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33 SECOND X-RAY PULSATIONS IN AE AQUARII

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ABSTRACT

We report the discovery of 33 s pulsations in the 0.1–4.0 keV light curve of the nova-like variable AE Aquarii. These pulsations agree in period and phase with the optical pulsations. The periodicity probably originated from an accretion-induced hot spot on a rapidly rotating, magnetized white dwarf. It is possible that transient pulsations at *nearby* periods, similar to those seen in the optical light curve, are also present in the X-ray light curve.
Subject headings: stars: pulsation — stars: rotation — stars: white dwarfs — X-rays: binaries

I. INTRODUCTION

Among the cataclysmic variables, one of the most extensively studied is the nova-like variable AE Aquarii. Spectroscopic studies have been made by Joy (1954), Crawford and Kraft (1956), Payne-Gaposchkin (1969), and Chincarini and Walker (1974). These have established that the star is a close binary system with an orbital period of 9.88 hours. A K dwarf fills its critical Roche surface and transfers matter to a white dwarf via an accretion disk. Recently, Patterson (1979, hereafter Paper I) discovered the existence of strictly periodic oscillations in the optical light curve, and presented a model in which the oscillations arise from the rapid rotation ($P = 33.0767$ s) of an accreting, magnetized white dwarf. For a wide range of physical conditions in the accretion shock (see Lamb 1979; Lamb and Masters 1979), the model requires the production of X-rays pulsed with the rotation period. In this *Letter*, we report the observation of 33 s pulsations in the X-ray light curve obtained by the *Einstein* Observatory.

II. OBSERVATIONS

X-ray observations of AE Aquarii were obtained from the *Einstein* Observatory for a total of 1.3 hours on 1979 April 27 and 28. The arrival time and pulse height for each photon detected by the imaging proportional counter (IPC) were recorded. (See Giacconi *et al.* 1979 for a description of the telescope and detector.) At a distance of 130 pc (Paper I), the observed IPC counting rate of 0.26 counts s^{-1} corresponds to a luminosity L_x (0.1–4.0 keV) = 10^{31} ergs s^{-1}. The ratio of IPC counts in the 0.55–4.0 keV range to that in the 0.1–0.55 keV range (the "hardness ratio" of Córdova, Mason, and Nelson 1980) is 2.2 ± 0.3. High-speed photometry in optical (unfiltered) light was carried out from McDonald Observatory on the same nights, using the two-star photometer described by Nather (1973).

Figure 1 shows the X-ray and optical light curves. Unfortunately, the large optical flare in run 2388 occurred just after the X-ray observation ended. We note that such flares are rather common (see Paper I), and it is likely that a few hours of simultaneous observation will reveal the connection, if any, between X-ray flux and optical flares. Also shown in Figure 1 are the power spectra of the optical light curves. Strong periodicities at 33.08 and 16.54 s are clearly present on both nights.

Power spectra of the X-ray light curves, and of the first and second halves (labeled A and B) of each run, are shown in Figure 2. On the first night, no pulsations were detected. Two statistically significant (3–4 σ) peaks near a period of 33 s were detected in each half of the second night. The power spectrum of the entire run is shown in the bottom frame; and excess of power near 33 s is seen, with the dominant peak occurring at 33.06 ± 0.10 s. The secondary peaks flanking it correspond to periods of 31.06 ± 0.12 and 36.31 ± 0.15 s. Third harmonics of all three peaks may be present in the power spectrum, but only the lowest-frequency peak ($3 F_1$) is statistically significant. Peaks in the range 31–39 s are commonly seen in the optical data of Paper I, where they are described as "quasi-periodic" since they are very transient and of low coherence. In addition, a 3 σ peak at 14.4 ± 0.15 s is present in run X-2. This peak is marginally significant, but does not correspond to any of the optically identified frequencies. More-extensive X-ray observations are needed to evaluate the significance of this peak, as well as to study the coherence of the $\sim$33 s oscillations.

Because the fundamental optical period is known to one part in 10^7, the light curves may be synchronously summed to yield the mean pulse shape. In Figure 3, this is done for all of the X-ray data, and for the nearly simultaneous optical data of run 2391. The X-ray summation was performed by dividing the data into 10 phase bins, and applying a three-point triangular smoothing filter. The same procedure was employed for the optical data, with 16 phase bins. In runs X-1 and X-2A, the mean waveform is consistent with the presence of low-amplitude pulsations, just below the detection limits of the power spectra. In run X-2B, the summations were independently performed for photons detected in three energy bins. The waveforms and pulse arrival times in all three bins are seen to be in good agreement. All of the data are consistent with an X-ray pulse arrival time 0.5 ± 1.1 s before the "main pulse" of the optical light curve. This optical pulse is known to provide a timing feature of extraordinary stability (see Paper I).

III. DISCUSSION

The probability of obtaining any peak as large as that at F_0 by chance from white noise is $\sim 10^{-2}$. The probability that it should accidentally occur at the known optical period is 5×10^{-3}, giving a net probability of accidental detection of 5×10^{-5}. Thus the data clearly establish that there is an X-ray counterpart to the stable optical periodicity, and that the pulse arrival times agree to within ~ 1 s. The significance of the nearby peaks in the power spectrum (e.g., F_1 and F_2 in Fig. 2) is unclear; it is possible that they represent independent periodicities, but it is also possible that they arise purely from amplitude variations of the principal signal. Further X-ray observations are required to resolve this important point.

The agreement of optical and X-ray pulse arrival times suggests that we may simply be observing the thermal emission from a hot spot on the white dwarf. If the emission is that of a blackbody, we may easily calculate the temperature required to match the optical and X-ray observations. We have $L_{\rm pulsed}$(3500–5500 Å) $\approx 2 \times 10^{30}$ ergs s^{-1} and $L_{\rm pulsed}$(3–100 Å) $\approx 2 \times 10^{30}$ ergs s^{-1}. The required spot has a temperature of 120,000 K, a radius of 700 km, and a bolometric luminosity of 10^{33} ergs s^{-1}.

However, several clues suggest that higher temperatures exist in the spot. First, it is very plausible that most of the pulsed optical flux arises from reprocessing in the disk, as found in the old nova DQ Herculis (Patterson, Robinson, and Nather 1978; Chanan, Nelson, and Margon 1978). This will increase the ratio $L_x/L_{\rm opt}$ for the light viewed directly from the spot, and hence will raise the required temperature. Second, the spectrum of the X-ray pulsations in run X-2B (see Fig. 3) is similar to the spectrum of the unpulsed light (i.e., the pulsed fraction has no severe dependence on energy). As discussed by Córdova, Mason, and Nelson (1980), an observed IPC hardness ratio of 2.2 requires temperatures far in excess of 10^6 K, regardless of whether a blackbody or bremsstrahlung origin is assumed.

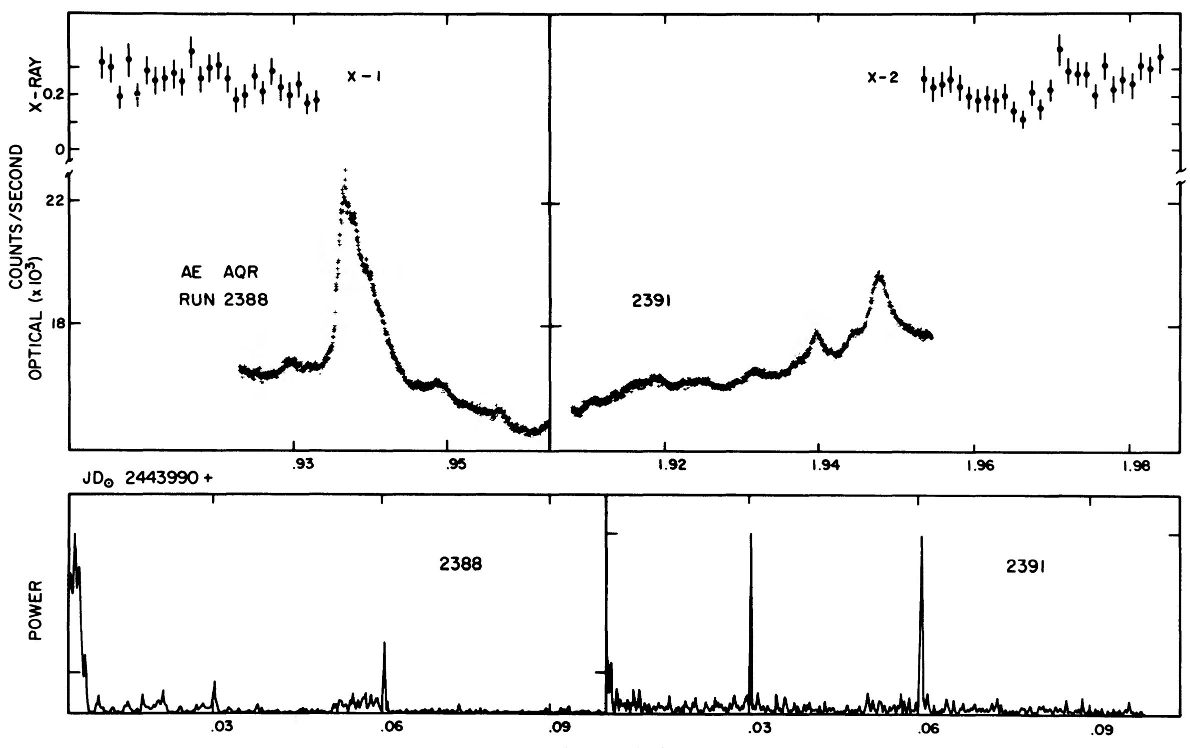

FIG. 1.—X-ray and optical observations of AE Aqr. The midpoint of the X-ray observations occurs at binary phase 0.27 and 0.83, respectively, for runs X-1 and X-2 (see Paper I). The top frame shows the X-ray and optical light curves obtained. The bottom frame shows the optical power spectra; the horizontal tick marks indicate the power in a periodicity of semi-amplitude 0.15%.

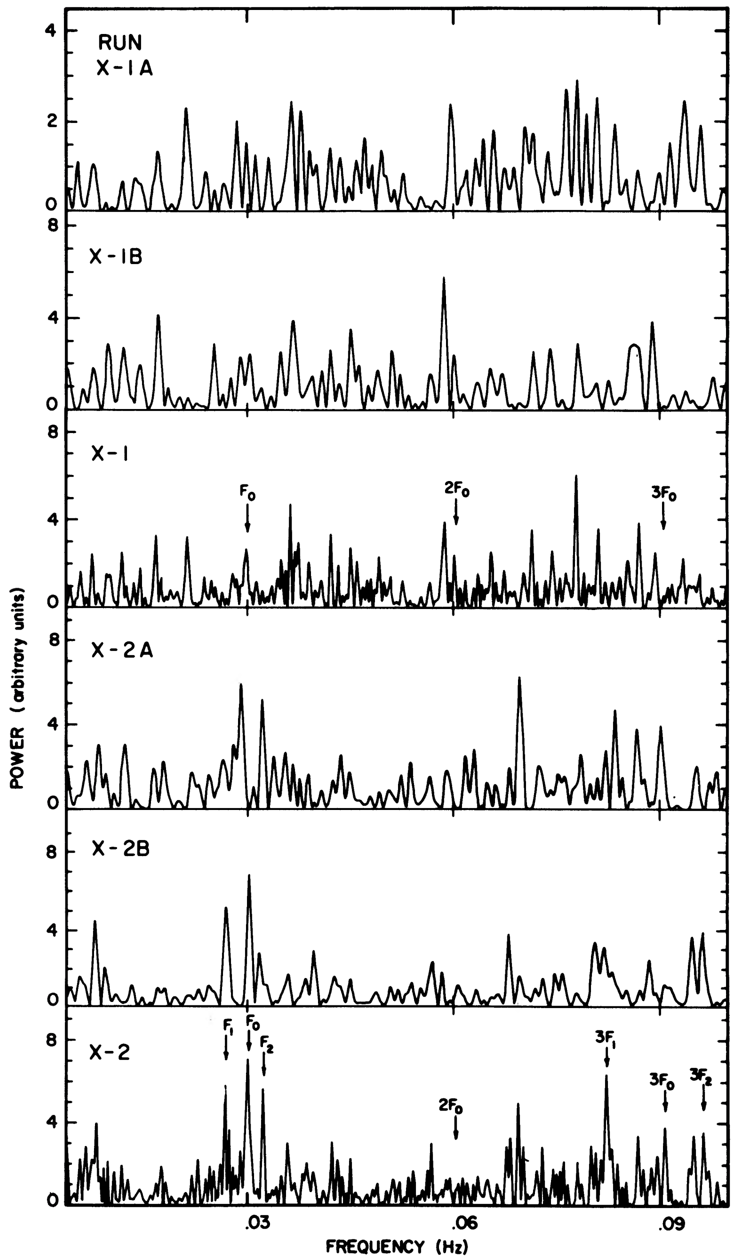

FIG. 2.—The power spectra of the X-ray light curves, normalized so that 4 represents the power in a periodicity of semi-amplitude 20%; F_0 is the fundamental period observed in the optical data.

Thus a significant fraction of the pulsed X-ray flux must emerge from a region with $T > 10^6$ K. If this region emits like a blackbody of that temperature, the corresponding limit on its radius is $R < 10$ km. Larger radii are permitted if, as seems likely, the radiation is optically thin bremsstrahlung.

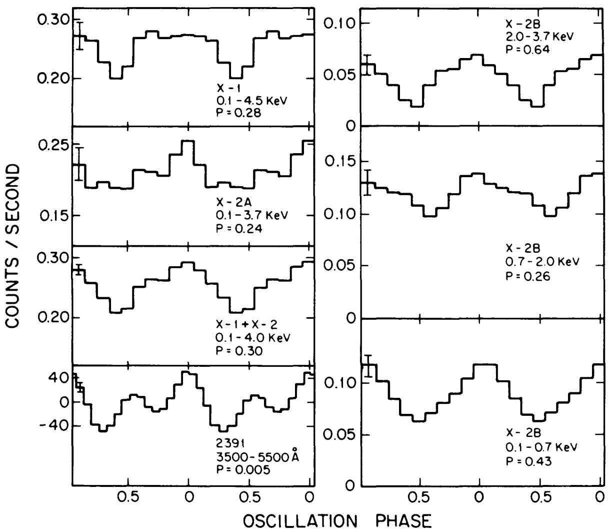

FIG. 3.—X-ray and optical light curves folded on the fundamental period of 33.0767 s. Phase zero is defined as the main pulse of the optical light curve. Each folded light curve is labeled by run number, photon energy or wavelength range, and deduced pulsed fraction P (defined as the peak-to-peak pulse intensity divided by the maximum intensity).

Two previous detections of X-ray pulsations in cataclysmic variables have been made: SS Cyg (~9 s; Córdova *et al.* 1980) and U Gem (~24 s; Córdova, Chester, and Garmire 1980), both dwarf novae in eruption. In contrast to AE Aqr, these pulsations were found to have very low coherence (7–12 orders of magnitude lower than the optical pulsation of AE Aqr) and a very soft spectrum (blackbody temperatures $\sim 3 \times 10^5$ K).

AE Aquarii is the only X-ray pulsar known in which the accreting star is certainly a white dwarf rather than a neutron star. The short period and high coherence of the oscillation require an origin in a compact star. If, as argued in Paper I, the observed frequency is the rotation frequency of the compact star, then the observed upper limits on period change ($|\dot{P}| < 10^{-13}$; Patterson 1980) require a moment of inertia $I \geq 2 \times 10^{50}$ g cm^2—five orders of magnitude too large for a neutron star. It seems likely that AE Aquarii is the "white dwarf pulsar" whose existence has been predicted for many years (e.g., Lamb 1974; Fabian, Pringle, and Rees 1976; Bath, Evans, and Pringle 1974).

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