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THE 1980 OUTBURST OF 4U 0115+63 (V635 CASSIOPEIAE)

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ABSTRACT

Optical observations of the proposed Be companion star (V635 Cas) to the hard transient X-ray pulsar 4U 0115+63 have been used to predict the 1980 December X-ray outburst, thus confirming the identification. V635 Cas increased in brightness by 1.7 magnitudes over the three months preceding the X-ray outburst, and strong, variable Hα emission was always present. These results demonstrate for the first time that increased optical activity in the Be companion star can lead directly to a "hard" transient X-ray outburst. There is a delay of ~ 60 days between the onset of optical activity and the X-ray outburst. This delay and the absence of orbital modulation of the 1980 X-ray outburst (or any of the previous X-ray outbursts) rule out direct accretion from a stellar wind. We suggest that the delay represents the time for material near the X-ray source to form an accretion disk and move inward toward the neutron star surface, and we discuss the observational implications of this interpretation. Future observations of similar transient events may provide a firm basis for the study of accretion disk dynamics.

Subject headings: pulsars — stars: accretion — stars: Be — stars: individual — X-rays: binaries — X-rays: bursts

I. INTRODUCTION

Several hard pulsating X-ray transients are associated with Be stars, e.g., A0535+26 (Liller 1975), A1118−61 (Chevalier and Ilovaisky 1975), and 4U 0115+63 (Johns *et al.* 1978; Cominsky *et al.* 1978). (For a comprehensive review see Rappaport and van den Heuvel 1982.) It has been suggested that the transient X-ray outbursts from these sources are due to increases in the rate of mass loss from the optical companion (Wickramsinghe and Whelan 1975; Maraschi, Treves, and van den Heuvel 1976; Li, Sprott, and Clark 1976). Prior to the present work, all the transient outbursts of these sources were first detected in X-rays; as a result, the preceding behavior of the optical companion was unknown. A number of optical observations have been made after the X-ray outbursts were reported (e.g., Margon *et al.* 1977), but no obvious correlations between the optical and X-ray variability have been seen for any "hard" transient X-ray source. This is in marked contrast to the optical properties of the "soft" X-ray transients in which a large fraction of the optical emission is believed to be from the accretion disk and is presumably reprocessed X-radiation (see Lewin and Joss 1981 and references therein). As a result, the increase in X-ray emission during a "soft" transient event produces a corresponding increase in the optical light. This correlated variability has been used to identify several "soft" transient X-ray sources, e.g., A0620+00 (Boley *et al.* 1976) and Cen X-4 (Canizares, McClintock, and Grindlay 1980).

By the end of October of 1980 the optical counterpart of 4U 0115+63 had increased dramatically in brightness (Kriss *et al.* 1980). This was followed in 1980 December by a new X-ray outburst detected by *Ariel VI* (Ricketts *et al.* 1981). In this paper we report on the activity of the optical companion of 4U 0115+63 before, during, and after the X-ray outburst, and attribute the X-ray activity to a short episode of mass loss from the Be companion (Johns *et al.* 1978; subsequently designated V635 Cas by Kholopov *et al.* 1981). Transient outbursts provide a unique opportunity to study time scales for mass transfer and accretion in binary X-ray sources. The sequence of optical and X-ray events can, with certain assumptions, permit us to estimate the infall time scale for material in the accretion disk surrounding the neutron star.

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TABLE 1

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Date (UT)	Instrument	Telescope	Aperture	Resolution	Weather
80/9/24......	Reticon scanner	1.3 m	8″	~15 Å	Clear
80/10/27	Reticon scanner	1.3 m	8″	~15 Å	Clear, windy
80/10/28	Reticon scanner	1.3 m	4″	~6 Å	Scattered cirrus
80/10/30	Reticon scanner	1.3 m	8″	~15 Å	Windy, poor seeing
80/10/31	Reticon scanner	1.3 m	8″	~15 Å	Clear
80/11/4......	Reticon scanner	1.3 m	8″	~15 Å	Clear
80/11/19	Reticon scanner	1.3 m	5″.6	~15 Å	Clear
80/11/26	Reticon scanner	1.3 m	5″.6	~6 Å	Cirrus
80/12/15	Photometer	1.3 m	15″	*UBV*	Clear
80/12/19	Photometer	1.3 m	15″	*UBV*	Clear
81/1/2.......	Reticon scanner	1.3 m	5″.6	~15 Å	Clear
81/2/8.......	IIDS	2.1 m	4″.2	~15 Å	Occasional cirrus
81/11/7......	Reticon scanner	1.3 m	4″.2	~15 Å	Occasional cirrus
81/11/25	Photometer	1.3 m	11″	*UBV*	Clear

II. OBSERVATIONS

a) *Optical*

All observations reported here except those of 1981 February 8 were made with the 1.3 m telescope of the McGraw-Hill Observatory[2] on Kitt Peak. Spectrophotometry on 1981 February 8 was obtained with the Intensified Image Dissector Scanner (IIDS) on the 2.1 m telescope of Kitt Peak National Observatory.[3] Spectrophotometry with the 1.3 m McGraw-Hill telescope used the 2000 channel photon counting intensified Reticon scanner (Schectman and Hiltner 1976; Canizares, McClintock, and Ricker 1978). The photometry in 1980 December was obtained with the one-dimensional scanning photometer of Petro, McClintock, and Remillard (1981), used in a chopping mode with a circular aperture. Table 1 is a journal of our observations of V635 Cas.

The spectrometer data were flux calibrated and reduced to a linear wavelength scale as described by Canizares, McClintock, and Ricker (1978). In addition, visual magnitudes and $B-V$ indices were calculated by integrating the flux-calibrated spectra with B and V band passes as given by Allen (1976). Intercomparisons between white dwarf standard stars give an rms scatter in the V magnitudes of 0.22. The $B-V$ index, however is independent of the absolute flux calibration, and it exhibits an rms scatter of 0.05 magnitudes for our observed white dwarf standards. The photometric *UBV* magnitudes obtained in 1980 December and 1981 November have estimated uncertainties of 0.05 and 0.02 magnitudes, respectively. We used the facilities at KPNO headquarters in Tucson to reduce and flux calibrate data obtained in 1981 February with the IIDS.

Results of our observations are summarized in Table 2. Apart from changes in the absolute flux level, all of our spectra are basically similar. Figure 1 shows our data from 1981 January 2 when the line emission was strongest. Emission from Hβ is visible in this spectrum but in none of the others. The most significant difference between each observation is the Hα line profile. Spectral profiles centered on Hα are shown in Figure 2 to illustrate these changes. All of the profiles have a moderate negative velocity of ~ 150 km s^{-1}, which is consistent with that found by Hutchings and Crampton (1981). An important feature of the profiles is the width of the Hα line. Prior to and during the X-ray outburst it was broadened beyond the instrumental response by 500–900 km s^{-1} full width at half-maximum (FWHM). In 1981 February after the X-ray emission had fallen off, the line was barely resolved at a width of ~ 300

[2]The McGraw-Hill Observatory is operated jointly by the University of Michigan, Massachusetts Institute of Technology, and Dartmouth College.

[3]Kitt Peak National Observatory is operated by the Association of Universities for Research in Astronomy under contract with the National Science Foundation.

TABLE 2

V635 Cassiopeiae Spectrophotometric Data

Date	V	$B-V$	Hα Flux (ergs cm^{-2} s^{-1})	E.W. (Å)
1980 September 24 ...	15.6	1.60	6.1×10^{-14}	14.3
1980 October 27	14.8	1.59	2.7×10^{-14}	3.8
1980 October 28	14.8	...	5.1×10^{-14}	8.3
1980 October 30	14.8	1.61	6.1×10^{-14}	5.7
1980 October 31	14.9	1.64	5.2×10^{-14}	6.6
1980 November 4	14.6	1.54	8.4×10^{-14}	8.2
1980 November 19 ...	14.9	1.60	6.7×10^{-14}	10.7
1980 December 15 ...	14.63	1.71[a]	...	...
1980 December 19 ...	14.67	1.60[b]	...	...
1981 January 2	14.7	1.70	9.3×10^{-14}	13.3
1981 February 8	15.5	1.41	4.4×10^{-14}	11.3
1981 November 7	...	...	...	< 4
1981 November 25 ...	15.51	1.50[c]	...	...

[a] $U-B=0.19$.
[b] $U-B=0.33$.
[c] $U-B=0.20$.

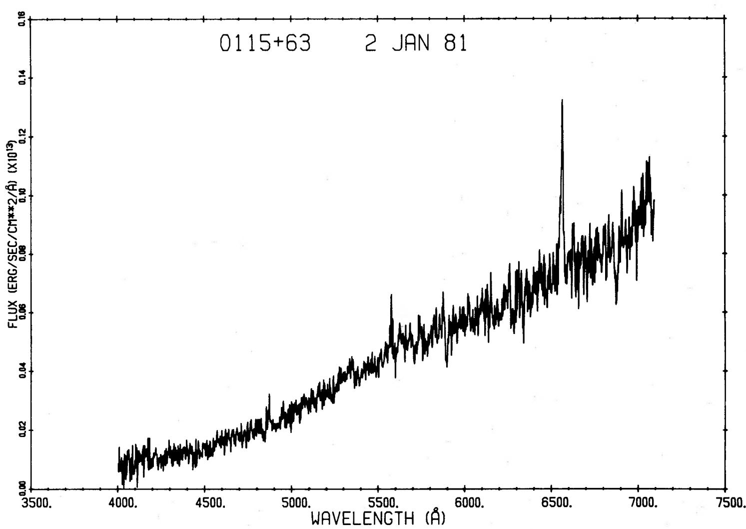

Fig. 1.—Flux per unit wavelength interval versus wavelength for the Be counterpart of 4U 0115+63 obtained on 1981 January 2 (UT)

km s^{-1}. From 1980 October 28 to November 19 the line was at its broadest, and during this time it was noticeably asymmetric—the red wing of the line was broader and stronger than the blue wing.

b) *X-ray*

Prior to the increase in optical emission from V635 Cas, an X-ray observation was made with the Imaging Proportional Counter (IPC) of the *Einstein Observatory* (Giacconi *et al.* 1979) on 1980 August 19. This yielded a 4 σ upper limit of 1.5×10^{-13} ergs cm^{-2} s^{-1} in the 0.1–3.0 keV band (Kriss *et al.* 1980). The *Hakucho* X-ray satellite team was notified of the increased optical brightness during the October observations. They observed 4U 0115+63 from 1980 November 14 to November 22, and have reported an upper limit of $\sim 3.5\times10^{-10}$ ergs cm^{-2} s^{-1} in the energy range 2–10 keV (Oda 1980). Additional X-ray observations of 4U 0115+63 were carried out with the *Ariel VI* satellite (Ricketts *et al.* 1981); an intensity of 0.15 that of the Crab ($\sim 4.3\times10^{-9}$ ergs cm^{-2} s^{-1}, 2–10 keV) was observed during 1980 December 16–30. This is a factor of 2 lower than that observed during the 1978 outburst by Rappaport *et al.* (1978). They also detected the characteristic 3.61 s pulsations (Cominsky *et al.* 1978). Following this detection by

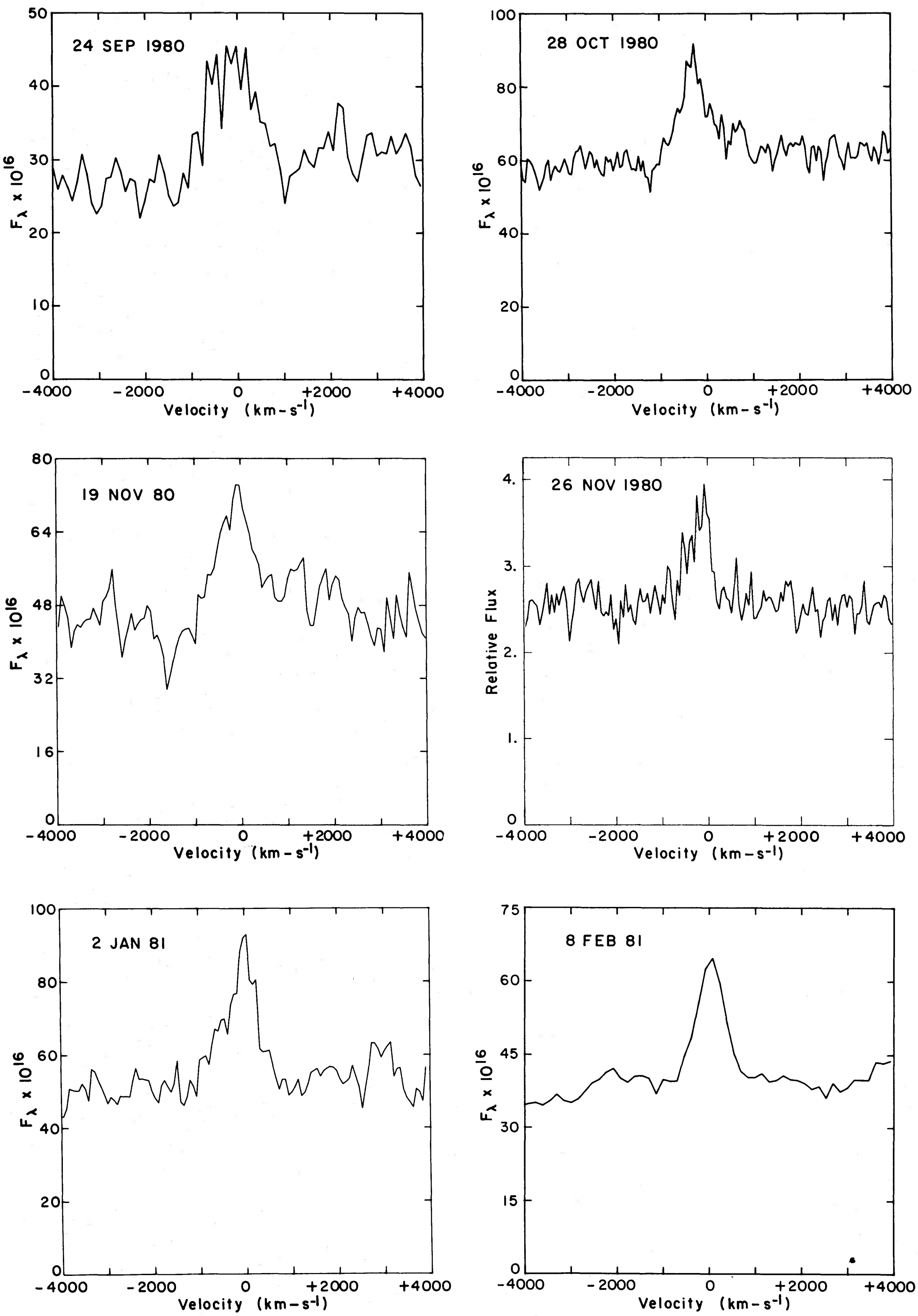

FIG. 2.—Hα profiles for the Be counterpart of 4U 0115+63

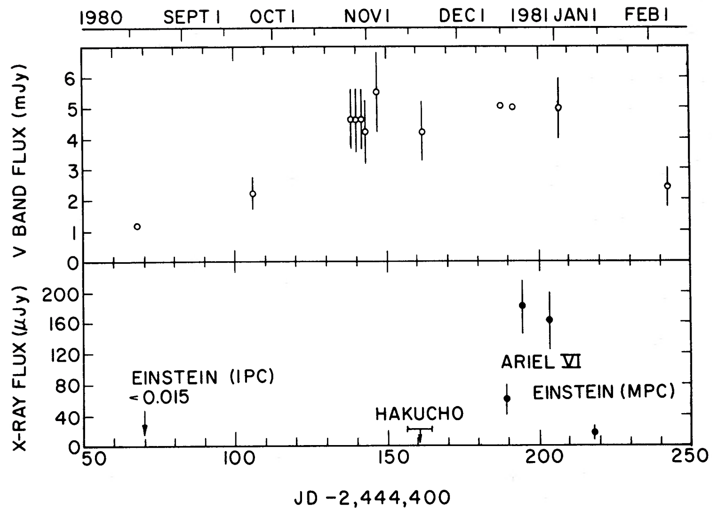

FIG. 3.—Optical (*upper*) and X-ray (*lower*) light curves for 4U 0115+63. Error bars are $\pm 1\ \sigma$. The V magnitude on 1980 August 16 was taken from Middleditch, Koski, and Burbidge (1980).

the *Ariel VI* satellite, 4U 0115+63 was observed once again on 1981 January 15 with the IPC on the *Einstein Observatory*. A flux of 3.5×10^{-11} ergs cm^{-2} s^{-1} was detected between 0.2 and 4.0 keV, also pulsating with a period of 3.61 s. The spectrum exhibits a low energy cutoff at ~ 2 keV, so that a comparison of this flux to that detected by *Ariel VI* in a higher energy bandpass is difficult. Concurrent observations made with the Monitor Proportional Counter (MPC), however, show a 2–10 keV flux of 3.3×10^{-10} ergs cm^{-2} s^{-1}. This is more than a factor of 10 lower than that observed by the *Ariel VI* group, and so by 1981 mid-January the X-ray flux decayed substantially from its peak level.

A comparison of the optical (V band) and X-ray light curves is presented in Figure 3. From the low level of $V = 16.3$ on 1980 August 16 reported by Middleditch, Koski, and Burbidge (1980), V635 Cas increased in brightness by 1.7 mag over 1–2 months. The $B - V$ index is slightly, but significantly, redder than the value of 1.50 reported by Johns *et al.* (1978) during the last X-ray outburst and also reported by Middleditch, Koski, and Burbidge (1980) in 1980 August. Strong X-ray activity did not occur until 1980 mid-December, ~ 2 months after the optical brightening; the X-ray activity persisted for only about one month. In view of the long intervals ($\sim$ years) of X-ray and optical quiescence in 4U 0115+63, the observed episodes of enhanced activity appear to be causally related. This secures the identification of V635 Cas as the optical counterpart.

III. DISCUSSION

Our optical observations prior to and during the 1980 X-ray outburst from 4U 0115+63 confirm the earlier suggestions (Maraschi, Treves, and van den Heuvel 1976; Cominsky *et al.* 1978; Rappaport *et al.* 1978) that increased activity in the optical companion Be star leads to "hard" transient X-ray outbursts. We have also confirmed the suggested Be star identification (Johns *et al.* 1978) for 4U 0115+63 due to the correlated optical and X-ray variability. The observed sequence of optical and X-ray events permits us to evaluate several possible mechanisms for mass transfer and accretion in the 4U 0115+63 system.

First, we rule out direct accretion from an enhanced stellar wind as proposed by Avni and Goldman (1981). Neither during this outburst nor in any previous one is there any apparent modulation of the X-ray emission with the orbital period of the neutron star. There are also at least 49 days between the onset of the optical activity and the X-ray outburst. If the enhanced stellar wind is associated with the increased optical activity, the upper limit to any X-ray emission imposed by the *Hakucho* satellite team would rule out direct wind accretion during this time. The stringent upper limit imposed by our *Einstein* IPC observation in August rules out low-level steady-state emission during quiescence.

We may interpret the increased optical activity in two different ways. In one view the change in optical brightness and the broad, variable Hα emission would be associated with the expansion of the Be star photosphere or the development of a circumstellar equatorial disk. The asymmetric Hα line profiles would indicate outflowing material, and the observed reddening of the $B - V$ index would imply that the expanding material is cooler than the quiescent Be star. This expanding material would then overflow the critical potential lobe of the companion and transfer material to the vicinity of the neutron star. Since maximum optical brightness is reached before 1980 late October, it seems reasonable to assume that the expanding material has reached its greatest extent about the Be star by this time and that mass transfer has begun. No X-rays are observed prior to 1980 December, so the transferred material must be stored in the interim, probably in an accretion disk. The delay of 49–82 days before the X-ray outburst would then represent the time scale for material to move inward through the accretion disk to the neutron star surface under the action of viscous forces.

This interpretation presents several problems. First, the change in optical brightness we have observed (1.7 mag or a factor of 5) is much larger than that observed in classic Be stars. Variable Be stars typically exhibit fluctuations of only a few tenths of a magnitude (Feinstein 1968). The observed change in flux corresponds to an increase in the area of the photosphere of a factor > 2. Second, the quiescent intensity of V635 Cas appears to be $m_v = 15.5$. This is the intensity observed prior to and following the events reported in this paper. In August V635 Cas was actually fainter than this. Third, we can only make a reasonable guess concerning when mass transfer begins. It is possible that a single, discrete episode of mass transfer takes place at any time during the four months preceding the X-ray outburst.

An alternative view of the increased optical activity is that the additional optical light is coming from material that has already been transferred to the vicinity of the neutron star and is radiating due to viscous heating in an accretion disk. It is possible that the Hα emission originates in the disk as well, but this seems unlikely. The broad, asymmetric profile of the Hα line is more indicative of material flowing outward from the Be star. Hα emission is also observed during periods of apparent quiescence (Hutchings and Crampton 1981). Material may have been ejected from V635 Cas prior to the 1980 August observation (by Middleditch, Koski, and Burbidge), leaving the star underluminous ($m_v = 16.3$) for a brief time (Bath 1975). The quiescent intensity of V635 Cas would then correspond to $m_v = 15.5$. Assuming an absolute magnitude of $M_v = -1.5$ for the Be star (Hutchings and Crampton 1981) then yields an implied absolute magnitude for the accretion disk of $M_v = -1.8$. Although it is difficult to create such an intrinsically luminous disk with a steady-state α-disk model (Pacharintanakul and Katz 1980), the disks observed during outbursts from both novae and recurrent novae are as bright as $M_v \approx -5$ to -8 (Mayo, Wickramsinghe, and Whelan 1980).

Assuming that the accretion disk is in fact the source of the additional optical light, we infer that it must have initially formed between September and late October of 1980 when the maximum optical brightness is reached. This gives a delay of 49–82 days for material to move from the outer edge of the newly formed disk to the neutron star surface where it produces the X-ray emission observed in 1980 December.

If we now accept the time delay between the optical and X-ray outbursts as the time for material to move from the outer edge of the accretion disk to the neutron star surface, we can estimate the viscosity parameter α in the steady-state α-disk model of Shakura and Sunyaev (1973) and Novikov and Thorne (1973). In their disk model the major portion of the infall time is spent in the outer region of the disk. The timescale is given by Novikov and Thorne (1973) as

$$\delta t = 210\alpha^{-4/5}\left(\frac{M_x}{1\ M_\odot}\right)^{1/4}\left(\frac{\dot{M}}{10^{-10}\ M_\odot\ \mathrm{yr}^{-1}}\right)^{-3/10}\left(\frac{R_d}{10^{11}\ \mathrm{cm}}\right)^{5/4}\ \mathrm{days},$$

where M_x is the mass of the neutron star, $\dot{M}$ is the accretion rate, and R_d is the outer radius of the accretion disk. We can estimate the accretion rate from the X-ray luminosity observed during the outburst. Assuming a distance of 2.5 kpc to 4U 0115+63 (Rappaport *et al.* 1978), a radius of 10 km for the neutron star, a mass of 1.4 $M_\odot$ for the neutron star, and an energy conversion efficiency of 0.1, we obtain $\dot{M} = 2.7\times10^{-9}\ M_\odot\ \mathrm{yr}^{-1}$.

Estimating the size of the accretion disk is more difficult. Flannery (1975) and Lubow and Shu (1975) have calculated the size of accretion rings formed by particles flowing through the inner Lagrange point of a binary system. Assuming that the neutron star mass is 1.4 $M_\odot$, that the inclination is 90°, and using the mass function of 5 $M_\odot$ and periastron separation of 3.5×10^{12} cm found by Rappaport *et al.* (1978) yields an accretion ring radius of 1.5×10^{11} cm. A still larger disk is possible. With the same parameters the largest stable orbit found by Paczyński (1977) is $\sim 6\times10^{11}$ cm.

Expressing the viscosity parameter in terms of the disk size gives

$$\alpha = \frac{85}{\delta t}\left(\frac{R_d}{10^{11}\ \mathrm{cm}}\right)^{25/16}.$$

If the α-disk model is to be applicable, α must be less than unity. For our observed time scale of ~ 60 days this implies a disk radius of less than 8×10^{10} cm. It is quite possible that a smaller disk with a correspondingly lower value of α was formed about the neutron star. Such a small α-disk would not be luminous enough, however, to produce the additional optical light during the outburst (see Pacharintanakul and Katz 1980).

Although the delay between the optical and X-ray outbursts can be explained in the context of a steady-state α-disk, it is still difficult to account for the relative duration of the X-ray and optical outbursts. The optical outburst lasts for ~ 3 months. If matter is present in the accretion disk for this entire time, the X-ray outburst should also have a similar duration. This is not the case since the X-ray outburst lasts for only one month, indicating that the disk may not be a stable feature in the system. If so, the steady-state α-disk calculations will not apply. Instead, there may be a sudden inflow of disk material onto the neutron star after the disk has reached some critical configuration. Recent models for accretion disks in white dwarf systems (Cannizzo, Ghosh, and Wheeler 1982) have, in fact, predicted this situation. As the disk in these models grows in height, it becomes convectively unstable, and a large amount of material is released suddenly onto the surface of the white dwarf. It is not yet clear whether the same mechanism can operate in strongly magnetic neutron star systems, but our observations of 4U 0115+63 may imply a morphologically similar process.

It is clear from the above discussion that regular observations of the luminous companions to "hard" X-ray transients are needed to clarify the situation. The "hard" X-ray transients provide a novel opportunity to see the response of an accretion disk about a neutron star to a single, impulsive mass transfer event in much the same way as recurrent novae are a probe of accretion disks about white dwarfs. Future observations with the *X-ray Timing Explorer* (*XTE*) in conjunction with a regular optical monitoring program may provide a valuable addition to our understanding of accretion disks.

IV. CONCLUSIONS

We have used an optical outburst in a Be-star X-ray binary system to predict a "hard" transient X-ray outburst for the first time, and have therefore confirmed the suggested identification of the Be star (Johns *et al.* 1978). It is not possible for the X-ray outburst to be the result of direct accretion of an otpically thin stellar wind from the Be star. Instead, we find the most plausible model to be interim storage of material in an accretion disk around the neutron star. A steady-state α-disk with radius less than 8×10^{10} cm can explain the ~ 60 day delay between the optical and X-ray outbursts. The relative durations of the optical and X-ray outbursts, however, indicate that a steady-state disk model may not be appropriate and that disk instabilities may be important. If our interpretations are correct, future transient events in Be star X-ray systems will provide additional opportunities to study the dynamics of accretion disk formation.

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