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IS 4U 2129+47 (=V1727 CYGNI) A TRIPLE SYSTEM?[1]

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ABSTRACT

The radial velocity variations and spectral type of the low-mass X-ray binary (LMXRB) 4U 2129+47 observed from 1987 June to 1988 October are very surprising. During this time the source was in an extended "off" state, showing neither the X-ray emission nor the photometric variations which originally attracted attention to it. If the system is an isolated LMXRB containing a 1.4 $M_\odot$ neutron star, as is widely believed, it should show radial velocity variations with $K \sim 300$ km s^{-1} on its 5.24 hr orbital period and have a late-K to M spectral type. Instead we find an F7 spectral type and a lack of radial velocity variations on the 5.24 hr orbital period. However, measurements of the radial velocity at four epochs show a shift in the mean radial velocity of ~ 40 km s^{-1}. The presence of these shifts, the lack of variations on the orbital period, and the anomalous spectral type, suggest that this system is a hierarchical triple with an inner binary consisting of a LMXRB with a 5.24 hr period, and an F7 V star in a much larger (~ 30 day period) orbit around the inner binary. A necessary consequence of such a triple would be an ~ 45 yr cycle in the mean eccentricity of the inner binary, which is consistent with the pattern of "on" and "off" states that have been observed since the 1930's. Other hypotheses (an anomalous accretion disk, a chance superposition of unrelated stars, an extremely low mass neutron star) appear to be less likely. These observations may be the first direct detection of the orbital motion of the outer star in an X-ray triple system. None of the currently popular evolutionary schemes for LMXRBs could account for a triple system with the parameters indicated for 4U 2129+47.

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

I. INTRODUCTION

The optical counterpart to 4U 2129+47 (=V1727 Cyg) was discovered as a ~ 17th mag star which showed ~ 1.5 mag photometric variations on a 5.24 hr period (Thorstensen *et al.* 1979). As the morphology of these variations is very similar to those seen in Her X-1, the 5.24 hr period was identified with the orbital period, and the photometric variations were believed to be due to the varying aspect of the X-ray heated face of the secondary. X-ray observations with the *Einstein Observatory* showed a partial eclipse at the same orbital phase as the optical minimum, lending further support to the X-ray heating model. Detailed analysis of the X-ray light curve led McClintock *et al.* (1982) and White and Holt (1982) to independently and simultaneously develop a model of the source in which the binary is viewed edge-on, in such a way that the accretion disk blocks our view of the central X-ray source, and the X-rays we do detect are scattered off a large ($\sim 10^{11}$ cm) accretion disk corona. Radial velocity measurements of the Hβ absorption line made in the X-ray "on" state led Horne, Verbunt, and Schneider (1986) to conclude that the mass of the compact object is 0.6 ± 0.2 $M_\odot$. This revived earlier speculation that the compact object is a white dwarf, as this mass is anomalously low for a neutron star. However, discovery of a type 1 X-ray burst in archival X-ray data clinched the identification of the compact object as a neutron star (Garcia and Grindlay 1987).

When the X-ray flux and large photometric variations were discovered to have ceased in 1983 (Pietsch *et al.* 1986), astronomers were presented with an opportunity to verify earlier anomalous mass measurements without the disturbing influence of emission lines from the accretion disk which are usually present in this system, and to search for the expected ellipsoidal variations in the light curve. Extensive photometry by Thorstensen *et al.* (1988) and Kaluzny (1988) set upper limits to any ellipsoidal variations of ~ 1%, many times below the expected value. This surprising result is very difficult to reconcile with the previously accepted models of 4U 2129+47. Recent radial velocity measurements by Chevalier *et al.* (1988) failed to detect the expected velocity variations of the secondary, leading these authors to suggest that 4U 2129+47 is a triple system.

II. OBSERVATIONS

We have used the MMT "Blue Channel" Spectrograph to obtain spectra with 1 Å resolution covering the wavelength range 4000–4900 Å. This region contains several features which are strong in either accretion disks or late type stars, i.e., He II 4686 Å, Hβ, the G-band, Hδ, Hγ, and various metal lines. Approximately 50 spectra with ~ 20 minute integration times were obtained during observing runs lasting a few days during 1987 June, 1987 November, 1988 June and 1988 October. All phases of the 5.24 hr orbit are covered. Radial velocities have been determined using the cross-correlation technique (Tonry and Davis 1979) against a template star BD +47°4219 (Aveni and Hunter 1969), and also against the sum of the 1987 June V1727 Cyg spectra. Repeated observations of BD +47°4219

[1] The observations reported in this paper were obtained at the Multiple Mirror Telescope Observatory, a joint facility of the University of Arizona and the Smithsonian Institution.

and the dawn (dusk) sky served as checks on the stability of the radial velocity determination and indicate that any systematic errors in the radial velocities are less than the statistical errors. There are no detectable systematic shifts in the radial velocity of the standards from run to run, as can be seen in Figure 1*b*. In Figure 1*a* we plot the relative radial velocity of V1727 Cyg versus the 5.24 hr period, using the ephemeris of McClintock *et al.* (1982). Errors on individual radial velocity measurements have been computed as $\sigma_V = C/(1 + r)$, where C is a constant determined by the observed scatter in the velocities of the standards, and r is the correlation coefficient (see Tonry and Davis 1979). It is immediately clear that the $K \sim 300$ km s^{-1} sinusoidal variations expected from the companion of the neutron star are not present, and also that there is a change in the average velocity between the 1987 June and 1987 November runs of ~ 40 km s^{-1}. In the 1987 June data set alone, there is some indication of sinusoidal variations which are phased approximately as expected from the close companion of the neutron star. However, because the amplitude of these variations is only $\sim 2\ \sigma$, we feel that these variations are best treated as an upper limit to radial velocity variations on the 5.24 hr period.

The mean relative velocities in the 1987 June, 1987 November, 1988 June, and 1988 October data sets are 2 ± 2 km s^{-1}, -44 ± 3 km s^{-1}, -33 ± 5 km s^{-1}, and -50 ± 10 km s^{-1}, respectively, where the quoted errors in the means have been computed assuming Gaussian statistics. When computed in the same way, the mean radial velocity of the standard is constant within the errors, showing that the assumption of Gaussian statistics is reasonable. Observations of the dawn and dusk sky indicate that the zero point of our relative velocity scale is 7 ± 15 km s^{-1}. Not included in the V1727 Cyg velocities are points with low signal-to-noise ratio, and also two points from the 1988 October data set which have relative velocities of ~ -5 km s^{-1}. One of these points was taken in substantially worse observing conditions (variable clouds, poor seeing), and the other with a larger slit than the other observations. While the net counts obtained were sufficient to result in strong correlation peaks, we strongly suspect that contamination from nearby stars and clouds has resulted in spurious radial velocities for these two points. V1727 Cyg is in a rather crowded region (see the finding charts in Pietsch *et al.* 1986 and Chevalier *et al.* 1988). Observing conditions and techniques during the 1987 June and 1987 November runs were very similar, so

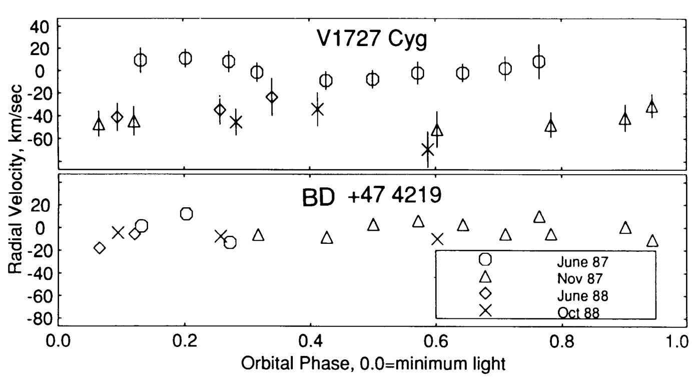

FIG. 1.—The radial velocities of BD +47°4219, and of V1727 Cyg modulo its 5.24 hr orbital period (McClintock *et al.* 1982) are shown. The relative radial velocities of V1727 Cyg have been determined using the cross-correlation technique against a template consisting of the sum of many V1727 Cyg spectra.

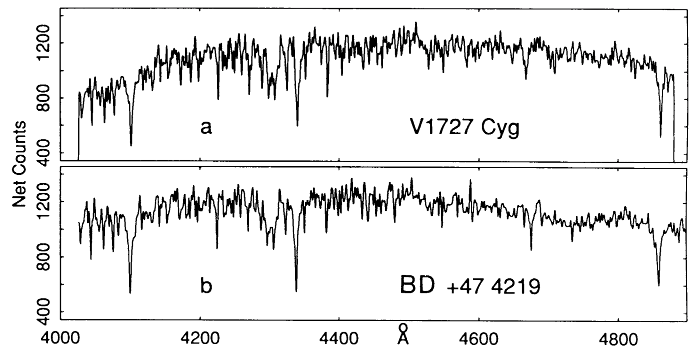

FIG. 2.—Summed spectra of V1727 Cyg and BD +47°4219 are shown. BD +47°4219 is a young F7 IV–V star (Aveni and Hunter 1969). The apparent difference in the shape of the two continua is an instrumental effect. The spectrograph counting rate for V1727 Cyg was typically 50% of the sky rate, and for BD +47°4219 was typically 10.0 times the sky rate.

we feel confident that the difference in the mean radial velocities found in 1987 June and 1987 November is intrinsic to V1727 Cyg.

A sum of all the 1 Å resolution V1727 Cyg spectra is shown in Figure 2*a* (30,000 s integration time). Based on comparison of the depth of the G band, Hγ, and Hβ with the spectral type standards of Jacoby, Hunter, and Christian (1984), we conclude that the spectral type of V1727 Cyg in quiescence is F6–F7. Note that any Hβ or He II 4686 Å emission must be much weaker than that found in most LMXRB accretion disks, and in V1727 Cyg during the "on" state. A spectrum of the F7 IV–V star BD +47°4219 (Aveni and Hunter 1969) obtained with the identical instrumentation is shown in Figure 2*b*.

III. DISCUSSION

The lack of radial velocity variations on the 5.24 hr orbital period, the F7 spectral type, and the shift in the average velocity between 1987 June and November are surprising. If one were to take the upper limit to radial velocity variations on the 5.24 hr period as indicative of the neutron star's mass, it would have a mass $<0.1\ M_\odot$. Of course, the anomalous nature of these observations strongly cautions against such a straightforward interpretation; and furthermore, this interpretation does nothing to explain the radial velocity shift between the 1987 June and November data.

We suggest that the F7 star is in a much wider orbit around the neutron star and that V1727 Cyg is a triple system. The spectral type of the neutron star companion must be later than late K for it to not overfill its Roche lobe (see McClintock *et al.* 1982). An F7 V star has a radius a factor of ~ 1.5 too big to fit into an 5.24 hr orbit around a 1.4 $M_\odot$ neutron star and therefore cannot be the mass-losing companion of the neutron star. In this case the lack of radial velocity shifts on the 5.24 hr period is due to the dominance of the F7 star in the quiescent state, and the long-term radial velocity shift is due to the orbital motion of this star about the inner binary. We note that even if we had not detected the long-term radial velocity shift, the lack of the expected ~ 600 km s^{-1} full-amplitude shift on the orbital period alone drives one to postulate the presence of a third star (see Chevalier *et al.* 1988). The shift in the radial velocity from 1987 June to November (which is detected at $\sim 10\ \sigma$) suggests that the F7 star is dynamically associated with V1727 Cyg. The likelihood of a chance positional coincidence between this F7 star and 4U 2129+47 has been estimated at

10^{-3} (Thorstensen *et al.* 1988). The chance that any interloper is also a binary with the relatively short period suggested by the observed radial velocity shift is clearly even smaller.

The presence of a third body could also explain the presence of "on" and "off" states in the system, the origin of which has heretofore been left to conjecture. The eccentricity induced in an inner binary due to the presence of a third body has been shown to vary on a precession time scale (Mazeh and Shaham 1979). We suggest that when the inner orbit is sufficiently close to circular, the secondary underfills its effective Roche lobe and ceases to transfer mass. Thus minima of inner binary eccentricity correspond to "off" states for the system. V1727 Cyg has undergone one other documented extended "off" state which began 45 yr before the current one (Wenzel 1983). We have numerically integrated coplanar hierarchical triple systems with $m_1 = 0.5\ M_\odot$, $m_2 = 1.5\ M_\odot$, and $m_3 = 1.0\ M_\odot$ (masses appropriate for a late K dwarf, a neutron star, and a F7 dwarf), and find that an outer orbit of ~ 30 days results in a time scale for changes in the inner binary eccentricity of 45 yr. The exact value also depends weakly on the inclination of the outer orbit to the inner orbit. This orbital period would result in an orbital velocity semiamplitude of ~ 70 km s^{-1}, consistent with the observed velocity shifts.

The evolutionary status of such a triple system is highly problematic. For a hierarchical triple system to be stable, the ratio of semimajor axes of the outer and inner orbits must be $\gtrsim 3$ (Harrington 1977). This constrains the past evolution of the binary system, in that the precursor of the binary system has a maximum size beyond which the triple system would be disrupted, and thus the precursor of the compact object is also limited in size (Bailyn and Eggleton 1983; Eggleton, Bailyn, and Tout 1988). In this case, this maximum size is much smaller than any reasonable precursor to the neutron star, and so it seems unlikely that the neutron star was created while part of the triple system. It has been suggested that such triple systems are formed through stellar encounters in globular clusters which were subsequently disrupted (Grindlay 1986, 1988); however, any main-sequence (see below) F star which originated in the globular cluster would long since have evolved into a giant. The probability of such an encounter taking place in the field (which is the current location of V1727 Cyg) is very small, due to the much lower stellar densities. Furthermore, such encounters are unlikely to produce hierarchical triple systems with period ratios as large as seem to exist in this system (Bailyn 1987).

Many of the conclusions reached in earlier studies of 4U 2129+47 need to be reexamined in light of the suggested presence of a third star in the system. The absorption lines in the F7 spectrum will introduce additional complications into radial velocity measurements made when the source is in the "on" state, which might explain the anomalously low value for the mass of the neutron star which was found by Horne, Verbunt, and Schneider (1986). Part of the evidence for X-ray heating of the companion comes from the observed periodic color change; but once the contribution from the F7 star is subtracted from the "on" state light curve, the color change is reduced to "0.1 mag at most" (Chevalier *et al.* 1988). This implies that the "on" state light curve may be due (in part) to the partial eclipse or varying aspect of an accretion disk. However, there is other strong evidence that X-ray heating occurs (i.e., the morphology of the light curve, and the measurement of radial velocity variations of the X-ray–illuminated face of the companion by Horne, Verbunt, and Schneider 1986). Previous "on" state distance determinations of 1–4 kpc (McClintock *et al.* 1982; Horne, Verbunt, and Schneider 1986; Thorstensen *et al.* 1979) would be in error if light from the accretion disk dominates at optical maximum. Assuming that this is indeed the case, Chevalier *et al.* (1988) determine the distance to the system to be ~ 4 kpc, implying that the outer star is a dwarf.

If one rejects the hypothesis that V1727 Cyg is a triple, one might argue that the current "off" state observations are consistent with an accretion disk or a foreground (background) star, although the probability of a chance alignment is very small. If this is such a system, high-resolution imaging observations with the Hubble Space Telescope may be able to resolve it. While the F7 spectrum and the lack of large radial velocity variations on the 5.24 hr period may be consistent with an accretion disk, we feel that the lack of emission lines, lack of optical variability, and the detailed correspondence between the spectrum and a typical F7 V star spectrum argue strongly against this interpretation.

In summary, we note that spectroscopic and photometric observations of V1727 Cyg in its extended "off" state are not as expected from an isolated LMXRB containing a 1.4 $M_\odot$ neutron star and a Roche lobe–filling secondary. Instead, the observations are consistent with the hypothesis that V1727 Cyg is a triple system, with a F7 V star in a ~ 30 day orbit around the compact, inner 5.24 hr binary which contains a neutron star and a lobe-filling late K secondary. We may have detected radial velocity variations from the outer member of an X-ray triple system for the first time. Our model also predicts that the F7 V star we now observe will show radial velocity variations on a ~ 30 day period with a semiamplitude of ~ 70 km s^{-1}. Future observations in search of this period in the radial velocities are highly desirable and would best be done during the current "off" state. If the "on/off" states are strictly periodic, the current "off" state should have ended in 1989 January, but we expect some variation in the length of individual "on/off" cycles.

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