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AUTO-CORRELATION TECHNIQUES IN SEARCHES FOR RAPID QUASI-PERIODIC MODULATION IN dMe FLARE STARS

Outside the classical flares in the dMe stars, variability has been reported on several short time-scales, excluding rotational modulation by starspots : slow quasi-periodic modulation (~ 30 mins to a few hours), small-amplitude fluctuations (~ 1 to 30 minutes), temporary pulse-like oscillations (a small number, each lasting a few seconds to about 1 minute) and large-amplitude spikes (usually randomly-spaced individual events, with duration only 0.1 to about 2 seconds). See Chugainov et al.1969, 1984, Cristaldi and Rodono 1970 and 1973, Rodono 1974, Moffett 1974, Jarrett and van Rooyen 1979, Zalinian and Tovmassian 1987, Doyle and Butler 1987. The importance of investigations into photometric micro-variability of dMe stars lies in relation to (i) the contribution to the total energy budget of the flaring mechanism, (ii) the understanding of the processes involved in the flaring and quiescent flux, (iii) the evolutionary status of low-mass stars, and their past and present interaction with the stellar environment, and (iv) the predictions of global oscillations from asteroseismology.

Observations Sequential UBV(RI) pulse-counting photometry (Kron - Cousins RI) of the dM2e flare star, V1285 Aql (= Gliese 735, $18^h53^m03^s$, $+8°20'18''$, Equinox 1950), was obtained with the 50cm telescope at the South African Astronomical Observatory. Flares on this star were first detected by Shakovskaya and Maslennikov (1970) and the star was subsequently studied by Byrne et al. (1984). V1285 Aql was observed for 4.6 hours over a 6-hour interval on 26 August 1985 (Table I). Combined with earlier observations from 20 and 23 August 1985, mean photometry for 3 nights gave $V = 10.110 \pm 0.009$, $U - B = 1.077 \pm 0.041$, $B - V = 1.526 \pm 0.010$, $(V - R) = 1.090 \pm 0.011$, $(V - I) = 2.468 \pm 0.014$, using 10 observations per night. On 26 August five-colour UBV(RI) pulse-counts of variable, sky and standard stars were made, and over some intervals two-colour (U and B)

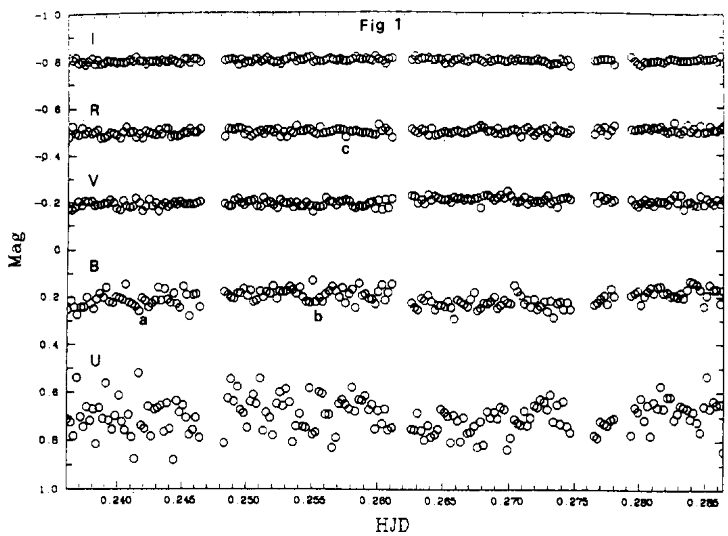

Figure 1

Sequential UBV(RI) monitoring of V1285 Aql from 17:35 to 18:48 UT on 26 August 1985 (HJD 244,6304.0 days). The time intervals for the multi-colour measurements are given approximately by :

$$t_U = t, t_B = t + 6, t_V = t + 10, t_R = t + 13.5, t_I = t + 17, t'_U = t + 22.5 (secs).$$

N.B. (a) Fragmented B-band eyeball "wave" of duration about 5 to 6 minutes and full-amplitude 0.05 mag. at 17:46:00 UT. (b) Another B-band "wave" at 18:02:20 UT, possibly associated with (c) an R-band "wave" with a maximum at 18:05:20 UT. with full-amplitude 0.013 mag.

observations were made for improved time resolution. These multi-colour observations were made during bright moon but in excellent seeing conditions, when the star passed maximum altitude (airmass 1.32) within a range of airmasses from 1.46 to 1.33. Figure 1 shows the five-colour observations from 17:35 to 18:48 UT using 5,2,1,1,1 sec integrations in UBV(RI), respectively. Sky measurements were taken about every 20 minutes and a standard star measured at the beginning and end of this run of 1.2 hours. A change to two-colour, U and B, monitoring immediately followed this run (Figure 2 and Table I). With print-out and on-line reductions the mean observing cycle in UBV(RI) was 22.5 seconds. Several variations atypical of classical flares with their sharp rise to maximum were suspected in the B, R and I bands, some with wave-like features. Quasi-periodic R band "waves" with a semi-amplitude of 0.007 magnitude were suspected from an inspection of the multi-colour plots. Also, wave-like features were detected in the B band with semi-amplitudes of about 0.025 mag. However, intrinsic stellar fluctuations cannot easily be unambiguously distinguished from brief moments of changing transparency and sky brightness. We do not know of any instrumental effects, e.g. periodic errors in the drive of the 50-cm telescope, which would account for these "waves".

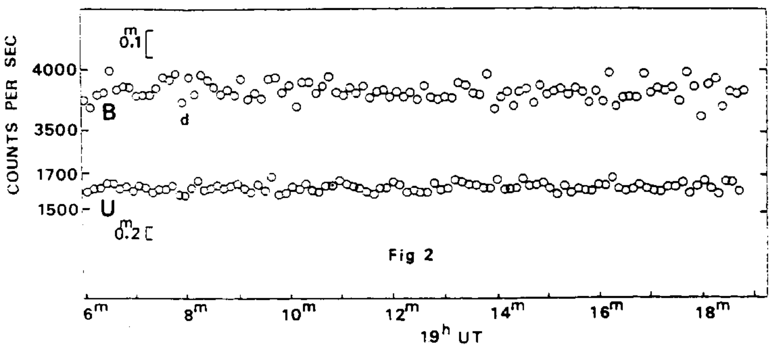

Figure 2

Sequential U and B monitoring of V1285 Aql from 19:06 to 19:19 UT on 26 August 1985 at a time resolution of 7 seconds. We see a B-band "wave" with duration (minimum to minimum) of 160 seconds and full-amplitude approximately 0.1 mag. at 19:08 UT., and continuously maintained U-band fluctuations of about the same "period". These data were not utilized in the analysis contained in the present paper, but illustrate the emergence of a further 2.5-minute "characteristic time interval" in B

Auto-correlation techniques Initially, we utilized Fourier techniques to construct periodograms of the time-series for the UBV(RI) magnitudes of V1285 Aql during the interval, 17:35 to 18:48 UT (HJD-2446304.0 = 0.236 to 0.286) which comprised 5 × 179 data sets. A test of significance was carried out using the false-alarm probability calculated for the strongest peaks in the power spectra for the UBV(RI) data (Scargle 1982). Quasi-periodicity was suspected at the 99% confidence level in the R and I bands, for periods of about 3.9 to 3.7 minutes, respectively, with a relative error in the period of 2%. Estimates of the relative error in the peak power for our data demonstrated that 50% errors were common in the presence of noise, and this strongly affects the calculation of the false-alarm probability. It is also difficult to unambiguously separate quasi-periods from atmospheric variations.

Auto-correlation analysis was found to be a preferable tool for detecting quasi-periodic trends in the time series. The auto-correlation parameter, $\Theta(\tau)$, used by Burki et al. 1978, where τ is the time lag or trial period, possesses several properties which allow the detection of trends in segments of data in the presence of noise. Their method of analysis was applied to the quasi-sinusoidal periodicity of supergiants where the amplitude and period are not constant over many cycles. The relatively small amount of data on the dMe stars and the short quasi-periods we are examining means, in fact, that a treatment similar to that in the case studied by Burki et al. is more appropriate.

From the observed B-band light curve, $B(t)$, between times t_o and t_f, a second time series, $B^{'}(t+\tau)$, was constructed in the range $t_o+\tau$ to $t_f+\tau$, where τ was the trial period. In the range $t_o+\tau$ to t_f over which $B(t)$ and $B^{'}(t+\tau)$ overlap, the

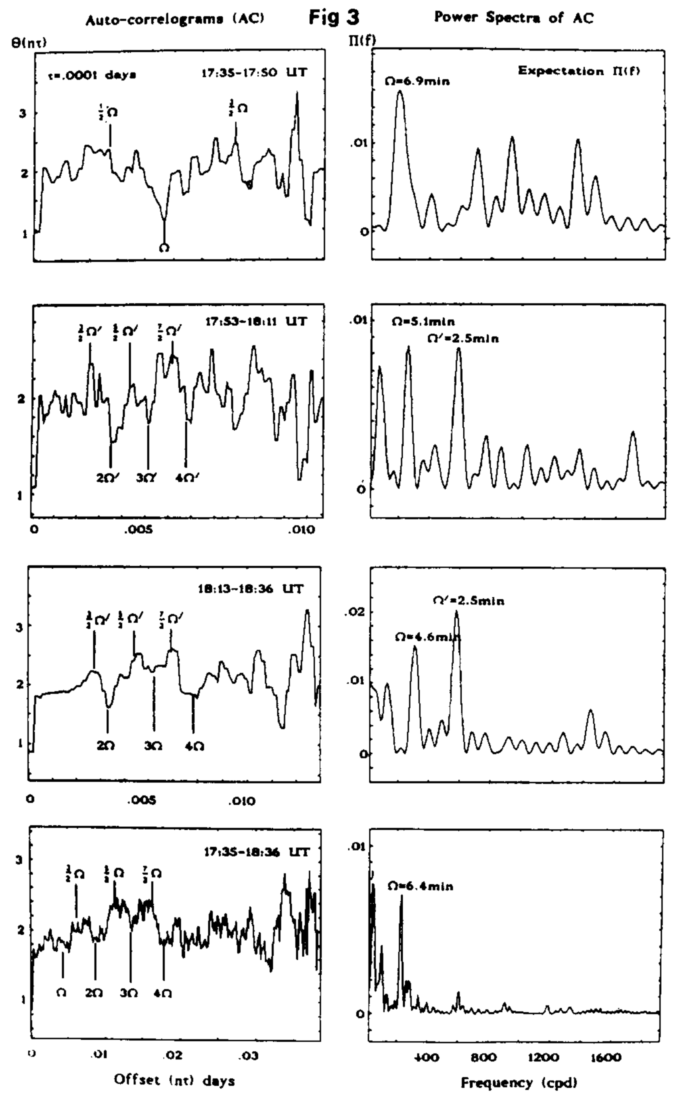

Figure 3

The auto-correlograms using the method of Burki et al. 1978 for the UBV(RI) data of V1285 Aql in Figure 1. The periodograms of the auto-correlation parameter, $\Theta(\tau)$, are shown on the right of their respective auto-correlograms, for the intervals 17:35-17:50, 17:53-18:11 and 18:13-18:36 UT (allowing for breaks in the data due to sky measurements), and for the total time, 17:35-18:36 UT. An auto-correlation time-lag, τ, of 0.0001 days (8.6 seconds) was used throughout. The suspected periods are indicated as multiples of the half-period (peaks) and the period (minima). When grouping the data we find periods of 6.9 and 2.5 minutes, compared with only 6.4 minutes in the total time interval.

two time series were re-ordered chronologically and an auto-correlation parameter, $\Theta(\tau)$, defined by the ratio of the mean square successive difference, δ^2, and the variance, σ^2 :

$$\Theta(\tau) = \delta^2/\sigma^2 = \sum[B'_{i+1} - B'_i]^2 / \sum[B'_i - B'_{mean}]^2 \qquad (1)$$

was evaluated. By substituting $\Delta_i = B'_i - B'_{mean}$, we have :

$$\delta^2/\sigma^2 \approx 2 - 2[\sum(\Delta_{i+1}\Delta_i)/\sum \Delta_i^2] \qquad (2)$$

neglecting $(\Delta_1^2 + \Delta_n^2)/\sum \Delta_i^2$. The parameter $\Theta(\tau)$ has the property that if the data do not possess a trend with time, $\Theta(\tau)$ remains approximately constant and close to the value 2. A quasi-periodic trend of *period,* Ω, causes $\Theta(\tau)$ to increase from zero until $\tau = \Omega/2$, and then to oscillate according to this *period* (see Figure 3). In practice the first and, possibly, the second peak is only seen, but when there is only "limited confusion" in the identification of peaks, use may be made of periodograms of the auto-correlation parameter to measure a periodic trend in the auto-correlograms themselves. In some cases an upward curvature also appears in the auto-correlograms indicative of a much slower trend, and oscillations appear superposed on the better-defined features in the auto-correlograms which may not be entirely noise. In the simplest cases, statistical levels of confidence may be estimated in the auto-correlograms using tables from Crow et al. (1960). The maximum *expectation* of the power spectrum (in the range f = *100 to 1900 cpd*) as given by the peak in the Fourier transform of the auto-correlation parameter occurred at f = *226 cpd,* corresponding to a period of 6.37 minutes (see bottom of Figure 3). This procedure produced a "period" which was approximately the duration (peak-to-peak) of the B-band "eyeball waves", but the overall fit to the B-band data using this period was poor, probably due to the increased noise in the latter half of the data in Figure 1.

We also divided the B data into three groups according to gaps occurring when sky measurements were taken, and formed auto-correlograms and periodograms for each group. We found a "period" of 6.92 minutes in the first group, but somewhat smaller periods in the second and third groups, and in addition, periods of 2.46 and 2.49 minutes, respectively, in the latter groups (see top three panels of Figure 3). There were confusing elements in this procedure due to the presence of additional peaks in the periodograms of the auto-correlograms. In Figure 2, however, we see a further fragments of a 2.5-minute "wave" in the B-band data (not used in the analysis) occurring half-an-hour later at 19:08 hrs U.T., during U and B monitoring only. It would appear that the procedure is capable of detecting a "characteristic time interval" between photometric outbursts.

Conclusions From periodogram analysis for V1285 Aql we found (a)quasi-periodicity at the 99% confidence level in the R and I bands with periods of 3.9

and 3.7 minutes, respectively, with amplitudes of about 0.01 mag. (max.to.min), sustained during the interval of our observations, i.e. for up to one hour, and (b) no significant periods in U, B or V. However, using auto-correlation techniques, we detected (c) waves in the B-band with two quasi-periods of about 6.4 and 2.5 minutes, which we interpret as "characteristic time intervals" between low-amplitude outbursts. We note that the R-band period given by our initial analysis is approximately related to those detected in the B band by auto-correlation analysis by : $[\Omega_R]^{-1} = [\Omega_B]^{-1} + [\Omega_B']^{-1}$, i.e. we possibly have interfering frequencies (370, 226 and 590 cpd). We do not appear to be observing micro-flares since the amplitude of flaring is invariably greater in the ultraviolet, and there was no evidence of flare-like events in the ultraviolet although this could be due to the poorer S/N ratio in the U band.

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