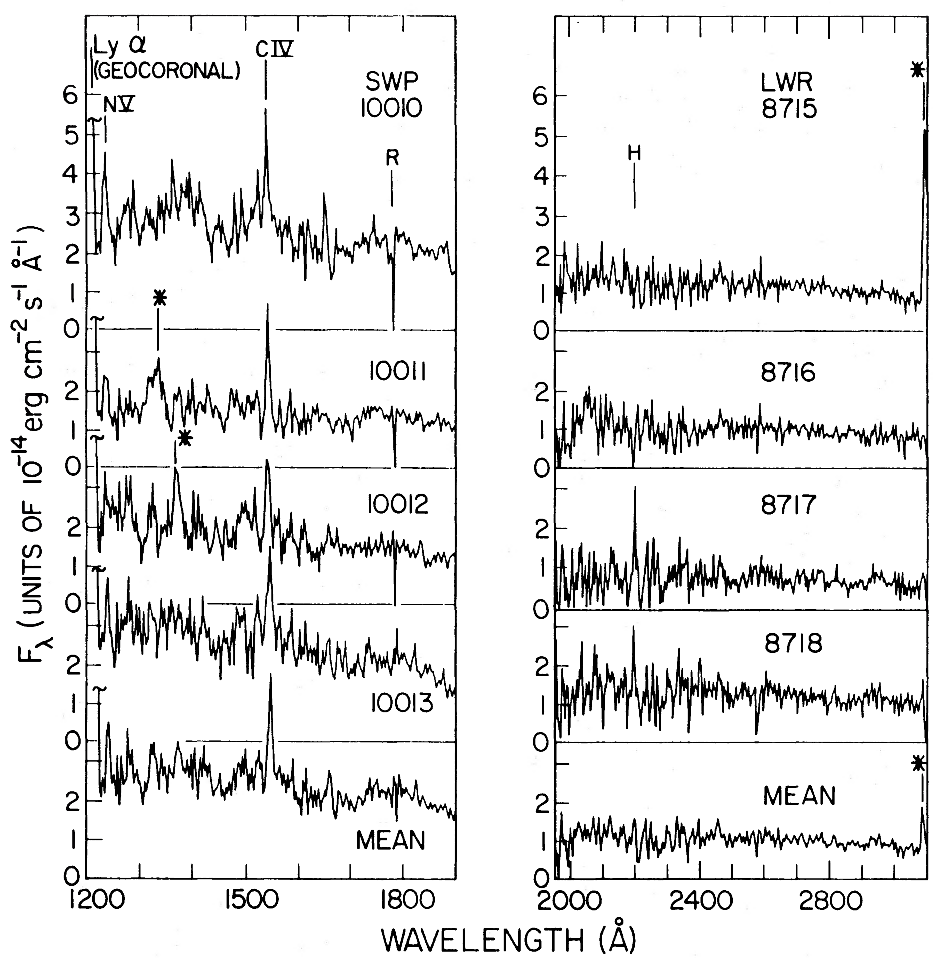

FIG. 1.—Reduced short wavelength (SWP) and long wavelength (LWR) *IUE* spectra of 2A 1822−371. Exposure times are listed in Table 1. The bottom panel in each case is the mean of the four SWP and four LWR exposures. Features marked by an asterisk are ion events in the detector; the feature marked "R" is due to camera reseaux; and that marked "H" is due to a hot pixel. The geocoronal Lyα line is truncated for clarity.

covered by each spectrum, calculated using the epoch of optical minimum given by M80, JD 2,444,105.668, and the period of $0^{d}.232110$ derived by W81. The reduced spectrum obtained from a line-by-line analysis of each of the observations is plotted as a function of wavelength in Figure 1, together with the mean LWR and SWP spectra. The *IUE* absolute calibration used is that of Bohlin and Holm (1980).

a) *Continuum Modulation*

The continuum flux in each spectrum has been integrated in approximately 300 Å intervals in order to determine how the ultraviolet flux of 2A 1822−371 varies as a function of time. The contribution to the flux due to emission lines and instrumental features was removed prior to the summation. The data in each ~300 Å wavelength interval have been normalized to the value for the first LWR or SWP spectrum, as applicable, and are plotted as a function of time in four exposure bins in Figure 2 on the same relative scale. The LWR data are plotted separately from the SWP data with which they are interspersed. The errors in the data points are dominated by systematic uncertainties due to background subtraction. They are estimated to be generally about 10% in the lowest intensity bins, but somewhat higher in the LWR spectra below about 2200 Å where the detector response is falling off and the data are noisy (see Fig. 1).

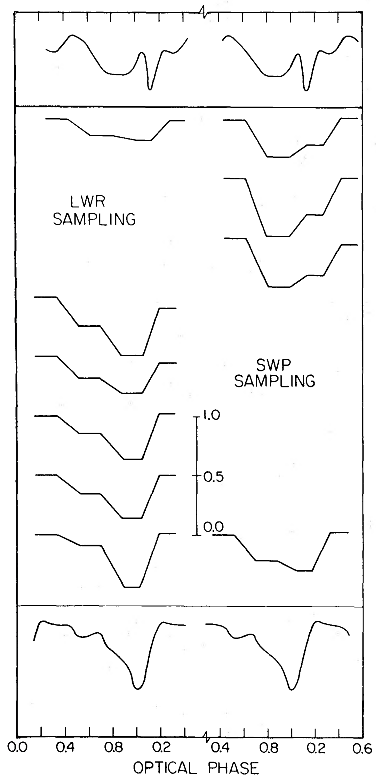

FIG. 2.—Wavelength dependent "light curves" of 2A 1822−371 derived by integrating the continuum flux in the *IUE* exposures in the indicated wavelength range. The optical and X-ray light curves of M80 and W81 are sketched, and these have also been binned in the same way as the *IUE* data for comparison. The data have been normalized to the flux value in the first LWR or SWP exposure in each case. Phase is calculated from an epoch JD 2,444,105.668 using a period of $0^{d}.232110$.

To compare the UV data with the optical and X-ray light curves of M80 and W81, we have sketched the latter in Figure 2. The optical and X-ray data have also been integrated in phase intervals corresponding to the sampling pattern of the *IUE* exposures. The flux levels so obtained have been normalized in the same way as the ultraviolet data and are plotted on the same scale as the latter in Figure 2. The intervals corresponding to the LWR and SWP sampling patterns are again treated separately. The differences between the binned X-ray and optical light curves reflect the different relative contributions of the broad and narrow modulation components in the two bands (M80; W81).

In comparing the ultraviolet data to the binned X-ray and optical light curves, we find evidence for an evolution in the 5.57 hr modulation as a function of energy. The relative flux levels in the four SWP exposures resemble those of the X-ray light curve more than the optical light curve. Furthermore, the depth of modulation is higher in the 1260–1600 Å band than in the 1600–1900 Å band, and both of these are more deeply modulated than the X-ray data. The ratios of the flux in the lowest and highest bins are 0.59, 0.51, and 0.78 for the 1600–1900 Å, 1260–1600 Å, and X-ray regions respectively. The absolute uncertainty in the UV ratios due to background subtraction is estimated to be at most 10%, while the relative uncertainty in the UV measurements is estimated to be ~5%.

The LWR data independently suggest a progressive change in the light curve with wavelength in the ultraviolet range. When binned in the same way as the *IUE* LWR measurements, the optical light curve has a pronounced minimum in "exposure" 3, whereas the X-ray light curve binned similarly is much shallower, with more nearly equal fluxes in "exposures" 2 and 3. The 2800–3000 Å, 2500–2800 Å, and 2200–2500 Å light curves measured with *IUE* demonstrate a gradual change between the extremes of shape defined by the optical and X-ray data. In agreement with the SWP measurements, however, the 2200–2500 Å light curve is more deeply modulated than the X-ray data, even though the relative distribution of flux in the four bins is very similar. The 1900–2200 Å data are noisy, as noted earlier, and do not usefully constrain the shape of the light curve in this band. Because of the relatively coarse binning of the *IUE* data, we cannot be certain that, if the UV light curve were observed at higher time resolution, there would be a one-to-one correspondence between the detailed shape of the optical and near-UV light curve at one extreme, and the X-ray and far-UV light curve at the other; but this would be consistent with the present data, apart from the differences in the depth of the modulation.

b) *The Continuum Distribution*

To measure the shape of the ultraviolet continuum of 2A 1822−371 in more detail, the SWP and LWR data have been summed and integrated in 100 Å bins (excluding lines and instrumental features). Because of the wavelength dependence of the 5.57 hr modulation, discussed in the previous section, we have summed data only from the flat maximum of the light curve—i.e., SWP 10010 and 10013; LWR 8715 and 8718—where we can be sure that the time difference between SWP and LWR exposures will be unimportant. The resulting data are plotted in Figure 3 together with U, B, and V measurements of 2A 1822−371 at maximum taken from M80.

There is evidence for some absorption in the spectrum due to the 2200 Å interstellar feature. To obtain a quantitative estimate of the depth of this feature, we have dereddened the continuum by various amounts using the extinction curve of Nandy *et al.* (1975). A power law has been fitted to each of the dereddened curves over the range 1200–3100 Å, and the degree of correlation between the residuals from this fit and the residuals from a similar power-law fit to the extinction correction curve has been calculated using a nonparametric distribution free test for independence (Kendall's K statistic; e.g. Hollander and Wolfe 1973). The best value for the reddening is taken to be that which yields the least correlation with the reddening curve (usually zero). This procedure provides a repeatable and comparatively unbiased measurement of the depth of the 2200 Å feature for a blue, single component spectrum. The method has been tested with the ultraviolet data of Willis *et al.* (1980) on Sco X-1. We find that the Sco X-1 data can be fitted best by $E(B-V)=0.35$ with 3 σ upper and lower limits of 0.42 and 0.26, respectively, in good agreement with Willis *et al.*'s eye estimates of $E(B-V)=0.35\pm0.05$. For 2A 1822−371 we find the best fit value of the color excess to be $E(B-V)=0.10$ with 3 σ upper and lower bounds of 0.29 and 0.01. $E(B-V)=0.0$ can be excluded at the 3.6 σ confidence level. The X-ray absorption column density of $\sim10^{21}$ atoms cm^{-2} (W81) implies $E(B-V)\approx0.15$, according to the calibration of Ryter, Cesarsky, and Audouze (1975).

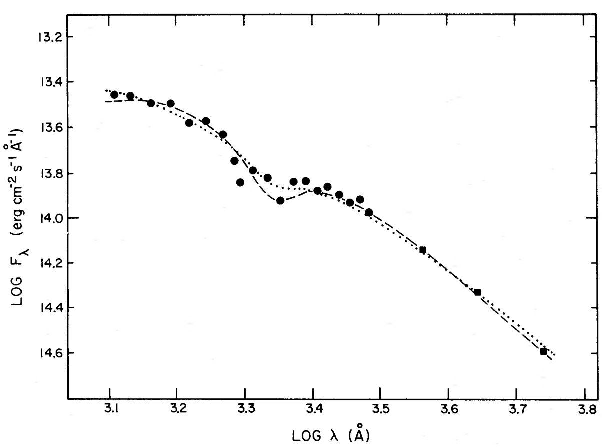

FIG. 3.—The ultraviolet and optical continuum of 2A 1822−371. The circles are the data from SWP 10010 and 10013 and LWR 8715 and 8718 integrated in 100 Å intervals. The squares are the U, B, V measurements of M80. The dashed line is a blackbody spectrum of temperature 2.7×10^4 K reddened by an amount corresponding to $E(B-V)=0.2$ using the extinction curve of Nandy *et al.* (1975). The dotted line is an optically thick disk model with parameters $T_*=1.2\times10^5$ K, $R_{out}/R_{in}=30$ and $E(B-V)=0.1$.

We have fitted power-law, blackbody, and simple optically thick disk models to the combined UV flux and broad-band optical data, allowing the degree of reddening to be a free parameter. Although power-law models fit the UV data alone, they predict fluxes substantially in excess of those observed in the B and V bands. A single blackbody with a temperature of 2.7×10^4 K will fit the data if the color excess, $E(B-V)$, is 0.2. An optically thick, steady state disk model (cf. Bath, Pringle, and Whelan 1980) is also consistent with the data for parameters $T_*=1.2\times10^5$ K, $R_{out}/R_{in}=30$ and $E(B-V)=0.1$. The two latter models are sketched in Figure 3.

The observed integrated flux of 2A 1822−371 between 1200 and 6400 Å is 3×10^{-11} ergs cm^{-2} s^{-1}. Based on the 0.5–50 keV flux of 1.0×10^{-9} ergs cm^{-2} s^{-1} given by W81, the observed ratio ($L_{0.5\text{-}50\ \text{keV}}/L_{1200\text{-}6400\ \text{Å}}$) is about 35. An amount of reddening corresponding to $E(B-V)=0.1$ suggests that the intrinsic 1200–6400 Å flux of the star is about 5×10^{-11} ergs cm^{-2} s^{-1}, and that the intrinsic ratio ($L_{0.5\text{-}50\ \text{keV}}/L_{1200\text{-}6400\ \text{Å}}$) is about 20.

c) *Emission Lines*

The *IUE* spectra of 2A 1822−371 were deliberately underexposed in order to resolve the 5.57 hr modulation. Consequently, they are not ideally suited to the measurement of the emission line spectrum of the star. The only lines convincingly detected in more than one exposure are C IV 1550 Å and N V 1240 Å. From the summed SWP spectra we measure line fluxes of 1.6×10^{-13} ergs cm^{-2} s^{-1} and 0.6×10^{-13} ergs cm^{-2} s^{-1} and equivalent widths of 9 Å and 4 Å respectively for the C IV and N V lines. The data do not allow reliable comments concerning the phase dependence of the lines.

III. DISCUSSION

The *IUE* observations demonstrate that the 5.57 hr light curve changes smoothly with energy in the ultraviolet range, resembling the *B* band light curve at the longest wavelengths, and the X-ray light curve at the shortest wavelengths. The modulated fraction is, however, significantly greater in the far ultraviolet than it is in the X-ray band.

To explain these phenomena we first consider the possibility that the broad component of the modulation is caused by obscuration of the emitting region along lines of sight centered on orbital phase ~0.8 (where optical minimum is defined as phase 0.0). Such obscuration might occur because of a bulge on the accretion disk at the point where the gas stream from the companion star collides with it, an explanation first suggested by M80. The model is sketched in Figure 4. If the bulge on the disk is regarded as a dark occulting object, the degree of modulation caused by it will depend on the relative extent of the emitting region. This will be a function of wavelength if the effective temperature of the accretion disk decreases with increasing radial distance from the central compact object. In this model most of the optical light would have to be emitted by the outer, cooler parts of the disk that subtend the largest solid angle at the bulge. The modulation resulting from a "dark" bulge would then be relatively broad and shallow in the optical band, as observed. If the far ultraviolet emission region is smaller, and is associated with the inner parts of the disk it will be more completely eclipsed by the bulge than the optical source. The ultraviolet modulation would thus be narrower and deeper than that in the optical band. The same holds true for the occultation by the companion star. If this could be resolved in the ultraviolet data, we would expect it to again be narrower and deeper than at optical wavelengths, if the above picture is correct.

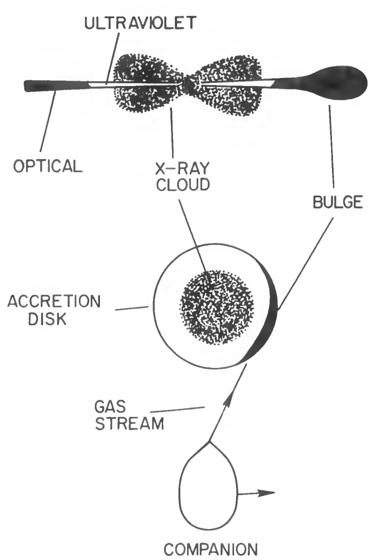

FIG. 4.—Sketch of the proposed model for 2A 1822−371 (not to scale).

In order to explain the relative depth of the X-ray and far ultraviolet modulations in this model, the X-ray emitting cloud would have to be more extended than the UV emitting region. The greater vertical extent of the X-ray cloud above the plane of the disk will contribute to this, particularly at inclinations close to 90°. However, it may be difficult to account for the magnitude of the observed effect unless the dimensions of the UV source are smaller than the extended X-ray source in the plane of the disk also. In the geometry envisioned in Figure 4, this would necessarily imply that the UV source is seen through the ionized gas that scatters the X-radiation. In this case the gas cloud must therefore be optically thin so as not to scatter a significant fraction of the UV photons. It then follows that only a small fraction of the X-ray photons emitted by the central source would be scattered by the cloud. Consequently, since most, if not all, of the X-ray photons seen at Earth appear to come from an extended region, the central X-ray source would have to be hidden from direct view, probably by the disk. The observed X-ray flux of 2A 1822−371 would then be only a lower limit to the true flux of the source, a possibility that has been noted previously by W81. A possible objection to this model is the shape of the X-ray spectrum which suggests that the X-ray photons have been scattered through at least five optical depths of material (W81). It is conceivable, however, that the optically thick part of the cloud is a small region confined to the central portion of the disk and is not viewed directly.

The assumption made above that the bulge on the accretion disk emits essentially no radiation itself requires examination and leads us to an alternate explanation of the optical and ultraviolet light curves and the high depth of the far-UV modulation. In cataclysmic variables, for instance, the point where the gas stream from the companion impacts the disk is often brighter than the rest of the disk in the optical band (Warner 1976). This may be due in part to the fact that the disk is underluminous in many of these systems (Paczynski and Schwarzenberg-Czerny 1980); but some contribution from the bright spot region might be expected regardless. In 2A 1822−371 significant emission from a bright spot of this sort would cause a modulation 180° out of phase with that observed. One reason that this is not prominent in 2A 1822−371 may be because of X-ray heating of the disk and the bulge. As noted earlier, X-radiation dominates the emission of 2A 1822−371. The energy emitted by the central X-ray source exceeds that emitted by the disk by at least a factor of 20. Much of the long wavelength luminosity of the system may thus arise because of X-ray heating (cf.

Pacharintanakul and Katz 1980), particularly since the X-ray emission is scattered by a cloud that is elevated above the disk, which increases the solid angle presented by the disk to X-ray photons. This can affect the modulation observed in two ways. First, the side of the bulge that faces away from the X-ray source will be shielded from X-ray heating. The bulge will therefore appear relatively "dark" when viewed against the unshielded disk at orbital phases near 0.8, so that the dark bulge model described earlier will be applicable. Second, the changing aspect of the X-ray heated face of the bulge (and the companion star if it is not completely shielded by the disk) with orbital phase will contribute to the observed 5.57 hour modulation of the optical and ultraviolet light. The bulge component will be in phase with, and therefore amplify, the modulation due to obscuration of the disk by the bulge. If the heated face of the bulge is a substantial far-UV source, this provides an alternate explanation for the high depth of modulation of the far-UV light curve with respect to the X-ray curve. Radiation from the cooler, outer face of the bulge may then be responsible for partially filling in the optical light curve.

Two further aspects of the data can be understood in the framework of the above description of 2A 1822−371. First, a comparison of the epochs of optical and X-ray minimum given by M80 and W81 suggests that there may be a displacement in phase between the narrow minima in the two bands such that the X-ray minimum occurs ~ 0.03 in phase after the optical minimum. This could come about if the bulge on the outer part of the disk distorts the centroid of the optical emission. Second, W81 have noted that the X-ray spectrum of 2A 1822−371 is slightly softer at minimum than at maximum. During the partial occultations of the X-ray emitting cloud by the bulge and the companion star, the outer regions of the cloud will be less completely occulted than the inner parts. The observed softening of the X-ray spectrum thus suggests that photons scattered from the outer parts of the cloud have a lower temperature distribution than those from the inner regions.

If we interpret the fit of the simple optically thick disk model to the optical and UV spectrum in the standard manner (Bath *et al.* 1980), we find that the inner radius of the disk is $<3\times10^9$ cm (assuming that the outer radius of the disk is less than the Roche radius of the compact star, taken to be $\sim 10^{11}$ cm), the total luminosity of the disk is $\sim 5\times10^{34}(R_{\rm in}/10^9 \text{ cm})^2$ ergs s^{-1} and the distance of the system is $\sim 3(R_{\rm in}/10^9$ cm) kpc. We stress, however, that if X-ray heating is important in determining the temperature profile and luminosity of the disk, as argued above, the parameters of this model lose their meaning, although the shape of the resulting spectral distribution could nevertheless resemble that of a disk. In this case the single blackbody model may in fact be more appropriate. A self-consistent calculation of the optical and UV spectrum of 2A 1822−371, including the effects of both internal (viscous) heating and X-ray heating, should take into account the geometry of the disk, the bulge, and the X-ray cloud.

The ratio of the X-ray to the optical plus ultraviolet flux of 2A 1822−371 substantially exceeds the value of <1 that has been found in cataclysmic binaries (Córdova, Mason, and Fenimore 1981). The integrated luminosity of 2A 1822−371, although more uncertain, probably also exceeds that of the cataclysmic systems (W81). Cataclysmic binaries are thought to contain an accreting degenerate dwarf. In a disk accreting star, approximately half of the original potential energy of the accreted matter is dissipated in passage through the disk. The remainder, corresponding to the Keplerian energy of the innermost disk orbit, is believed, in normal cataclysmic binaries, to be dissipated in a boundary layer close to the degenerate star (cf. Pringle and Savonije 1979) and gives rise to the X-radiation observed. For the typical accretion rates of $<10^{18}$ g s^{-1} found in cataclysmic binaries, the maximum temperature of the inner disk is $\sim 10^5$ K if the innermost disk orbit is limited by the radius of a degenerate dwarf to be $\sim 10^9$ cm (e.g., Bath *et al.* 1980). Consequently, most of the disk luminosity in these systems is emitted in the optical and ultraviolet range, and the observed ratio of $L_x/(L_{\rm UV}+L_{\rm opt})\sim 1$ reflects the equipartition between the energy emitted in the disk and that emitted close to the degenerate dwarf. In principle, higher ratios of $L_x/(L_{\rm UV}+L_{\rm opt})$ could occur if matter is funneled by a magnetic field directly onto the degenerate dwarf without an intermediate disk. However, the observation of broad absorption lines in the spectrum of 2A 1822−371 (Mason *et al.* 1981), together with the arguments presented in the present paper, strongly suggest that there is a disk in this star. The high ratio of $L_x/(L_{\rm UV}+L_{\rm opt})$ in 2A 1822−371 is therefore a strong indication that the compact star in this system is one that has a deeper gravitational potential well than a degenerate dwarf, such as a neutron star or black hole. The maximum disk temperature could thus be such as to shift the majority of the disk luminosity to energies above the ultraviolet band. The total observed luminosity of 2A 1822−371, $L=2\times10^{37}(d/10 \text{ kpc})^2$ ergs s^{-1}, requires a mass accretion rate of $2\times10^{17}(d/10 \text{ kpc})^2$ g s^{-1} if the accreting object is a one solar mass neutron star and d is the distance of the source. This accretion rate is of the same order as that determined for cataclysmic variables.

The modulation mechanism discussed above for 2A 1822−371 does not require that the X-ray source be beamed (W81). In any case, beaming of the X-ray source cannot alone explain the light curves in the optical and ultraviolet bands: if the X-ray source preferentially illuminated the disk in the direction $\phi\sim 0.4$, so as to reproduce the phase of the X-ray modulation, one would expect maximum optical and ultraviolet light to occur when the star is viewed from the direction of phase ~0.9, when in fact the optical and UV emission is declining. Elimination of the requirement that the X-ray source be beamed removes any bias towards a magnetic star as the compact object in this system.

IV. SUMMARY

It is suggested that the 5.57 hr modulation of 2A 1822−371 is caused by the combined effects of an occultation of the emitting region by a companion star and by a bulge on the accretion disk which surrounds the X-ray source. The changing aspect of the X-ray heated inner face of the bulge with orbital phase will probably also contribute to the modulation at ultraviolet and optical wavelengths. The position angle of the bulge suggests that it is probably the result of turbulence caused by the impact of a gas stream that transfers matter from the companion. 2A 1822−371 provides the most direct indication so far of the existence of such structure in an accretion disk. Various mechanisms have been discussed to explain the morphology of the 5.57 hr light curves at different wavelengths. It is anticipated that high time resolution far ultraviolet observations capable of resolving the broad modulation from the occultation caused by the companion star will improve our understanding of the degree to which these various mechanisms operate in 2A 1822−371. A comparison of such an ultraviolet curve with the optical and particularly the X-ray light curves would permit more information to be deduced regarding the size, structure and location of the far-UV emitting region.

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