THE ASTROPHYSICAL JOURNAL, 235:L159–L161, 1980 February 1

THE X-RAY LIGHT CURVE OF 4U 2129+47

M. P. ULMER[1]
Department of Physics and Astronomy, Northwestern University
AND
S. SHULMAN, D. YENTIS, W. D. EVANS, D. MCNUTT, J. MEEKINS, K. WOOD, E. T. BYRAM, T. A. CHUBB, AND H. FRIEDMAN
E. O. Hulburt Center for Space Research, Naval Research Laboratory
Received 1979 August 14; accepted 1979 October 16

ABSTRACT

We present the light curve of 4U 2129+47 and show that it almost certainly has a period of ~0.22 days. This is the same period as the optical candidate proposed by Thorstensen *et al.* Binary X-ray source models, consisting of an M dwarf plus either a neutron star or a white dwarf, are briefly discussed.

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

I. OBSERVATIONS AND ANALYSIS

Thorstensen *et al.* (1979, hereafter TEL) proposed an optical identification for the X-ray source 4U 2129+47, and found that the optical candidate had a ~0.22 day light curve similar in shape to that of HZ Her. We used the *HEAO* 1 NRL X-ray experiment to search for this periodicity in the 0.5–10 keV X-ray range. The observations were made from 1977 December 9–17 with the $1° \times 4°$ detector field of view that scanned over 4U 2129+47 once every ~0.5 hours. Each scan consisted of a ~10 s observation of the source with a total geometric aperture of ~3200 cm^2 (see Ulmer *et al.* 1979). The background counting rate was $\sim 45 \times 10^{-3}$ counts cm^{-2} s^{-1} in the 0.5–10 keV energy range.

We derived the intensity for the source from each scan taking the background rate from adjacent ~1° wide regions of the sky. The superposed data from many scans showed that there were no detectable X-ray sources in these background regions. We assumed that the X-ray source was located at the position of the optical candidate [$\alpha(1950) = 21^{h}29^{m}36^{s}.2$, $\delta(1950) = +47°04'08''$], and the background-subtracted intensity was then corrected for the collimator response.

We obtained 87 sightings of the source which were folded modulo the optical period reported by TEL (0.21826 days). These results are shown in Figure 1 along with the average light curve. We chose phase 0.0 according to the ephemeris for minimum light from TEL. As can be seen in Figure 1, the minimum intensity in the average light curve is at phase 0.0 ± 0.05.

In order to demonstrate that the data are periodic on the ~0.22 day time scale, we performed a summed epoch analysis as follows: (1) We folded the data modulo various periods to produce average light curves; (2) we then fitted the average light curves to a constant (with phase) intensity; (3) finally, we compared the resulting χ^2 from these fits.

The χ^2 values for a range of periods near $P_0 = 0.21826$ days are shown in Figure 2 (plot II). With this we show two examples: plot III is the same data *except* that the times and intensities have been scrambled randomly, and plot I shows a similar analysis on Cyg X-3 using $P_0 = 0.199614$ days (cf. Parsignault *et al.* 1977). Note the larger values of χ^2 for the Cyg X-3 data. We see from the figure that both Cyg X-3 and 4U 2129+47 show several artifact peaks in χ^2 besides the one near P_0.

The artifact peaks in the χ^2 distribution can be explained, in part, by the effect of the periodic chopping of the data. This generates power in beat frequencies such as $|(1/P_0 \pm 1/n \times P_{\rm spin})|/2$ and $|(1/P_0 \pm 1/n \times P_{\rm orbit})|/2$, where n is an integer, $P_{\rm spin} = 0.58$ hours, and $P_{\rm orbit} = 1.5$ hours. The larger the power in a peak in Fourier space, the larger the amplitude of the corresponding average light curve. This in turn produces a peak in the χ^2 plot versus period.

Related to this cause for multiple peaks in the χ^2 plot is the variability of the X-ray source at a given phase of the light curve. At or near beat frequencies, such as mentioned above, a periodic sampling rate makes it more likely (for our limited data sample) that some bins of an average light curve will have only one data point in a particular phase bin. (Bins with no data are not counted.) Then a large deviation (and a large χ^2) in the average light curve is produced. For example, the reader is referred to phase 0.85 in Figure 1 which has only one point in that bin. Therefore, both Cyg X-3 and 4U 2129+47 will produce artifact peaks, but the peaks in curves (I) and (II) of Figure 2 will not necessarily have the same relative power. In Figure 2 peaks A, B, C, and E were initially chosen by inspection of curve (II), whereas D was chosen from curve (I).

We can calculate the probability of a peak at P_0

[1] *HEAO 1* Guest Observer at the NRL, E. O. Hulburt Center for Space Research.

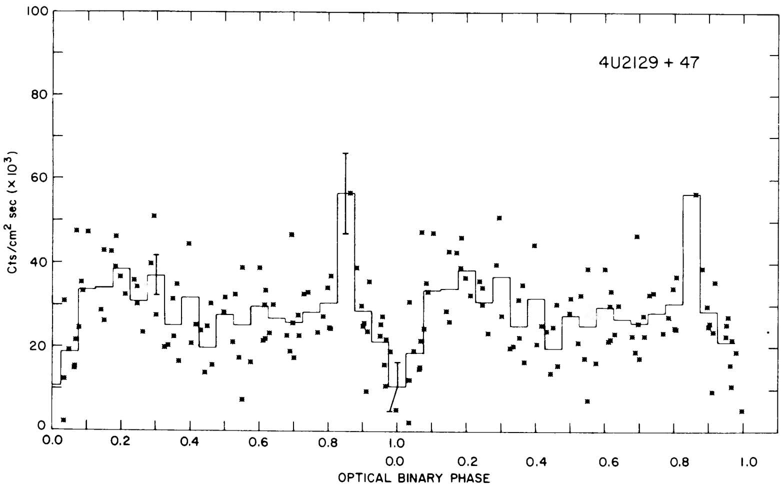

FIG. 1.—X-ray light curve of 4U 2129+47 assuming a period of 0.21826 days. All 87 data points from the 9 days of observations are shown together with the average light curve obtained by averaging all data points within a 0.05 phase bin. The very high bin at phase 0.85 has a large error since only one observation fell in this phase bin. The typical error bar is repeated by these shown at phases 0.30 and 0.00.

by assuming the average deviation ($\sim$25) in the χ^2 curve for the scrambled data applies to the unscrambled data. Then the peak at P_0 of curve (II) is about 3 σ in height. Alternatively, we found one peak larger than 150, the size of the peak at P_0 in curve (II), in the scrambled data. Assuming that a χ^2 peak found within ± 2 bins of the center would be taken as verification of the optical period, we estimate that the probability of a large peak occurring near P_0 is $\lesssim 1/25$. Furthermore, the coincidence of the minimum in the light curve at phase zero tends to confirm the existence of a true periodicity. Note that it is the depth of the minimum, and not of the phase bin, that is strongly correlated with the existence of the χ^2 peak.

Any calculation that treats the central peak alone is conservative, however, because a true periodicity should show the beat frequency peaks in χ^2 (as is seen for Cyg X-3), and these are not seen in the scrambled data. We conclude that the $\sim$0.22 periodicity in the X-ray data is almost certainly real and that the optical identification by TEL is correct. Independently, we determine the period of the X-ray source to be 0.2177 ± 0.0008 days, which is in agreement with their 0.21826 day optical period.

II. DISCUSSION

We estimate the X-ray eclipse width half-angle to be $\Theta_e = 18°–27°$. This permits us to calculate the radius R_a of the occulting normal star. We use the geometric relationship

$$R_a{}^2 = [1 - \sin^2(i) \cos^2(\Theta_c)]d^2$$

The binary separation d can be obtained directly from Kepler's laws assuming that the total mass in the system is in the range 1-4$M_\odot$ (see TEL). The separation is then in the range $d = 1.0–1.6 \times 10^{11}$ cm. For $\sin(i) = 1$, $R_a = 3.1–7.8 \times 10^{10}$ cm. This independent estimate brackets the range deduced previously by TEL assuming that the normal star is on the main sequence and fills its Roche lobe. It seems likely, then, that the TEL estimate of the mass (0.6–0.8 $M_\odot$) and spectral class (early M) are correct.

AM Her is superficially similar to 4U 2129+47 in

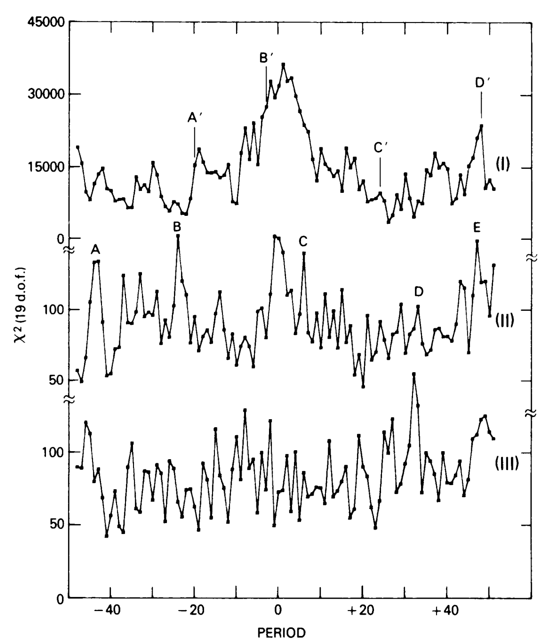

FIG. 2.—Plots of χ^2 versus period for the best fit of the light curves of Cyg X-3 (I), 2U 2129+47 (II), and 2U 2129+47 "scrambled" (III—see text for explanation of "scrambled") to a constant intensity. The central period (P_0), labeled "0", is 0.199614 days for plot I, and 0.21826 days for plots II and III. The period increment or decrement is 5.00×10^{-4} days per point on either side of the central period. The letters mark peaks due to beat frequencies between $1/P_0$ and the orbital and satellite scan frequencies.

several respects (cf. Tuohy *et al.* 1978, and references therein). Its period is short, 3.1 hours, its total mass is 1–2 $M_\odot$, and the eclipse width half-angle is about 27°. However, as pointed out by TEL, the optical light curves for the two sources are completely different. AM Her has a double-peaked light curve with complex features associated with "hot spots" on a disk or stream (cf. Cowley and Crampton 1977). The optical light curve of 4U 2129+47 has only a single peak which appears to be dominated by X-ray heating of the surface of the M star.

The difference between AM Her and 4U 2129+47 may simply be in the way in which the matter is supplied to the compact object. If 4U 2129+47 is wind-fed, then the matter would be more evenly distributed and less likely to affect the optical light curve. The density in the required wind is small enough that the optical depth for electron scattering is $\sim$0.01. There would not be a large effect on the X-ray light curve, in contrast to some models of Cyg X-3 where the large densities required to supply a 10^{37} ergs s^{-1} X-ray source produce enough scattering to erase all trace of a sharp X-ray eclipse (cf. Davidsen and Ostriker 1974; Pringle 1974).

TEL have raised an objection to the white dwarf model based on the large accretion rate, $\sim 10^{-8}\ M_\odot$ yr^{-1}, required to produce the observed X-ray flux of $\sim 10^{34}$ ergs s^{-1}. However, the detection of a large, soft X-ray flux from AM Her (Touhy *et al.* 1978) puts its total luminosity above 10^{34} ergs s^{-1}. Therefore, at least in the case of AM Her, a low-mass companion can provide the required mass transfer to the white dwarf.

The evidence presented here for an X-ray periodicity with the same period and phase as the optical emissions from 4U 2129+47 requires confirmation and suggests several improved new observations. Since the source is weak and variable and difficult to study from a scanning satellite on the required time scales, pointed observations are needed to define the X-ray eclipse more sharply. Observations at both low energies ($\sim$100 eV) and high energies ($>$10 keV) should be made so that a comparison with AM Her can be made in more detail. We used summed epoch analysis and Fourier analysis techniques to place an upper limit of 0.15 on the pulsed fraction assuming a 50% pulse duty cycle in the period range 25 ms to 10 s. More-sensitive searches should be undertaken, especially in the period range $>$1 s.

M. P. U. thanks the *HEAO* 1 group at NRL for its hospitality during the data analysis phase of this project. This research was supported in part by NAS8-33010 (at Northwestern University) and DPR-7023A (at Naval Research Laboratory).

REFERENCES

Cowley, A. P., and Crampton, D. 1977, *Ap. J.* (*Letters*), **212**, L121.
Davidsen, A., and Ostriker, J. P. 1974, *Ap. J.*, **189**, 331.
Parsignault, D. R., Grindlay, J., Gursky, H., and Tucker, W. 1977, *Ap. J.*, **218**, 232.
Pringle, J. E. 1974, *Nature*, **247**, 21.
Thorstensen, J., Charles, P., Bowyer, S., Briel, U. G., Doxsey, R. E., Griffiths, R. E., and Schwartz, D. A. 1979, *Ap. J.* (*Letters*), **233**, L57. (TEL).
Tuohy, I. R., Lamb, F. K., Garmire, G. P., and Mason, K. O. 1978, *Ap. J.* (*Letters*), **226**, L17.
Ulmer, M. P., Kinzer, R., Cruddace, R. G., Wood, K., Evans, W., Byram, E. T., Chubb, T. A., and Friedman, H. 1979, *Ap. J.* (*Letters*), **227**, L73.

E. T. Byram, T. A. Chubb, W. D. Evans, H. Friedman, D. McNutt, J. Meekins, S. Shulman, K. Wood, D. Yentis: E. O. Hulburt Center for Space Research, Naval Research Laboratory, Code 7120, Washington, DC 20375

Ulmer, M. P.: Department of Physics and Astronomy, Northwestern University, Evanston, IL 60201