THE ASTROPHYSICAL JOURNAL, 334: L25–L29, 1988 November 1

DISCOVERY OF A POSSIBLE X-RAY TRIPLE: 4U 1915−05

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Received 1988 March 21; accepted 1988 August 12

ABSTRACT

The optical counterpart of the 50 minute binary and X-ray burst source 4U 1915−05 has been identified with a 21st mag blue object. Extensive CCD photometric observations show that the optical modulation of the system defines a period of 50.4567 minutes with high precision and is thus probably the true orbital period, whereas the range of X-ray dip period values (49.7 – 50.1 minutes) reported previously are excluded. A model is described whereby the optical modulation is due to partial eclipse of the rim of the accretion disk by a low-mass ($\sim 0.1\ M_{\odot}$) companion star and the X-ray dips are due to absorption and scattering by blobs of material above and below the disk plane and with density proportional to the current mass transfer rate from the companion star. The 1% difference in periods may suggest that the system is a hierarchical triple with a third companion star of low-mass orbiting the binary in a $\sim$2.5 day retrograde orbit. The possible origin of such a system by tidal capture in a globular cluster, since disrupted, is briefly discussed.

Subject headings: clusters: globular — stars: binary — stars: neutron — X-rays: sources

I. INTRODUCTION

Observations of the X-ray source burst 4U 1915−05 (Forman *et al.* 1978; Becker *et al.* 1977) with the *Einstein Observatory* revealed that it displays erratic dips (typically with $\sim$20%–40% amplitude) in its quiescent X-ray flux, with the dips occurring periodically every $\sim$50.0 minutes (Walter *et al.* 1982; White and Swank 1982). This was the first direct evidence for a periodicity probably related to the binary nature of an X-ray burster. 4U 1915−05 remains of great interest for it is one of the small class of ultracompact X-ray binaries with a degenerate companion star and thus very likely an exotic evolution. In this *Letter*, we report the discovery of the optical counterpart of 4U 1915−05 and the measurement of its optical period and stability over a 5 month period which indicates a significant difference between the X-ray and optical periods. We suggest that the shorter X-ray dip period is due to the presence of a third body in the system, and we discuss how such a hierarchical triple ultracompact X-ray binary may have formed and evolved in a globular cluster (Grindlay 1984).

II. OBSERVATIONS AND ANALYSIS

UBV photometry was initially carried out with the CTIO 4 m prime focus CCD (PF/CCD) in 1985 May, and a UV-excess object with $m_V = 20.99$, $(B-V) = +0.41$ and $(U-B) = -0.52$ (typical errors ± 0.05 mag) was noted (Grindlay 1986) as a probable candidate identification. Although, at 2″.1 NW of the $m_V \sim 19.5$ "star 3" in the finding chart of Doxsey *et al.* (1977), it was formally outside (by 3″) the original HRI error circle (3″ radius) of Walter *et al.* (1982), this displacement is now understood as due to the significant coma in the X-ray image because the only HRI observation of 4U 1915−05 was with the source placed at the extreme edge of the field of view of the *Einstein* telescope. Bad weather prevented us from following up this observation until 1987 April 27–28, when we again carried out CCD photometry of the field with the 1.5 m telescope and TI-CCD at CTIO. To maximize blue throughput from the $\sim$21st mag candiate and allow short (vs. the 50 minute period) integration times to be used, we used a broad-band *B* filter (a Corning 4780 glass, 3 mm thick, with nearly flat transmission between $\sim$4000 and 5500 Å). With 7 minute integrations, it was clear that the optical candidate was varying in magnitude with an $\sim$50 minute period, thus confirming the candidate as the optical counterpart (Grindlay and Cohn 1987). In response to our finding, P. Schmidtke conducted extensive monitoring at CTIO (using the 1.5 m with RCA-CCD) on four nights during 1987 May 3–8 and at Steward Observatory (using the 2.3 m and a TI-CCD) on 1987 June 21, and has reported these results separately (Schmidtke 1988). Our observations continued at CTIO (J. T. using the 1.5 m and TI-CCD) on June 21–25 and at McGraw Hill (G. W. using the 1.3 m and RCA CCD) on 1987 September 17–18. The McGraw Hill observations, which were nonphotometric (but allowed relative photometry), were simultaneous with X-ray coverage from *Ginga* and MMT spectroscopy; a detailed comparison of these optical and X-ray observations will be reported separately.

The photometry data have been reduced with the program DAOPHOT (Stetson 1987). For each of the data sets, typically six to eight stars were selected in the field for determining the point spread function and as reference standards for the object. From our original (photometric) observations of April 28–29, reductions to an equivalent Johnson *B* magnitude were derived for the reference standards and the object by using photo-

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metric standards (Landolt 1987). The broad-band *B* data were found to transform well, as also noted by Schmidtke (1988), to a *B*-magnitude scale (with typical errors ±0.05 mag). However, our McGraw Hill data were obtained under nonphotometric conditions and sufficiently blue secondary standards were not available so that only magnitudes (with typical errors ±0.1 mag) relative to the nearby field stars were obtained. The times of each exposure were taken as the midpoint and are typically accurate to a few seconds (except for the McGraw Hill data, accurate to ~30 s); all times were corrected to the heliocenter for a common reference frame using a program kindly supplied by P. Schmidtke.

In Figure 1 we show the results of a periodogram analysis on all our data combined with those reported by Schmidtke (which add ~40% more data points and are distributed between our April and June observations). We use the method described by Roberts, Lehar, and Dreher (1987) as implemented in a program kindly provided by J. Lehar. In this algorithm, the window function created by the unequal sampling of the data is deconvolved from the periodogram by successively finding the highest peak in the periodogram, and replacing some fraction of that peak and its sidelobes by a "clean" Gaussian beam. This procedure is the one-dimensional analog of the CLEAN algorithm often used in two-dimensional image reconstruction. The bottom half of Figure 1 shows the periodogram prior to cleaning while the top half shows the cleaned periodogram created by 100 applications of the algorithm described by Roberts, Lehar, and Dreher (1987) with a gain of ±0.3. The large spike is at a frequency 28.5394 ± 0.004 day^{-1} or $P = 50.4567 \pm 0.007$ minutes (the errors are determined from the half-maximum of the peak). The fact that this frequency represents by far the largest peak in the reconstructed periodogram demonstrates that the structure and aliases present in the uncleaned periodogram result from a convolution of a single frequency in the signal and the window function created by the peculiar spacing of the observations. (We note, however, that nearly as significant a cleaned periodogram results if the cleaning begins with the second highest peak; rejection of the alias period requires extended sampling times. Preliminary analysis of new data from 1988 June unambiguously confirms a ~50.4 minute period.)

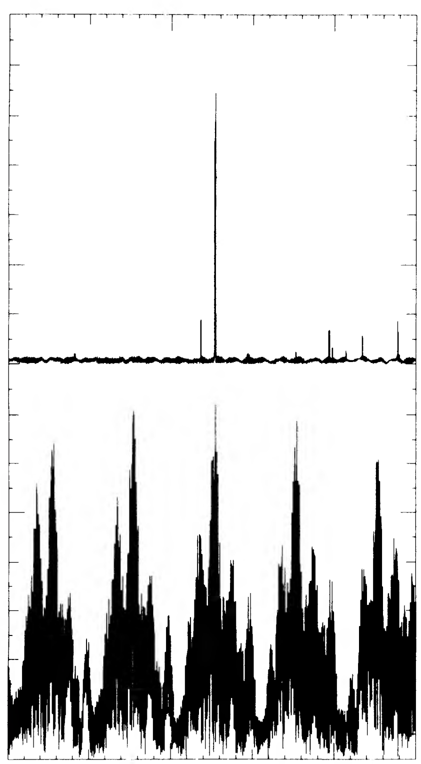

FIG. 1.—Periodograms of all available photometry of 4U 1915−05 showing (*bottom*) the uncleaned periodogram and (*top*) cleaned version using the formalism of Roberts, Lehar, and Dreher (1987), where the window function of the unequally spaced observations has been deconvolved.

The optical period is therefore *longer* than the X-ray period for dips, which has been reported as 49.93 ± 0.06 and 50.06 ± 0.03 minutes (White and Swank 1982) and 49.83 ± 0.17 and 49.70 ± 0.17 minutes (Walter *et al.* 1982). Recent *Ginga* observations taken simultaneously with our McGraw Hill data yield X-ray dip periods of 49.74 ± 0.11 and 50.08 ± 0.11 minutes (Smale *et al.* 1988). We note that the periodogram peak at 29.541 day^{-1} preferred by Schmidtke (1988) is in fact an alias; his data alone also showed a peak at 28.538 day^{-1}, nearly as large, which *is* consistent with our value for the period. The best-fit ephemeris to describe all the 1987 optical data is therefore

$$T = 2{,}446{,}900.01012 \pm 0.0003 + [(50.4567 \pm 0.007 \text{ minutes})/1440]N$$

for the times of minima T (in HJD), where N is the elapsed cycle count.

In Figure 2 we plot the individual light curves for the eight nights of our observations with the expected times of optical minima marked (*vertical dashed lines*) using the best-fit ephemeris given above. It can be seen that the variation of the object is typically 0.3–0.5 mag and that the phase of minimum is remarkably stable, with the minima occuring within a fixed phase interval of ~10% of the period.

Finally, in Figure 3 we plot our data (as well as that of Schmidtke 1988) folded at the best-fit period. The data were first adjusted to the same average magnitude by subtracting the difference of the average magnitude on each night (for an integral number of periods) from the average of all the observations. This allows better comparison of the shape of the 50.4 minute modulation even if the mean brightness of the system is changing. In fact, the mean magnitude does change from night to night by up to 0.2 mag. This effect may be related to the 199 day X-ray period (of Priedhorsky and Terrell 1984). However, the ~50 day span of our photometric coverage (as noted, the September observations were not possible to reduce to *B* magnitudes) prevents us from searching for the longer period.

We have fitted the data in Figure 3 to a sine curve with a period of 50.4567 minutes and a second harmonic whose amplitude is 0.4 that of the fundamental. While the addition of the second harmonic provides a significantly better fit to the data than the fundamental alone, the reduced χ_ν^2 is still 2.3, assuming typical errors in *B* magnitude of ±0.05 (or ±0.1 for the McGraw Hill data). Adding higher harmonics does not improve the fit, which indicates that intrinsic variations in the light curve are responsible for the bad fit.

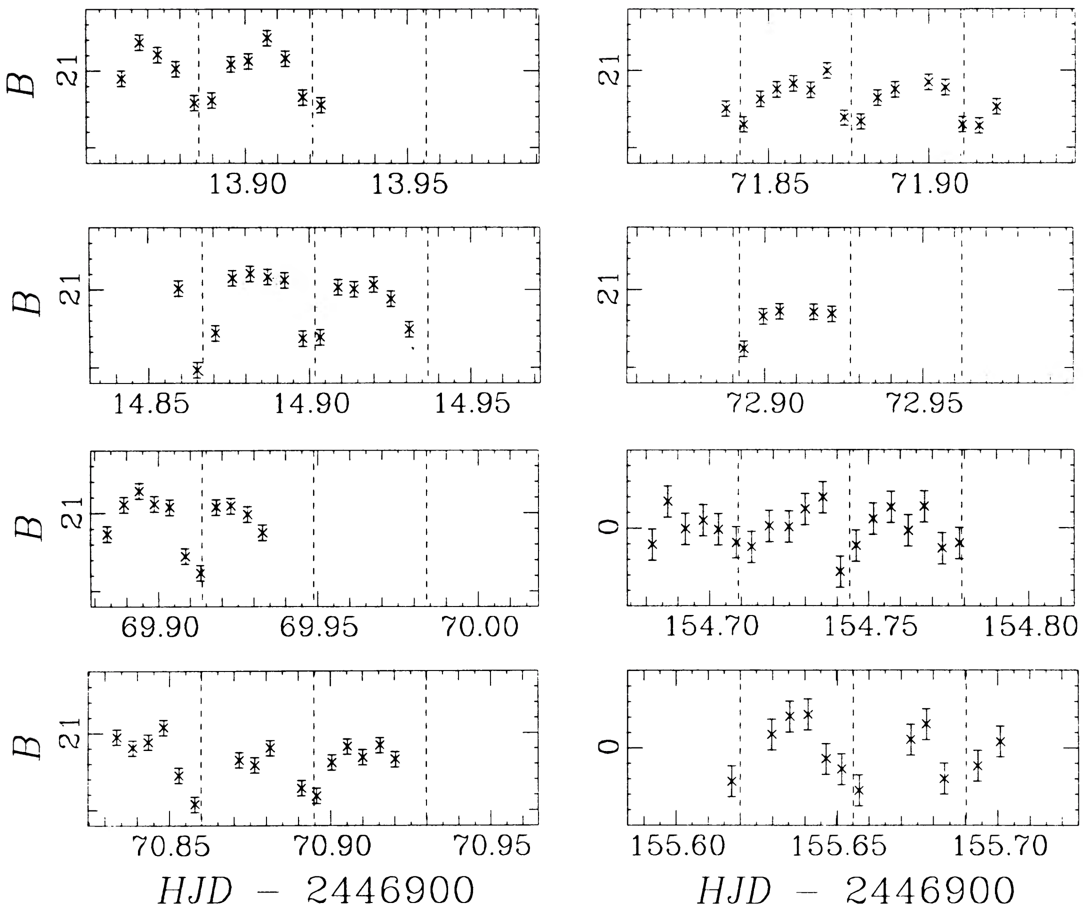

FIG. 2.—Individual light curves of 4U 1915−05 with times of expected minima from best-fit 50.4567 minute period marked (*vertical dashed lines*). Only the data obtained by us are shown; the dips in the Schmidtke (1988) data are also aligned at this period. The mean apparent *B* magnitudes (over an integral number of orbits) are 21.00, 21.09, 21.08, 21.20, 21.17, and 21.23 for the first six panels (in chronological order).

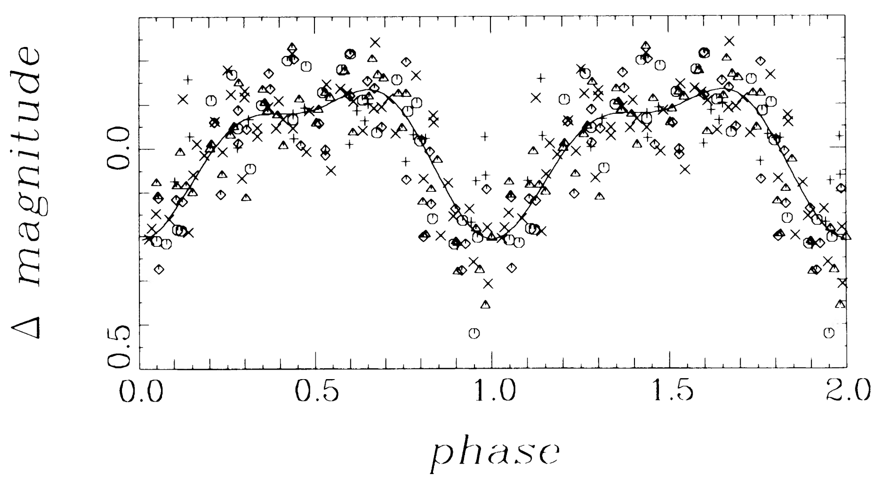

FIG. 3.—Folded light curve for best-fit period and ephemeris given in text. Each symbol denotes a different epoch of observation: circles are Grindlay and Cohn, 1987 April; triangles and plusses are Schmidtke's CTIO and Steward observations, 1987 May and June; crosses are Thorstensen, 1987 June; and diamonds are Wegner, 1987 September. The superposed curve is a model sine curve with second harmonic equal to 0.4 the amplitude of the fundamental.

III. DISCUSSION

The stability of the optical period suggests that it is the true orbital period of the system. The optical modulation is consistent with a 0.1 $M_{\odot}$ secondary star with a degenerate (He) core and a ~ 0.1 $R_{\odot}$ envelope (Swank, Taam, and White 1984) which partially eclipses a raised bulge or ring on the disk. Because this ring may be expected to form at ~ 0.5 of the disk radius (Frank, King, and Lasota 1987), its radius is ~ 0.3 $R_{\odot}$ for an expected binary separation of 0.6 $R_{\odot}$. Therefore it must have a thickness of ~ 0.1 $R_{\odot}$ to be partially eclipsed by the secondary star; the lack of X-ray eclipses then implies an inclination $\sim 80°$. The azimuthal extent of the bulge is expected (Frank, King, and Lasota 1987) to be $\sim 180°$ (although this is highly uncertain), and so the expected duration of the partial eclipse of the bulge is ~ 0.3 in phase when the ring versus secondary star separation and projection effects are considered. This is in reasonable accord with the light curves in Figure 2. To produce the modulation depth, the projected size of the secondary must eclipse about 20%–30% of the projected area of the bulge and disk, implying the bulge constitutes a similar percentage of the projected area of the total. Since the physical size of the bulge is given by the disk and eclipse geometry (and is $\sim \pi \times 0.1 \times 0.3$ $R_{\odot}$), the absolute magnitude of the bulge ($M_V \sim 4.5$) and disk ($M_V \sim 4$) can be estimated if they are X-ray–heated to the expected disk temperatures of $\sim 30{,}000$ K. These are in agreement with our observed optical values for a distance of ~ 10 kpc and extinction $A_V \sim 1$ mag as derived from the X-ray spectrum (Smale *et al.* 1988).

The X-ray dip period probably represents the period with which clumps of matter injected near the outer disk intersect our line of sight and both scatter and absorb X-rays from the central neutron star. The clumps may be the two-phase medium (dense and relatively cool clouds in a hot disk corona) which was suggested for compact binaries by Frank, King, and Lasota (1987). The clumps should accumulate in a disk bulge (above and below the disk) or ring as also implied by the optical modulation. Models involving precessing disks have been developed to account for periodicities differing from the orbital period by a few percent in SU UMa stars (Whitehurst 1988). In this case, however, unlike 4U 1915−05, the orbital period is the *shorter* period, and therefore such models may not apply here. A more promising possibility, that 4U 1915−05 is a hierarchical triple, has been already suggested for this system (Grindlay 1986, 1988) to account for the long-term 199 day period as well as the possible origin of the system. A triple leads to several implications:

First, the 1% optical versus X-ray period offset implies a tertiary in a ~ 2.5 day orbit, or $\sim \frac{2}{3}$ of the apparent ~ 4.4 day synodic period (the beat between the X-ray and orbital periods). This 2.5 day period is the period at which the inner binary separation and thus mass transfer would be modulated (Bailyn 1987*a*, *b*). The fact that the mass transfer period is shorter than the binary period requires a *retrograde* orbit which bears directly on the nature and origin of the system as discussed below. Such a hierarchical triple with period ratio ~ 70 would be stable.

Second, the precession in the inner binary eccentricity that would be induced by the tertiary, would induce a long-term modulation of the mass transfer in the system at the long-term precession period $P_{\rm long} = K \times P_{\rm outer}{}^2/P_{\rm inner}$, where $P_{\rm outer}$ and $P_{\rm inner}$ refer to the orbital periods of the tertiary and secondary, respectively, and K is a constant of order unity (Mazeh and Shaham 1979; Bailyn 1987*a*). For the periods 50 minutes, 2.5 days and 199 days observed in 4U 1915−05, $K = 0.7$. Thus a hierarchical triple nature for 4U 1915−05 is entirely consistent with the three different periodicities exhibited by the system; precession models like that of Whitehurst (1988) and those invoked to explain Her X-1 would not seem to "connect" the three periods.

Finally, the possible phase glitches in the X-ray dips reported by Smale *et al.* (1988) are predicted by detailed studies of the expected times of maximum mass transfer in a triple system (Bailyn 1987*b*).

If the system is indeed a hierarchical triple with a retrograde companion, it has a natural origin in a globular cluster (Grindlay 1984, 1986). This is because a compact binary has a significant cross section for capturing a third companion into an orbit with a semimajor axis ~ 4–8 times that of the binary if it encounters the tertiary on a *retrograde* orbit (Bailyn 1988). The actual tertiary-capture cross section is approximately equal to that for tidal capture of the compact binary originally and so can produce significant numbers of retrograde triples in the dense cores of globular clusters (but not, of course, in the Galactic bulge at large where the density of both stars and binaries is many orders of magnitude lower). For 4U 1915−05, the tidal capture model would suggest that the triple companion, with a ~ 2.5 day orbit, was captured by a compact binary with orbital period in the range ~ 3–9 hr (yielding stable triples) and thus longer than the present 50 minute binary period of the system. The expected binary period range encompasses, however, the ~ 8 hr period expected for the initial binary period in a capture in which mass transfer does not begin until the secondary star (with mass initially near 0.8 $M_{\odot}$) evolves off the main sequence and develops a white dwarf core (Bailyn and Grindlay 1987). This "dormant tidal capture" model, developed to explain the 11 minute white dwarf–neutron star binary 4U 1820−30 in the globular cluster NGC 6624 (Stella, Priedhorsky, and White 1987), could equally well account for the 50 minute WD–NS system 4U 1915−05. Thus the initially longer binary period required to capture a triple companion in the presently suspected ~ 2.5 day orbit is also a natural consequence of the origin of the system in a globular cluster.

Since 4U 1915−05 is not now in a globular cluster, the above arguments for its origin suggest that it was either ejected or that its parent globular was disrupted (Grindlay 1984). The possible triple nature of 4U 1915−05 would now argue strongly for the cluster disruption hypothesis since it is very unlikely to eject a triple without disrupting it by encounters with single (or even other binary) stars in the cluster. Although general arguments for the disruption of globular clusters (e.g., disk clusters on prograde galactic orbits which encounter giant molecular clouds) have been given by a number of authors (Grindlay 1984, 1986; Chernoff and Shapiro 1988), it is possible that confirmation of the retrograde-triple nature of 4U 1915−05 could provide direct evidence that cluster disruption has actually occurred.

We thank the CTIO staff for generous support and J. McClintock for helpful comments. This work was partially supported by NSF grants AST 84-17846 (J. E. G.), AST 86-13865 (H. C. and P. M. L.), and AST 85-15219 (G. W.); by NASA grants NAGW-624 and NAS 8-30751 (J. E. G.); and by the Harvard Society of Fellows (C. D. B.).

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Note added in proof.—A tertiary with $R = 0.5\ R_\odot$ and $M = 0.5\ M_\odot$ in a $2^{\mathrm{d}}.5$ orbit would intercept $\approx 10^{34}$ ergs s^{-1} from the X-ray source. One might therefore hope to confirm the triple nature of 4U 1915−05 by observing optical variations due to X-ray heating with a time scale of a few days.

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