THE ASTROPHYSICAL JOURNAL, 253:L67–L71, 1982 February 15

DISCOVERY OF A 50 MINUTE BINARY PERIOD AND A LIKELY 22 MAGNITUDE OPTICAL COUNTERPART FOR THE X-RAY BURSTER 4U 1915−05[1]

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Received 1981 October 9; accepted 1981 November 13

ABSTRACT

We have observed absorption dips which recur with a period of 2985 s from the X-ray burst source 4U 1915−05 (= MXB 1916−05). We suggest that the dips are caused by obscuration of the X-ray source by material at the point where the gas stream from the companion meets the accretion disk, and that the 2985 s periodicity is the orbital period of the binary system. Assuming this model is appropriate, these observations represent the first direct evidence of the binary nature of X-ray burst sources. We have also observed secondary dips that occur approximately half a cycle away from the primary dips; these secondary dips probably reflect the complex interaction of the gas stream with the star. We suggest a new optical identification of 4U 1915−05: a 22d magnitude candidate observed in a CCD image of the optical field at the arcsecond-accurate HRI X-ray position. The X-ray emitting region must have an extent of less than $\sim 10^8$ cm for reasonable system parameters.

Subject headings: X-rays: binaries — X-rays: bursts

I. INTRODUCTION

The X-ray source 4U 1915−05 has been previously studied with *OSO 8* by Becker *et al.* (1977) and with *SAS 3* (Lewin, Hoffman, and Doty 1977; Cominsky 1981); these observations showed a number of X-ray bursts that most likely emanated from that source. The X-ray spectrum of both the bursts and the steady source is unusual among burst sources, however, because it is relatively hard ($kT > 10$ keV). A proposed optical counterpart of 4U 1915−05 was suggested by Charles *et al.* (1980).

In this *Letter* we report X-ray observations of 4U 1915−05 made with the Imaging Proportional Counter (IPC), High Resolution Imager (HRI), and Monitor Proportional Counter (MPC) detectors on the *Einstein Observatory*. A number of short dips in the X-ray count rate have been observed which occur at intervals consistent with a period of ~50 min. (These dips have been independently discovered by White and Swank 1982, as first reported by Walter, White, and Swank 1981). The optical identification of 4U 1915−05 has also been investigated based on a new arcsecond-accurate HRI position which excludes the Charles, *et al.* candidate. A new candidate has recently been reported (Bowyer, Clarke, and Henry 1981).

Although it is generally believed that X-ray burst sources, like most other strong galactic X-ray sources, are close binary systems containing a degenerate object, there is as yet no direct proof of this conjecture. The observation of stellar absorption features from the optical counterparts of Aql X-1 (Thorstensen, Charles, and Bowyer 1978) and Cen X-4 (van Paradijs *et al.* 1980) during X-ray quiescence can be construed as indirect evidence for the binary nature of these two transient X-ray burst sources (Koyama *et al.* 1981; Matsuoka *et al.* 1980). In addition, sinusoidal modulations in the intensities of these sources have been detected (but not confirmed) during X-ray transient outbursts (Watson 1976; Kaluzienski, Holt, and Swank 1980). The observations of periodic dips in the X-ray flux from 4U 1915−05 represent the first direct evidence of the binary nature of X-ray burst sources and afford an opportunity to examine the physical nature of the components of such systems.

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II. X-RAY OBSERVATIONS

4U 1915−05 was observed on three occasions with the *Einstein Observatory*: twice with the IPC, and once with the HRI. MPC data were obtained during all of these occasions. A total of eight primary X-ray dips, each lasting a few minutes, were observed; seven with the IPC/MPC combination of detectors, and one with the HRI/MPC combination. The residual intensity in these dips varied from 10% to 75% of the continuum level. A montage of the IPC/MPC dips is shown in Figure 1. The dips are irregular and are most pronounced at the lowest energies; these characteristics are consistent with absorption by a variable amount of gaseous material that intervenes in the line of sight to the X-ray source. The steady source temperature as measured by the 1–10 keV MPC pulse-height data is variable between 9 and 15 keV for a thermal bremsstrahlung model. Alternatively, power laws of energy index α between 0.60 and 0.75 are acceptable. The hydrogen column density is less than 5×10^{21} cm^{-2}. The dip spectra are all noticeably harder ($20 \leq kT \leq 30$ keV or $0.35 \leq \alpha \leq 0.50$), presumably due to photoelectric absorption. However, interpretation in terms of an equivalent hydrogen column density is not straightforward because, as is discussed below, the absorption is variable on time scales equal to or less than the 2.56 s integration time.

In addition to the eight dips already noted, we also observed two other events of a slightly different nature. We refer to these as secondary dips. The secondary dips are only observed with the IPC detector and are much smoother and shallower than the primary events, with a residual intensity in the dips of ~ 80% of the continuum level. We have estimated the time of ingress and egress of the various dips observed by smoothing the count rate and measuring the time at which the intensity reaches 90% of the average inter-dip level. In some cases (cf. Fig. 1) the ingress and egress times can be reliably measured to within 2 s. The times of the centers of the primary dips, defined as $(Te + Ti)/2$, are listed in Table 1. The duration of the dips varies from 191 s to 588 s, and the dip residual intensities (in the fraction of continuum) are listed in Table 1. Some dips are preceded by weak precursors of ~ 10% the central depth of the main dip, but these precursor dips are not included in the dip timing.

The intervals between the primary dips are consistent with a constant period of 2985 s ± 10 s (see Table 1). The amount of phase jitter in the timing of the dip centers can be estimated from the three complete eclipses observed on day 1015 (Nos. 1, 2, and 5 in Table 1): the phase jitter is $\lesssim 0.5\%$, assuming a period of 2985 s. In the longer IPC observations, the expected times of five of six consecutive primary dips were observed and dips were observed on all five occasions, although the duration of two of these is uncertain because of Earth occultations of the line of sight to the source. If the period of 2985 s is adopted, the two secondary dips both occur about 0.4 cycles after the primary dips. This phase of the cycle was clearly observed only on the two occasions when the secondary dips were seen, hence the data are consistent with the dips being persistent features of the light curve.

III. OPTICAL OBSERVATIONS

We have used an improved position for 4U 1915−05 obtained with the HRI detector of the *Einstein Observatory* (Grindlay 1981). The new position has an ~ 3″ error radius; the only correction which has not been included in the error circle is the effect of off-axis aberrations in the mirror which are believed to be quite small. The error circle is superposed on a CCD image of the optical field in Figure 2 (Plate L5). Star 16, which was the previously suggested optical counterpart of Charles *et al.* (1980), is outside the new error circle. The only star visible in the error circle on the Lick 0.9 m Crossley plates used by Charles *et al.* is star 2. Another star lies at the NW extreme, on the edge of the error circle. We have obtained spectra of both star 2 and the NW star with the 3 m Shane telescope at Lick Observatory. Star 2 is of spectral type G, the other is type G–K. Neither showed emission lines or any other unusual features that might associate it with the X-ray source. There are two further arguments that suggest that neither of these stars is the optical counterpart. First, assuming the stable 50 minute period is the orbital period of 4U 1915−05, as is argued in the following section, the companion cannot be as large as a normal G or K star for any reasonable X-ray source mass. Second, it has been shown empirically that the peak luminosity of X-ray bursts is approximately 3 times the Eddington luminosity of ~ 10^{38} ergs s^{-1} (Grindlay *et al.* 1980; Cominsky 1981). The peak burst flux seen from 4U 1915−05 implies that its distance is 10–13 kpc, which is considerably farther than either of these stars if they are normal stars. It could be argued that the bursts seen by Becker *et al.* (1977) originated from another source within their 3° radius field of view, but the *SAS 3* error box (Lewin, Hoffman, and Doty 1977) is only 0.07 deg^2 and contained this source. In addition, our IPC observations show only one other X-ray source in the vicinity of 4U 1915−05; this source has been identified with the late-type star 26 Aql and appears constant with a flux of 8.5×10^{-3} ergs cm^{-2} s^{-1}. If a source other than 4U 1915−05 were responsible for the bursts, its ratio of steady-to-burst luminosity would be very much below the value of ~ 100 expected from helium-burning flash models (Joss and Li 1980, and references therein). We therefore conclude that both star 2 and the NW star are probably foreground stars.

To pursue this question further, we have obtained images of the 4U 1915−05 field with the CCD camera

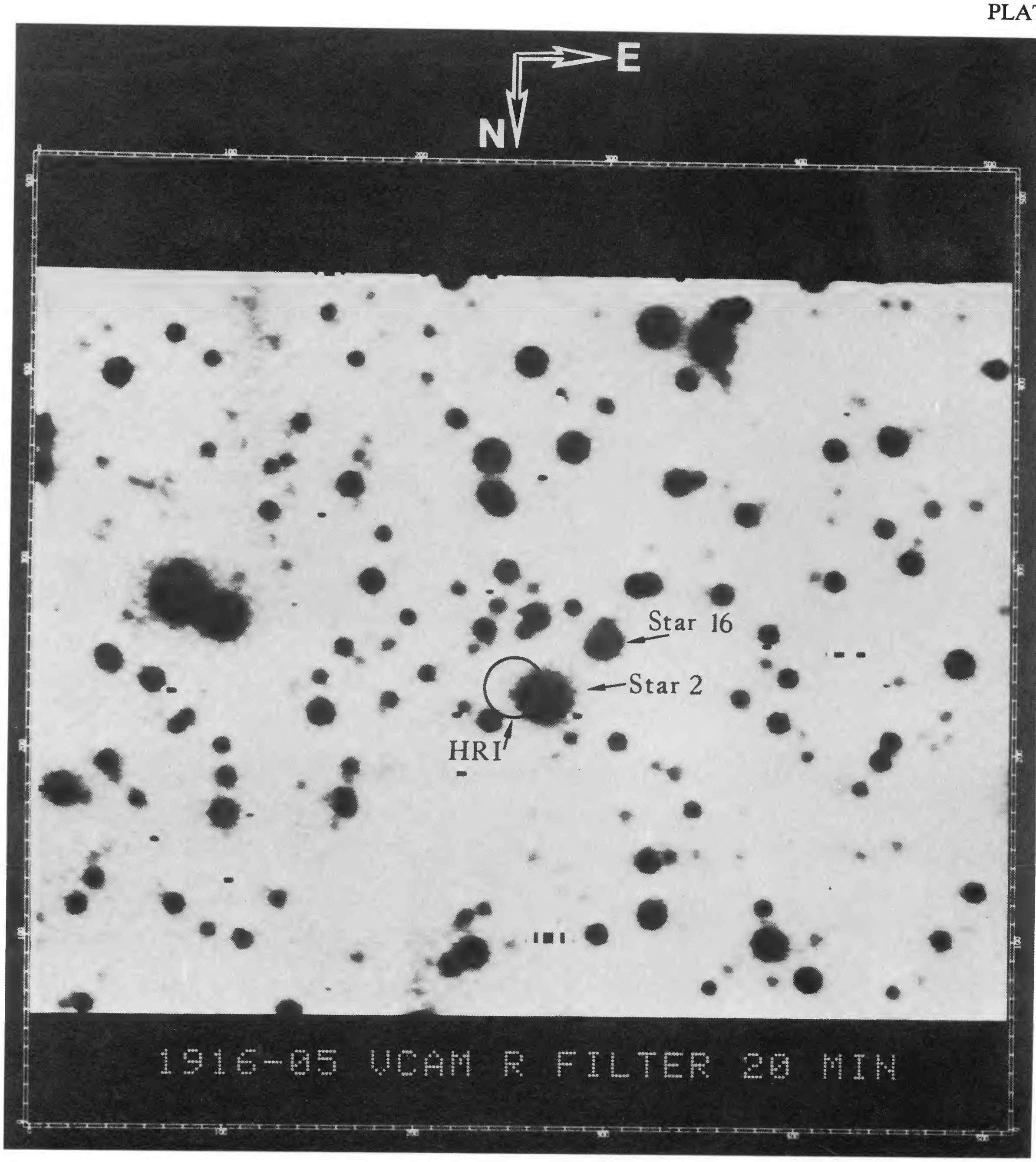

FIG. 2.—The KPNO CCD red image of the field of 4U 1915−05. The HRI error circle is centered at $19^h16^m8^s.03$, $-5°19'42''$ (1950.0). Previous candidate stars for the optical counterpart are indicated. The small off-tone rectangular segments are due to bad pixels on the chip. The faint stellar image near the center of the HRI position and just resolved from star 2 is the proposed optical counterpart.

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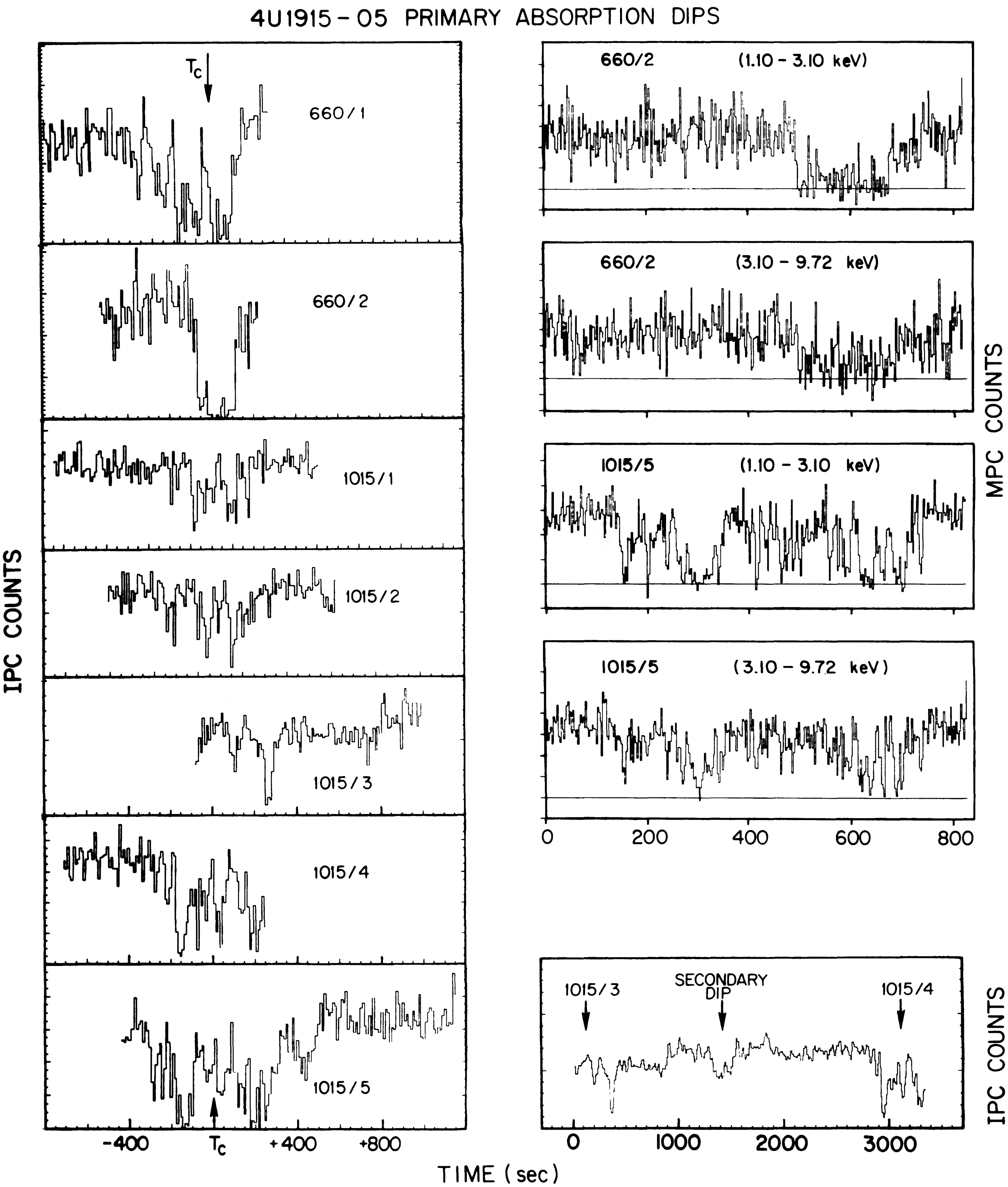

FIG. 1.—A montage of the primary X-ray absorption dips as seen with the IPC detector (*left*) and the MPC detector divided into two energy ranges (*right*); the IPC bin size is 10 s and the MPC bin size is 2.56 s. The central time of each dip is shown along with the day of 1978 of the observation (either 660 or 1015) and the number of the eclipse seen on that date. Parts of some of the dips were not observed due to Earth occultations of the source. Also shown is the secondary dip seen in the IPC data between eclipses 3 and 4 on day 1015 (*lower right*); these data have been smoothed by a 3 bin running average.

TABLE 1
X-RAY OBSERVATIONS OF 4U 1915−05

Date (days of 1978) Primary Dips	Eclipse Start (s)	Eclipse Stop (s)	Duration (s)	Interval (s)	In-Dip Residual Intensity
477	34397	34610	213	...	...
660 (1)	18840	19132	291	...	0.252 ± 0.018
660 (2)	24870	25061	191	5980	0.097 ± 0.014
1015 (1)	16261	16647	378	...	0.743 ± 0.017
1015 (2)	22224	22598	374	5953	0.746 ± 0.017
1015 (3)	< 25295	25675	> 380	< 3174	0.705 ± 0.017
1015 (4)	28191	> 28593	> 402	> 2807	0.540 ± 0.017
1015 (5)	31074	31662	588	< 2976	0.459 ± 0.011

NOTE.—Intervals: day 660 = 2990 s ± 10 s; day 1015 = 2982 s ± 10 s.

at the prime focus of the 4 m telescope at Kitt Peak National Observatory (KPNO). A 20 min CCD image taken with an R filter is shown in Figure 2 (Plate L5). This reveals a third fainter star within the X-ray error region in addition to star 2. The image of this star is free from any bad pixels on the chip, and the KPNO reduction scheme has removed cosmic-ray events by dividing the frame into six time segments and removing any images that do not appear in all segments. Although this new star is only slightly resolved from the blur of star 2, its magnitude has been determined from comparison with other nearby faint stars as $R \sim 22$. If this star is the optical counterpart, the ratio of X-ray-to-optical flux from this source is $\sim 10^4$, which is within the range of ratios for the other bursters ($180–1.2 \times 10^4$; Bradt, Doxsey, and Jernigan 1979). Since its position is within the HRI error circle, the ratio $L_x/L_{\rm opt}$ for the candidate is reasonable, and since there are no other reasonable candidates, we regard this star as the most likely optical counterpart for 4U 1915−05. We note that the existence of both primary and secondary absorption dips suggests a nearly edge-on disk inclination in 4U 1915−05 and a correspondingly high value of $L_x/L_{\rm opt}$ because of the small projected area of the disk.

IV. DISCUSSION

The X-ray dips, which are most pronounced at low energies, are variable in duration and are also variable in depth on short time scales. Clearly occultation by a solid body cannot cause this behavior. A more likely explanation is that the dips result from absorption and perhaps scattering in an inhomogeneous gas cloud passing through the line of sight. Note that the absorption dips seen on day 660 were both shorter and deeper than those seen on day 1015, suggesting an anticorrelation between dip duration and mean residual intensity. We have also noted a small jitter in the X-ray flux levels (always toward lower intensity) outside of the dips on a time scale of less than 10 s, as though small clumps of material projecting above the edge of the disk randomly pass through the line of sight and obscure some of the X-ray flux.

There are a number of possible candidates for the source of the absorption in the primary dips. Absorption by gas stream from the companion that feeds the accretion disk is an unlikely possibility, since the stream would be in the plane of the orbit where one would also expect obscuration by the disk and the companion. Absorption by matter in an accretion column above the compact object is also unlikely because it would be difficult to keep such material sufficiently cool to produce photoelectric absorption close to the X-ray source, unless the density was unreasonably high (Hatchett, Buff, and McCray 1976).

Lubow and Shu (1975) have modeled the interaction of a gas stream from Roche-lobe overflow as the stream interacts with an accretion disk surrounding the companion. At the point of impact with the disk, the gas stream projects well above the disk (Lubow and Shu 1976). Material in the stream above and below the disk which is not entrained will stream out to the Roche lobe before returning to the disk. At the turning point at the Roche lobe, material will have a very low velocity relative to the accreting star and, therefore, a high density.

This model is well supported by data for the case of Her X-1 (Middleditch and Nelson 1976); in particular, in that system the eclipses produced by the bulge in the gas stream where it interacts with the disk are associated with the orbital period of the system. The data presented here for 4U 1915−05 seem to provide even stronger support for the model of Lubow and Shu. Not only does this system not have the perplexing complexities of Her X-1, it is obviously appealing to associate the secondary dips observed here with obscuration by material at the turning point in the returning stream.

Milgrom (1978) has suggested that the previous lack of observed X-ray eclipses may be due to shadowing by accretion disks which would make it impossible to observe X-ray emission from an accreting X-ray source at nearly 90° orbital inclination. This source appears to be inclined at exactly the proper angle so that the line of sight just misses the top of the accretion disk; a small difference in inclination would likely result in either a "normal," steady galactic X-ray source or an obscured source.

Interpreting the 50 min periodicity as the orbital period of the binary system, we can derive constraints on the dimensions and nature of the system. Kepler's law implies that $(M_c + M_x)/a^3 = 11.4$, when the dimensions are expressed in solar units. The standard model for the X-ray bursters contains a central neutron star with $M_x \sim 1.4\ M_\odot$. If the companion star is of comparable mass or less, then the separation of the stars is $\lesssim 0.5\ R_\odot$. As a consistency check, the rapid variability of the X-ray flux from 4U 1915−05 suggests that the angular extent of the X-ray source is small. Our data show that the X-ray flux can change by a factor of 10 from one 2.56 s integration to the next, i.e., in $\sim 1/1000$ of a period. If the separation is $\lesssim 0.5\ R_\odot$, then the X-ray source must be $\lesssim 10^8$ cm in extent, which is inconsistent with a white dwarf but consistent with a neutron star.

A further constraint on the masses can be obtained if it is assumed that the mass-donating companion fills its Roche lobe (Paczyński 1971). If the companion star is assumed to be a main-sequence star with a mass-radius relation $M \sim R$ and $M_x = 1.4\ M_\odot$, then $M_c = 0.11\ M_\odot$. This value is relatively insensitive to changes in M_x. Another possibility is that the companion has already evolved into a low-mass degenerate dwarf. Although it might be argued that a configuration of this type would not result in sufficient mass interchange to provide Roche lobe overflow and, hence, to form an accretion disk, Rappaport, Joss, and Webbink (1982) have shown that the orbit of a short-period system of this type would decay rapidly by emission of gravitational radiation with resultant mass loss from the white dwarf. Using the mass-radius relation for a white dwarf, $R_c = M_c^{-1/3}(0.013)(1 + X)^{5/3}$, where X is the mass fractional hydrogen content (Paczyński 1967), we find the mass of the companion to be 0.078 $M_\odot$ for a hydrogen white dwarf and 0.018 $M_\odot$ for a helium white dwarf. In regard to this model, however, it should be noted that the mass flow envisaged by Rappaport *et al.* ($\lesssim 10^{16}$ g s^{-1}) is nominally sufficient to produce X-ray luminosities of only $\sim 10^{36}$ ergs s^{-1}.

In conclusion, we have observed dips in the X-ray flux of 4U 1915−05 that recur with a period of 2985 s. This is the first instance of such a periodic phenomenon occurring in a burst source and is the best indication so far that bursters are accreting binary systems. We have identified a likely candidate for the optical counterpart of 4U 1915−05 based on positional coincidence, the appropriate ratio of L_x/L_{opt} for the candidate, and the exclusion of alternate possibilities on physical grounds.

We wish to thank Frank Shu for useful discussions and Lynn Cominsky for a critical reading of the manuscript. This work was supported by NSF grant AST 78-06873 and NASA grant NAG 8301 to the University of California, and NASA contract NAS 8-30751 to the Center for Astrophysics.

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