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High Speed Photometry of AN UMa

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I. INTRODUCTION

The AM Her objects are low mass, short orbital period, mass transfer, X-ray binary systems composed of a magnetic ($B \sim 10^7$ G) accreting white dwarf and a mass losing late type main sequence star (for reviews see Liebert and Stockman 1985, Lamb 1985). The magnetic fields of the white dwarfs are so strong that their magnetospheres extend beyond the orbits of the companion stars enforcing synchronous rotation and field aligned flows from near the inner Lagrangian points of the systems to one or both of the magnetic poles of the white dwarfs. This leads to the formation of accretion funnels rather than accretion disks suggesting that the bulk of the emission from these systems comes from (or near) a radiative accretion shock formed as the plasma merges onto the dwarf. The AM Her systems are characterized by strongly polarized optical emission and intense soft and hard X-ray emission.

As a class, the AM Her objects exhibit temporal variability on time scales ranging from seconds to years. Most of the variations can be adequately described by "shot noise" models (Cordova and Mason 1982). Exceptions to this are the strictly periodic features modulated on the orbital periods of the systems (typically several hours) and the one to two second features which show up as "excesses" of power in the time averaged power spectra of AN UMa (Middleditch 1982) and E1405-451 (Mason et al. 1983, Larsson 1985). It has been suggested that the short time scale features are due to an oscillatory "instability" of radiative accretion shocks discovered by Langer, Chanmugam, and Shaviv (1981, 1982). This is an interesting suggestion because, if true, it would allow the masses of the accreting white dwarfs to be inferred and would provide other significant constraints on the physics of the accretion flows (see Langer et al 1981, 1982, Chevalier and Imamura 1982, Imamura, Wolff, and Durisen 1984, Imamura 1985). Unfortunately, a direct physical relationship between the one to two second optical variations and shock oscillations has not yet been demonstrated. Because of the potential importance of such a result further study of these systems is clearly warranted. In this work, we examine the short time scale behavior of AN UMa in more detail and improve on the work of Middleditch (1982) by resolving the feature in time.

The rest of this paper is organized as follows. In Section II, we present our observations. In Section III, we describe our analysis and present our results. In Section IV, we discuss the implications of our results. In Section V, we summarize our principal conclusions.

II. OBSERVATIONS

High speed photometry of AN UMa was obtained on 20 February 1985 UT in white light using the Hooker 2.5 m telescope of the Mount Wilson Observatory. The observations were made using one channel of an automated dual channel photometer equipped with a Ga-As photomultiplier. The date were obtained with a time resolution of 1 or 2 ms through a 16 arc second aperture. We alternately observed the sky, a comparison star, and AN UMa to ensure that any power seen in the power spectrum of AN UMa could be shown to be intrinsic to the source and not due to variations produced by the atmosphere. We observed AN UMa for a total of about three and one-half hours or approximately two orbital periods (P_{orb}= 114.84 minutes).

AM Her objects are observed to exist in several distinct luminosity states. AN UMa, during its high, intermediate, and low states has V ~ 14-15, 16, and 19-20, respectively (Liebert *et al*. 1982). During our observations, AN UMa was about V = 16, and so was in its intermediate state Middleditch (1982) observed AN UMa when it was V ~ 16 and when it was V ~ 17 - 18.

The time history of our observations, corrected for the sky contribution, is presented in Figure 1. The count rates are in units of counts per 8.192 s. The light curves are phased using the ephemeris of Liebert *et al*. (1982). In the convention of Liebert *et al*. (1982), φ = 0 corresponds to the peak of the linear polarization pulse in 1979.

III. ANALYSIS

a) Power Spectra

We searched our data for variations on time scales ranging from 4 ms to about ten seconds using standard Fourier techniques (*e.g*., see Middleditch and Nelson 1976, Jensen *et al*. 1983). We calculated power spectra by first breaking the data into blocks of time 65.536 s long. Each block was "detrended" by fitting and then subtracting a third order polynomial from the data. The first 10 % and last 10% of the data points in each sequence were then "filtered" using a cosine bell function to minimize the effects of "ringing" due to the "edges" in the data sets. The detrended, filtered data sets were then Fourier transformed and power spectra calculated The power spectra were normalized such that the average power per bin was equal to 1. To enhance the signal-to-noise ratio of our result, the individual power spectra were summed

We found, for frequencies ranging between 1 Hz and 250 Hz, that there are no coherent variations exceeding the 5 σ level. This puts an upper limit on the pulsed r.m.s. fraction for coherent variations of ~ 0.9 %. For frequencies less than 1 Hz, significant power was found over the range 0.5 to 0.8 Hz. This can be seen in figure 2, where we present the power spectrum of our data over the frequency range f = 0 to 7.8125 Hz. The power spectrum is the sum of 113 individual power spectra (the power level 113 is the horizontal line in Figure 2). Power levels of 160 (4.3 σ), 180 (6.2 σ), and 200 (8 σ) have probabilities of 5.53 x 10^{-5}, 5.53 x 10^{-8} and 1.40 x 10^{-11} of being exceeded by chance, respectively. The power spectrum contains 512 independent frequencies below the Nyquist limit (f = 7.8125 Hz). An r.m.s. pulsed amplitude of ~ 3.2 % is required to produce the power in the frequency range f = 0.5 to 0.8 Hz.

To study the short time scale features in more detail, power spectra of time intervals of one to five minutes were examined. Only in selected data sets were significant signals found. In figure 3a, we present an expanded plot of the data interval marked by the letter "A" on figure 1. The count rates are in units of 0.256 s. In figure 3b, we present the power spectrum of this data. This data interval produced the strongest signal we found. The large amplitude feature in Figure 3b, at f = 0.46 Hz, has a width of 0.03 Hz. It is not spread over the range 0.5 to 0.8 Hz suggesting that the "excess power" in Figure 2 is due to the averaging of many discrete periodicities (see also Larsson 1985). A feature of power level ~16 appearing in the frequency range f = 0.5 - 08 Hz has a ~ 0.01 % probability of occuring by chance and requires a 4.3 % r.m.s. variation in the light from AN UMa.

The r.m.s. pulsed amplitudes over the frequency range 0.5 to 0.8 Hz, as functions of the orbital phase, are presented in Figure 4. The pulsed fraction does not seem to be correlated with any particular orbital phase.

IV. DISCUSSION

a) Light Curve

The white light light curve in figure 1, has two distinct minima; one at phase 0.55 and one at phase 0.0. The published light curves of AN UMa for its high state (Gilmozzi et al. 1981, Liebert et al. 1982), for its intermediate state (Szkody et al. 1981), and for its low state (Liebert et al. 1982) are different from our white light light curve in that they usually show only one distinct minimum. Further, the minimum occurs near phase 0.35. The phase shift is significant as the ephemeris of Liebert et al. (1982)

$$HJD = 2443190.9921 \pm 0.0002 + [0.07975320 \pm 0.00000003]\ EPOCH. \qquad (1)$$

predicts an error in phase of $\lesssim$ 0.0025 at the epoch of our observations. Here HJD stands for Heliocentric Julian Date.

When our white light light curve is compared to the Exosat X-ray light curve (Osborne et al. 1984), several features are found in common. In particular, both light curves show two distinct minima. However, there again appears to be a phase shift. A phase shift has also been noted in a comparison of the SAS-3 X-ray light curve (Hearn and Marshall 1979) and the Exosat X-ray light curve (Osborne et al. 1984).

Phase shifts could be produced by several effects. For example, the direction of the accreting magnetic pole with respect to companion star could drift (e.g. see Joss, Katz, and Rappaport 1979, Lamb et al 1983, Chanmugam and Dulk 1983, Campbell 1983) or the active spot on the surface of the white dwarf could move. Either is a reasonable possibility.

b) Short Time Scale Variability

Short time scale features have been searched for in the ten known AM Her objects. Only AN UMa and E1405-451 were found to have such features (Middleditch 1982, Mason et al 1983, Larsson 1985). Remarkably, both objects showed these features over the same frequency range (f ~ 0.5 - 1 Hz). Further, AN UMa only showed them when it was V ≈ 16, not when it was V ≈ 17 - 18 (Middleditch 1982). It has been suggested that these variations are due to the oscillatory modes of radiative shock waves discovered by Langer, Chanmugam, and Shaviv (1981, 1982). The oscillations have also been extensively discussed by

Chevalier and Imamura (1982), Imamura, Wolff, and Durisen (1984), and Imamura (1985).

The aforementioned theoretical works found that the cooling regions of bremsstrahlung dominated radiative shocks were unstable to oscillatory motions under certain circumstances and that cyclotron dominated shocks were always stable to oscillatory motions. The results for bremsstrahlung dominated shocks, rather than those for cyclotron dominated shocks, are thought to be relevant to the magnetic AM Her systems based on both theoretical and observational arguments (see Liebert and Stockman 1985; and Lamb 1985).

White Dwarf radiative shocks were found to oscillate in several distinct modes. Following Chevalier and Imamura, we refer to these modes, in order of increasing oscillation frequency, as the fundamental (F), the first overtone (1O), the second overtone (2O), and so on. The lowest order modes were shown to have periods of $\tau_F = 3.1\ \tau_{br}$, $\tau_{1O} = 1.1\ \tau_{br}$, and $\tau_{2O} = 0.63\ \tau_{br}$, where τ_{br} is the postshock bremsstrahlung cooling time scale (e.g., see Imamura 1985). The time scale τ_{br} ranges from tenths of a second to several seconds for parameters typical of the AM Her objects. Further, τ_{br} can easily be shown to be a function only of the dwarf mass, M_*, the accretion luminosity, L, and the area of the emitting region, A, so that an observation of a shock oscillation, plus information on L and A would lead to an estimate of the mass of the accreting white dwarf.

The question of which τ relation applies to the AM Her objects is controversial, however. Langer <u>et al</u>. (1981, 1982) found for weakly magnetic white dwarfs that the F mode was unstable, while the overtone modes were stable. Imamura (1985) found for weakly magnetic white dwarfs that the F mode was always stable, while the 1O mode was unstable for $M_* \lesssim 0.3\ M_\odot$ and the 1O and 2O modes were unstable for $M_* \lesssim 0.9\ M_\odot$ for the cases where electron thermal conduction was included and where it was suppressed, respectively (see also Imamura, Wolff, and Durisen 1984). Future work, both observational and theoretical, may help to resolve this issue.

The short period optical features observed in AN UMa and E1405-451 have time scales compatible with shock oscillations. However, they have not been unambiguously linked to shock oscillations. Several scenarios for the production of the pulsed emission may be advanced. The pulsed emission may conceivably arise in: (1) the heated surface of the white dwarf; (2) the preshock flow, and (3) the hot shocked plasma. We consider each of these possibilities in turn.

The pulsed optical emission could be produced by the absorption and subsequent emission of the pulsed hard X-ray bremsstrahlung photons produced by the shock in either the stellar surface or the preshock flow. In the case of the stellar surface, the amount of energy that the dwarf radiates in the optical can be easily estimated. The typical temperatures of the X-ray heated areas on the white dwarfs in AM Her objects are thought to be 10_o– 50 eV. Therefore the energy radiated in the wavelength interval 3500 to 8000 A, given by the integral of the Planck function, B(E), times the area of the emitting region, is

$$L_{opt} = A \int_{E_{8000}}^{E_{3500}} B(E)dE \approx \frac{A\ kT_{bb}}{1.5c^2h^3/\pi}\ E_{3500}^3 \text{ if } E \ll kT_{bb}, \tag{2}$$

where c is the speed of light, A is the area of the emitting region (presumably the base of the accretion funnel), h is the Planck constant, and E is the photon energy. For $kT_{bb} = 50$ eV and $A/S_* = 10^{-4}$, where S_* is surface area of the dwarf, $L_{opt} = 3.6 \times 10^{28}$ $(R_*/5 \times 10^{8}$ cm$)^2$ ergs s^{-1} (see Lamb 1985). This is four orders of magnitude smaller than AN UMa's inferred optical luminosity during its high state (Schmidt et al. 1985). Choosing values for kT_{bb} and A which maximize L_{opt} produces a value twenty times larger than the above estimate.

The preshock flow could be Compton heated by the pulsed bremsstrahlung photons. The heated preshock flow would then radiate the energy in the optical as cyclotron emission. For parameters typical of the AM Her systems, however, the Compton heating rate is much too low to account for the observed optical emission. This occurs because of the low optical depth to electron scattering perpendicular to the magnetic field in an accretion funnel. The low optical depth allows most of the bremsstrahlung photons to escape from the funnel without scattering (Imamura and Durisen 1983).

The pulsed optical emission may be directly produced by the shock as cyclotron emission. Although cyclotron emission cannot be the dominant cooling mechanism in the shock, it can be present at levels of up to around 10 % and still allow oscillations to exist (Chanmugam, private communication). For parameters typical of the shocks in the AM Her objects, cyclotron emission is optically thick up to harmonics around 10 – 15 (Chanmugam and Dulk 1981). For $B \sim 3.5 \times 10^7$ G (Liebert et al. 1982; Schmidt et al. 1985), this leads to emission which has an E^2 dependence up to an energy of $E_* \sim (10\text{–}15)\, h\nu_{cyc} = (4\text{–}6)$ eV and then steeply falls-off for $E > E_*$.

The luminosity of the cyclotron component can be estimated using equation (2) by noting that the shocked plasma has a temperature of 50 keV and setting $A/S_* = 10^{-4}$. The optical cyclotron luminosity is then $L_{cyc} \sim 3.6 \times 10^{31}$ $(R_*/5 \times 10^{8}$ cm$)^2$ $(A/10^{-4}$ $S_*)$ $(T/5 \times 10^{8}$ K$)$ ergs s^{-1}. This value for L_{cyc} is much less than the high state L_{opt} of 4×10^{32} ergs s^{-1} (Schmidt et al 1985). However, it is consistent with the intermediate and low state luminosities.

The optical spectrum may be more problematic for shock models. During AN UMa's high state, its spectrum rises towards the "blue" as does the percentage of circularly polarized light (Krzeminski and Serkowski 1979, Liebert et al. 1982). This suggests that the cyclotron emission also rises towards the blue implying $E_* \geq 2\text{–}3$ eV. During AN UMa's intermediate state, the spectrum peaks in the range $E \sim 1 - 2$ eV (Liebert et al. 1982). There are no polarization measurements available for this state and thus the value of E_* cannot be determined. During AN UMa's low state, the spectrum rises towards the "red" peaking at $E \leq 1$ eV. Further, the percentage of circularly polarized light in the red also increases suggesting that $E_* \leq 1$ eV too. In shock models, the value of E_* is primarily determined by the plasma temperature and the magnetic field, it is only weakly dependent on the plasma density (Lamb 1985). The variation in E_* can thus be understood if the shock radius (R_*+d_s) varies by $\geq$ 30 % from the high to low states. Such variations in the shock radius could occur if (L/A) decreases by at least 30 % in going from the high to the low states of AN UMa. However, because this type of shock (with cyclotron emission) has not been modeled, it is not known if the detailed shape of the optical continuum can be reproduced.

So, although a shock origin for the optical variations is plausible, it is clear that the case has not been made that they are due to shock oscillations. A resolution of this issue could be made by observations of the hard X-ray emission from AN UMa. At the present time, however, AN UMa is undetected in hard X-rays. Further, only the X-ray emission from AM Her itself has been searched on the proper time scales. No large amplitude coherent oscillations were found in the HEAO1-A2 soft X-ray data (Tuohy et al. 1981) and the HEAO1-A1 hard X-ray data (Imamura et al. 1985). Other AM Her objects need to be studied.

The notion that the optical pulsations are due to a radiating shock could explain why the variations go away during the low state of AN UMa and why there is a minimum frequency ($f \sim 0.5$ Hz) in both AN UMa and E1405-451. For shocks with (L/A) satisfying the constraint,

$$(L/A) \lesssim 6.5 \times 10^{18} \left(\frac{5\times10^{8}\,\mathrm{cm}}{R_*}\right)^2 \left(\frac{B}{2\times10^{7}\,\mathrm{G}}\right)^{5/2} \mathrm{ergs\ cm^{-2}\ s^{-1}}, \tag{3}$$

cyclctron emission dominates bremsstrahlung (Lamb and Masters 1979), and so are expected to be stable. Suppose that during its high state AN UMa is bremsstrahlung dominated. As it makes the transition to its low state, if the value of A remains approximately constant, the quantity (L/A) decreases. As (L/A) decreases, the importance of cyclotron emission increases. Presumably, a point will be reached where cyclotron emission will be able to damp the oscillations. This threshold for the excitation of oscillations could explain why the optical feature goes away as AN UMa goes into its low state. Further, because the shock oscillation frequencies decrease as (L/A) decreases, the existence of this threshold could naturally explain why the optical features always have frequencies ≥ 0.5 Hz. Unfortunately, because equation (3) is valid only in an order-of-magnitude sense, we cannot quantitatively predict the lower limit, in terms of (L/A), for the existence of pulsations and hence, the lower limit for the frequency of optical features.

V. SUMMARY

We studied the 1 to 2 second feature of the AM Her object AN UMa (Middleditch 1982). We found that the broad feature in the time averaged power spectra of AN UMa found by Middleditch (1982) could be resolved into discrete features if the data were averaged over time intervals of one to five minutes, i.e., the broad feature is due to the superposition of many discrete periodicities. The features could not reliably be isolated to any particular orbital phase. However, it did not appear that they disappeared during times of minima.

The short time scale features could not be unambiguously linked to shock oscillations. However, they could plausibly be produced by such a phenomenon. If a direct physical relationship between the short time scale features and shock oscillations could be demonstrated, constraints could be placed on the mass of the accreting white dwarf in AN UMa and on the physics of its accretion flow, e.g., upper limits on the importance of cyclotron emission and electron thermal conduction

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References

Campbell, C. 1983, M.N.R.A.S., 205, 1031.

Chanmugam, G., and Dulk, G. A. 1981, Ap. J., 244, 569.

_____. 1983, in Cataclysmic Variables and Related Objects, eds. M. Livio and G. Shaviv (Dordrecht: Reidel), p. 223.

Chevalier, R. A., and Imamura, J. N. 1982, Ap. J., 261, 543.

Cordova, F. A., and Mason, K. O. 1982, Pulsations in Classical and Cataclysmic Variable Stars, eds. J. P. Cox, and C. J. Hansen (Boulder: Univ. of Colorado Press), p. 23.

Gilmozzi, R., Messi, R., and Natali, G. 1981, Ap. J. (Letters), 245, L119.

Hearn, D. R., and Marshall, F. R. 1979, Ap. J. (Letters), 232, L21.

Imamura, J. N. 1985, Ap. J., 296, 000.

Imamura, J. N., and Durisen, R. H. 1983, Ap. J., 268, 291.

Imamura, J. N., Wolff, M. T., and Durisen, R. H. 1984, Ap. J., 276, 667.

Imamura, J. N., Wood, K. A., and Durisen, R. H. 1985, Ap. J., in preparation.

Jensen, K. A., Cordova, F. A., Middleditch, J., Mason, K. O., Grauer, A. D., Horne, K., and Gomer, R. 1983, Ap. J., 270, 211.

Joss, P., Katz, J. I., and Rappaport, S. A. 1979, Ap. J., 230, 176.

Krzeminski, W., and Serkowski, K. 1977, Ap. J. (Letters), 216, L45.

Lamb, D. Q. 1985, Cataclysmic Variables and Low Mass X-ray Binaries, eds. D. Q. Lamb, and J. Patterson (Dordrecht: Reidel), p. 179.

Lamb, D. Q., and Masters, A. R. 1979, Ap. J. (Letters), 234, L117.

Lamb, F. K., Aly, J.-J., Cook, M. C., and Lamb, D. Q. 1983, Ap. J. (Letters), 274, L71.

Langer, S. H., Chanmugam, G., and Shaviv, G. 1981, Ap. J. (Letters), 245, L23.

_____. 1982, Ap. J., 258, 589.

Larsson, S. 1985, As. Astr., 145, L1.

Liebert, J., and Stockman, H. S. 1985, in Cataclysmic Variables and Low Mass X-ray Binaries, eds. D. Q. Lamb and J. Patterson (Dordrecht: Reidel), p. 151.

Liebert, J., Tapia, S., Bond, H., and Grauer, A. D. 1982, Ap. J., 254, 232.

Mason, K. O., Middleditch, J., Cordova, F. A., Jensen, K. A., Reichert, G., Murdin, P. G., Clark, D., and Bowyer, S. 1983, Ap. J., 264, 575.

Middleditch, J. 1982, Ap. J. (Letters), 257, L71.

Middleditch, J., and Nelson, J. 1976, Ap. J., 208, 567.

Osborne, J., et al. 1985, in X-ray Astronomy '84, ed. Y. Tanaka (Tokyo: Inst of Sp. and Astr. Science Press), in press.

Schmidt, G. D., Stockman, H. S., and Grandi, S. A. 1985, Ap. J., submitted.

Szkody, P., Schmidt, E., Crosa, L., and Schommer, R. 1981, Ap. J., 246, 223.

Tuohy, I. R., Mason, K. O., Garmire, G. P., and Lamb, F. K. 1981, Ap. J., 245, 183.

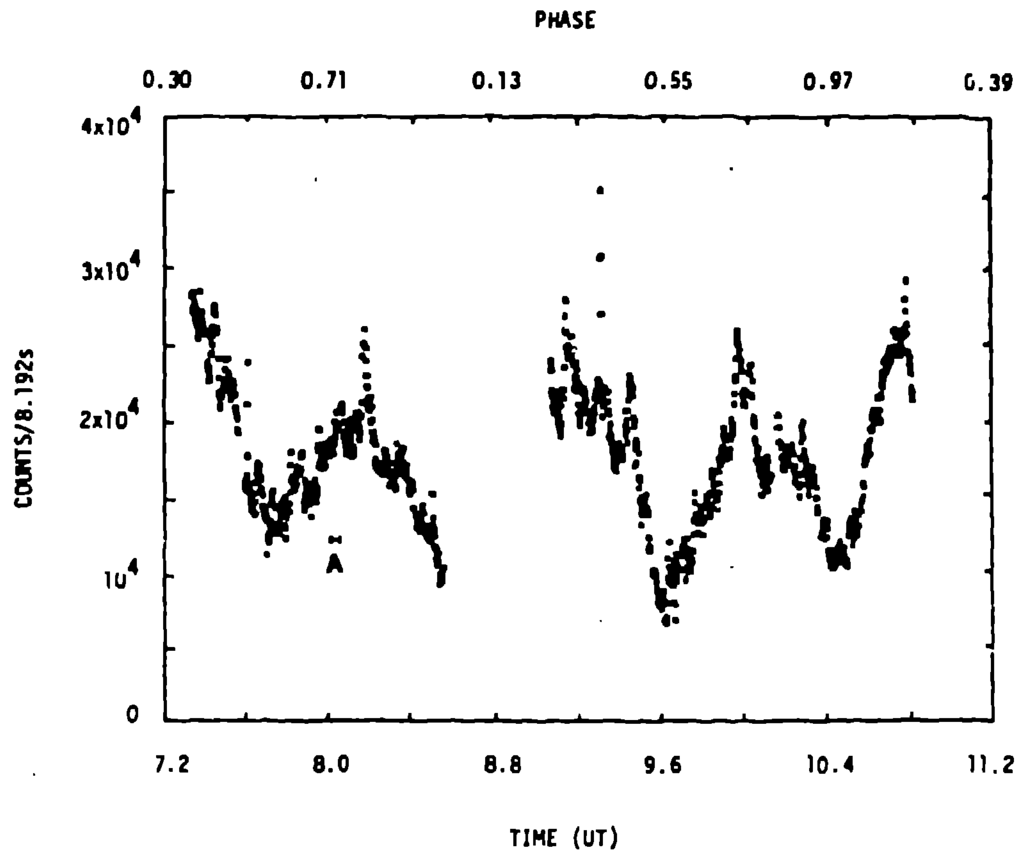


Figure 1: The time history of our white light observations (corrected for the sky contribution) taken on 20 February 1985 UT. The count rates are in units of counts per 8.192 s and the times are the UT. The orbital phases are based upon the ephemeris of Liebert et al. (1982).

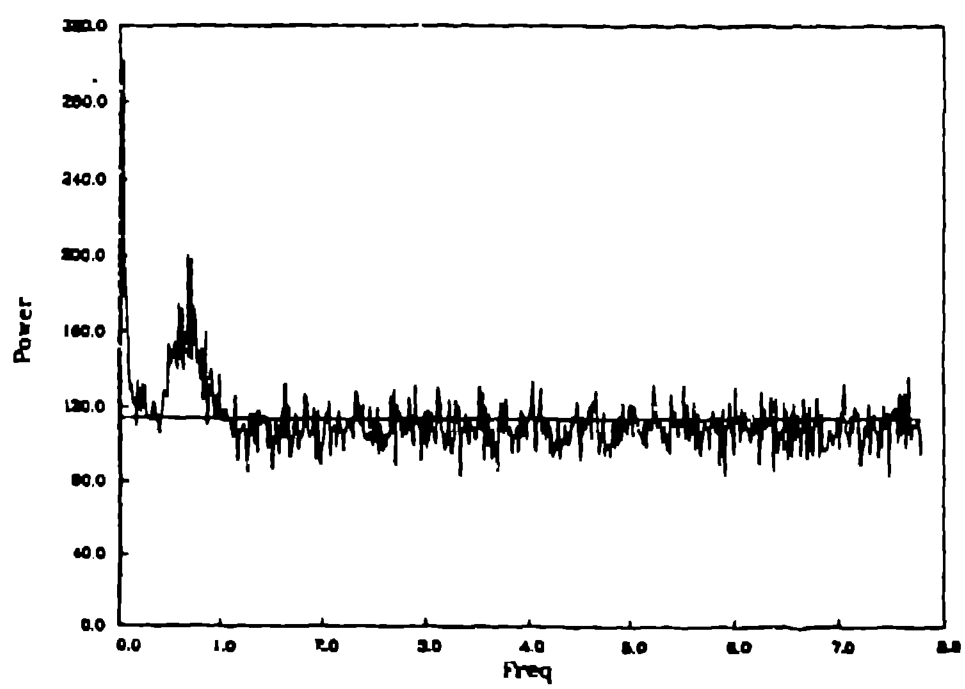
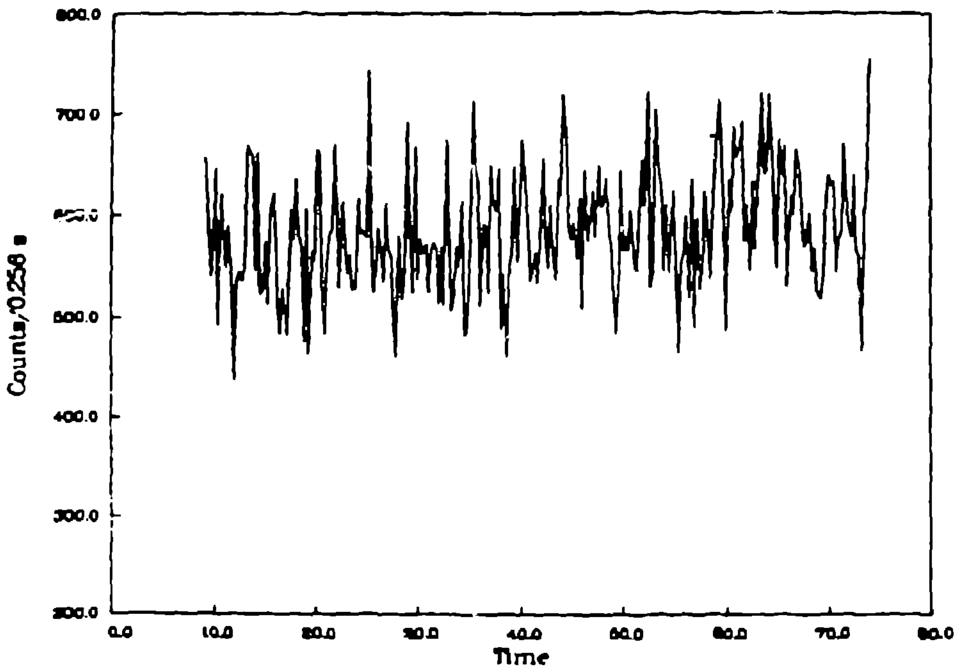


Figure 2: The power spectrum of the data presented in Figure 1. The resolution in frequency is 0.015 Hz and the Nyquist limit is 7.8125 Hz. The power spectrum is the sum of 113 individual power spectra.



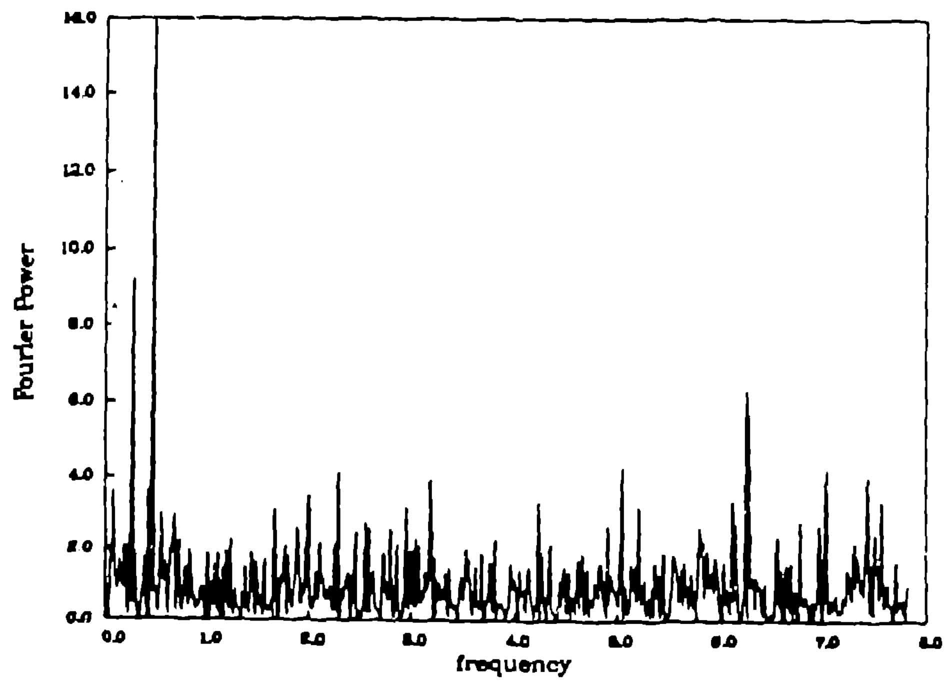


Figure 3: a) The data interval marked by the letter "A" on Figure 1. The count rates (corrected for the sky contribution) are in units of counts per 0.256 s. b) The power spectrum of the data string given in Figure 3a. The resolution in frequency is 0.015 Hz and the Nyquist limit is 7.8125 Hz.

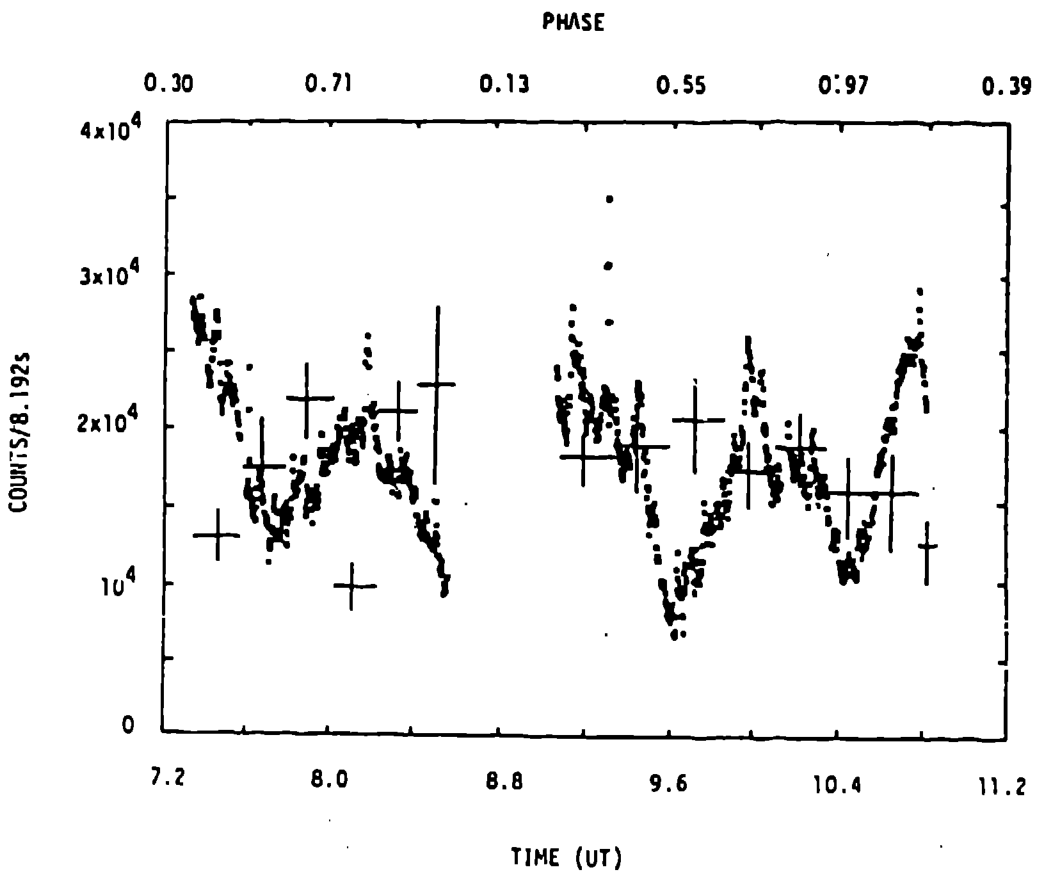


Figure 4: The variation of the pulsed fraction of the oscillations as a function of the orbital phase.