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AN 8.5 HOUR X-RAY PERIOD IN THE M15 X-RAY SOURCE 4U 2129+12

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ABSTRACT

Photometric and spectroscopic periods have been reported recently for AC 211, the variable ultraviolet excess star in the core of the globular cluster M15. AC 211 is the proposed optical counterpart of the high-luminosity globular cluster X-ray source 4U 2129+12. We have searched the *HEAO* A-1 data base and discovered periodic modulations of the X-ray source at a period of 8.66 ± 0.08 hr; this period is consistent with the optical period. The X-ray light curve has a pulse fraction of 24%. The probability that a $\geq$ 24% pulsed periodic modulation of the *HEAO* A-1 data, with a period consistent with the optical period, could be spurious is less than 0.001.

The discovery of X-ray modulation at the optical period confirms the identification of AC 211 as the optical counterpart of 4U 2129+12. The large X-ray modulations are consistent with the proposal that X-rays from the compact object in 4U 2129+12 are shielded by an extended accretion disk and only X-rays scattered from an accretion disk corona are observed. The implied high intrinsic luminosity and high mass transfer rate explains why 4U 2129+12 is the only globular cluster X-ray source which does not emit X-ray bursts. No mechanism has been identified which will drive the high accretion rate required.

Subject headings: clusters: globular — stars: binaries — X-rays: binaries — X-rays: sources

I. INTRODUCTION

The recent identification of AC 211 as a likely optical counterpart for the X-ray source 4U 2129+12, located in the core of the globular cluster M15 (Aurière, Le Fèvre, and Terzan 1984; Aurière *et al.* 1986; Charles, Jones, and Naylor 1986), is an important step toward understanding the nature and evolutionary history of low-mass X-ray binaries (LMXRBs) both in globular clusters and in the Galactic bulge. Globular cluster X-ray sources provide essential information for understanding LMXRBs since they possess several properties not shared by Galactic bulge sources. These include (1) known distances and thus known luminosities and luminosity function (Hertz and Grindlay 1983*b*; Hertz and Wood 1985), (2) location in a known gravitational potential and thus a statistically determinable mass (Grindlay *et al.* 1984), and (3) a generally accepted formation mechanism, i.e. tidal capture (Hertz and Grindlay 1983*a*; Hertz and Wood 1985).

The X-ray source in M15 is one of the eight bright X-ray sources whose positions were accurately determined with the *Einstein Observatory* high-resolution imager (HRI) (Grindlay *et al.* 1984). The ultraviolet excess star AC 211, located near the HRI error circle, has been proposed as the optical counterpart to the M15 X-ray source (Aurière *et al.* 1984). AC 211 shows several properties similar to the optical counterparts of Galactic bulge X-ray sources (van Paradijs 1983), including a UV excess (Aurière *et al.* 1984), photometric variability (Aurière, Le Fèvre, and Terzan 1984; Aurière *et al.* 1986), and He II λ4686 and Balmer emission lines (Charles, Jones, and Naylor 1986).

These properties make a strong case that the identification of AC 211 with the X-ray source is correct. Recently an 8.5 hr period has been discovered in AC 211, both photometrically (Ilovaisky *et al.* 1986) and spectroscopically (Naylor *et al.* 1986). We have analyzed the observations of the M15 X-ray source obtained with the *HEAO* A-1 experiment in 1977 November and have discovered X-ray modulations at a period consistent with the optical period. The detection of X-ray modulations at the optical period provides confirmation that AC 211 is the optical counterpart of the M15 X-ray source 4U 2129+12.

II. DATA AND ANALYSIS

All of our data come from the *HEAO* A-1 data bank and were obtained when the *HEAO 1* satellite was in scanning mode (Wood *et al.* 1984). The light curve for any source is a time series of fluxes with random time sampling. We briefly summarize our methods for analyzing *HEAO* A-1 time series below; more complete details may be found in Hertz and Wood (1987*a*, *b*). The results presented here supersede those given in our discovery telegram (Hertz 1986).

The M15 X-ray source 4U 2129+12 exceeded a 50% collimator response during 1977 November 19.3–23.3. For every acceptable scan that included 4U 2129+12, we fitted a point source collimator response function at the known position of the X-ray source. The source was detected at $> 2\ \sigma$ significance 58 times. The light curve for the observation is shown in Figure 1. The source is clearly variable; variability by a factor of 3 in 3.5 hr is observed.

To search for the presence of periodic flux variations in the data, we construct a periodogram according to the algorithm of Scargle (1982) and Horne and Baliunas (1986). The periodogram for 4U 2129+12 is shown in Figure 2. The Scargle periodogram algorithm is equivalent to fitting sinusoids to the data. The number of independent frequencies, N_f, which are

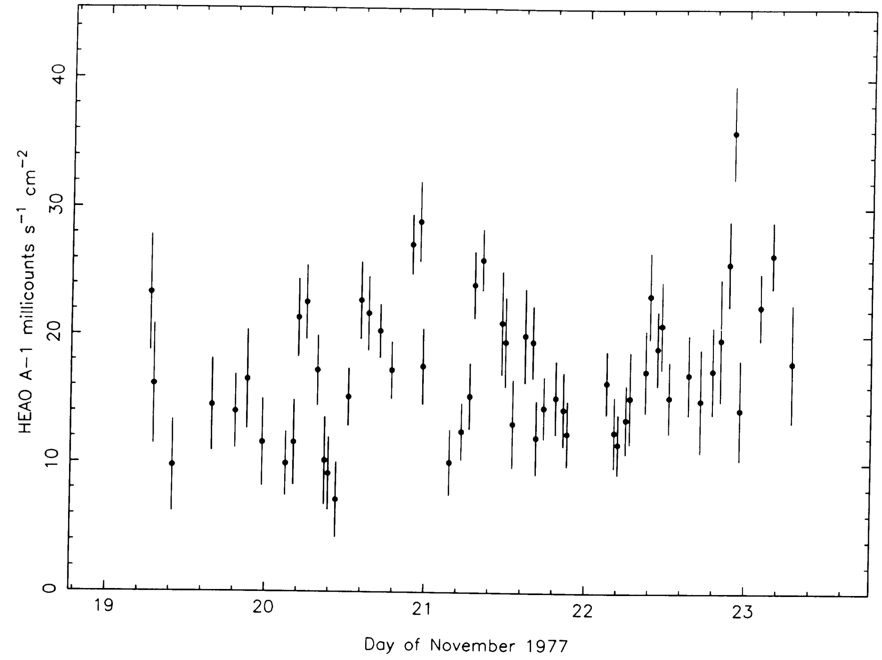

FIG. 1.—The collimator-corrected light curve for the M15 X-ray source 4U 2129+12. The 58 detections were obtained with the *HEAO* A-1 instrument on 1977 November 19.3–23.3. The 1 σ uncertainty for each flux measurement is shown. Variability of the X-ray source by factors of 2–3 on hourly time scales can be easily seen.

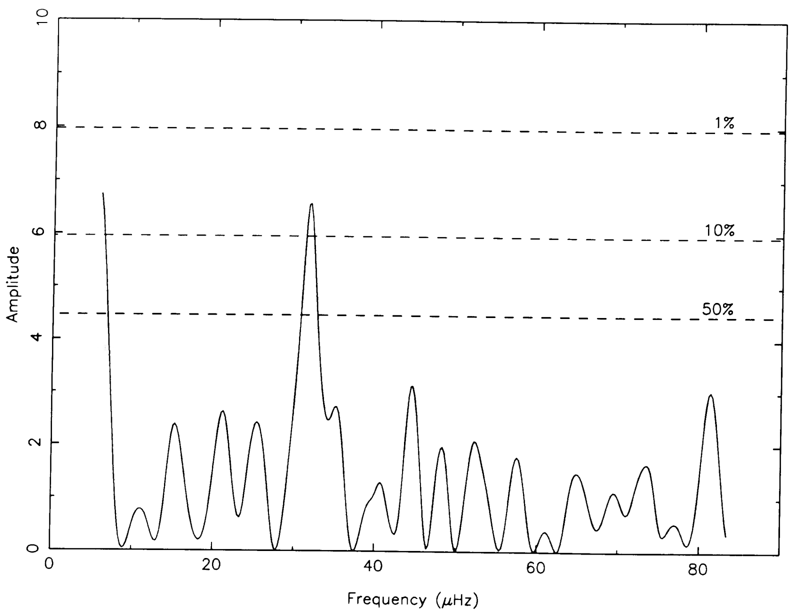

FIG. 2.—The periodogram for the 4U 2129+12 data shown in Fig. 1. The prominent peak in the periodogram is at a frequency of 32.0 μHz; the corresponding period is 8.7 hr. The dashed horizontal lines show the probability for a peak to exceed that amplitude from noise alone. The method by which the significance levels were calibrated is described in the text.

present in the time series depends on the time sampling in the time series (e.g., for evenly spaced data, $N_f = N_d/2$, where N_d is the number of data points). Using Horne and Baliunas's (1986) Monte Carlo method, we estimate that $N_f = 57$ for our data.

In order to estimate the significance of any peak in the periodogram, we performed a second Monte Carlo calculation. We scrambled the flux data while preserving the time series, calculated a Scargle periodogram, and noted the amplitude of the highest peak. The data presented in a random order has no intrinsic periodicities, yet the resulting periodogram has all of the features due to the source's intrinsic variability and the window function of the time series. The distribution of highest periodogram peaks derived in this

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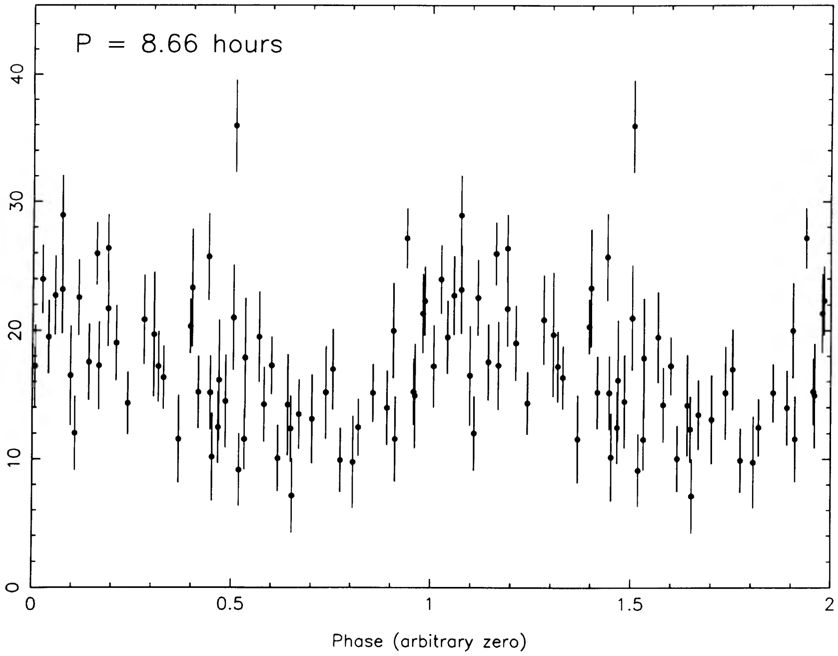

FIG. 3.—The X-ray light curve for 4U 2129+12 shown in Fig. 1 folded at the best X-ray period, 8.66 hr. The period is derived by fitting a sinusoid to the data (see text). The light curve is repeated for two cycles.

manner gives the significance of finding a peak of a given height due to chance alone. We have used 1000 simulations of this kind to determine to an accuracy of ±0.001 the confidence limits plotted in Figure 2.

The data cover an elapsed time $T = 96.4$ hr (4.0 days). We searched for periodicities from the pseudo-Nyquist period of 3.3 hr ($= 2T/N_d$) to 48.2 hr ($= T/2$). A clear peak is seen at 8.7 hr with a probability of < 0.05 of occurring by chance; this alone is a marginally significant period detection. However, the uncertainty in the period, corresponding to the $N_f = 57$ independent periods searched, is 0.2 hr. Thus this X-ray period is consistent with the 8.538 ± 0.001 hr photometric (Ilovaisky *et al.* 1986) and 9.1 ± 0.4 hr spectroscopic (Naylor *et al.* 1986) optical periods. The probability of detecting a spurious X-ray periodicity consistent with the optical period is $\sim 0.05/N_f$ or 0.0009, making the X-ray period detection highly significant.

We fitted a sinusoid to the data and determined the best-fit period, amplitude, unmodulated flux, and residual noise or variability. The best-fit X-ray period is 8.66 ± 0.08 hr, where we have estimated the 1 σ uncertainty using the method of Kovacs (1981; cf. Horne and Baliunas 1986). The unmodulated flux (at this epoch) was 17.0 A-1 millicounts s^{-1} cm^{-2} (~ 3.7 μJy at 5 keV). The pulse fraction (sinusoidal amplitude/mean flux) is 0.24 and the residual noise is also 24% of the mean flux.

In Figure 3 we show the X-ray light curve folded at the best determined X-ray period. The large ratio of residual noise to pulse fraction (~ 1) makes it difficult to detect the periodic modulation in 4U 2129+12 without data covering many periodic cycles (e.g., our observation covers 17 8.5 hr cycles). The longest *EXOSAT* observation of 4U 2129+12 covers 1.5 cycles; there is a hint of X-ray modulation at the 8.5 hr period, but the source's intrinsic variability may change the X-ray pulse shape from cycle to cycle (Aurière 1986). This is consistent with the data shown here.

III. DISCUSSION

A consistent model of the 4U 2129+12/AC 211 system in M15 has been proposed based on the identification of AC 211 as the optical counterpart (cf. Aurière *et al.* 1986; Grindlay 1986; Charles, Jones, and Naylor 1986). The large modulation of the X-ray flux at the optical period is then a natural consequence of this model.

The X-ray properties of 4U 2129+12 show it to be a low-mass X-ray binary (cf. Lewin and Joss 1983). These sources consist of a compact object (usually a neutron star) and a low-mass companion star in a close binary. The companion star overflows its Roche-lobe critical surface. The accretion of matter from the secondary by the compact primary powers the X-ray emission from the system. X-ray heating of the companion star or an accretion disk gives rise to the optical emission-line systems and blue continua typically observed.

The X-ray to optical flux ratio of 4U 2129+12/AC 211, as defined by Bradt and McClintock (1983), is $L_x/L_V \approx 50$; this is at the low end for LMXRBs. Since the distance and reddening to M15 are known, the absolute optical properties of AC 211 can be calculated (Aurière, Le Fèvre, and Terzan 1984), and they are typical for the optical counterpart of an LMXRB (van Paradijs 1983). This implies that the X-ray source is underluminous. The most likely explanation (Grindlay 1986; Charles, Jones, and Naylor 1986) is that the X-ray source is shielded by the accretion disk. The X-ray flux is dominated by X-rays scattered by an extended accretion disk or an accretion disk corona. If the outer rim of the accretion disk varies in height with azimuthal angle then it can modulate the fraction of X-rays which are visible. The true luminosity of the X-ray source must be greater than that inferred from the observed flux. This explains why 4U 2129+12 is the only high-luminosity globular cluster X-ray source not producing X-ray bursts, as high accretion rates inhibit burst activity (Lewin and Joss 1983). It is not clear what physical mechanism can drive the very high mass transfer rate required, $\sim 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$ (Charles, Jones, and Naylor 1986).

Although the mechanism driving mass transfer in 4U 2129+12 is not known (as it is not known for the entire class of high-luminosity Galactic bulge X-ray sources), a model of the physical nature of the system has been constructed. Further X-ray observations, including continuous monitoring of the source through several orbital cycles (e.g., by *ASTRO-C* or *XTE*), will be needed to determine if there is a partial X-ray eclipse (the duty cycle for the A-1 observations is too low to observe a partial eclipse) and to further constrain the source geometry.

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