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The determination of the rotational periods of Rapidly Oscillating Ap stars from their mean light variations–I. The Rapidly Oscillating Ap star, HD 6532; the F2 IV/V star, HD 6491; and the He-weak B star, HD 5737 (HR 280, α Scl)

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Summary. We have obtained *UBVRI* mean light observations of HD 6532, HD 6491 and HD 5737 with respect to the F5IV comparison star HD 7259. A frequency analysis of the HD 6532 data shows that it has a rotation period of $P_{\rm rot}=1.9455\pm0.0019$ day. We have discovered that HD 6491 has sinusoidal light variations with a period of either 0.82841 ± 0.00011 day, or twice that period, or, slightly less likely. 4.868 ± 0.004 day. No unequivocal variation was found in HD 5737 although a period of 58.8 day is consistent with our data and previous magnetic observations.

1 Introduction

The Rapidly Oscillating Ap stars are a group of 12 cool magnetic SrCrEu Ap stars which oscillate with periods between 4 and 15 min with peak-to-peak light variations of $\Delta B \leqslant 0.016$ mag. The oscillations in these stars have been successfully interpreted as high-overtone p-modes with the pulsation axis aligned with the magnetic axis of the star which is itself oblique to the rotation axis (the oblique pulsator model) (Kurtz 1982; Dziembowski & Goode 1985a, b; Kurtz & Shibahashi 1986). Recent reviews of these stars are given by Kurtz (1985a) and by Shibahashi (1986).

One of the important observations in support of the oblique pulsator model is that for HR 3831 the rotation frequency determined from the mean light variations* is the same as the equal frequency splitting in the amplitude spectrum of the rapid oscillations to an accuracy of 5×10^{-5} (Kurtz & Shibahashi 1986; Shibahashi, Kurtz & Goode, in preparation). Less direct evidence indicates that the same equality of rotation frequency and frequency splitting probably holds true in HR 1217 (Kurtz 1982, 1985a). It is therefore important to find out whether other Rapidly Oscillating Ap stars also have amplitude spectra with equally split frequency triplets and quintuplets and whether the rotation frequency in those stars is the same as that frequency splitting.

*Throughout this paper we use the phrase 'mean light variation' to refer to the light variability which occurs with the rotation period of the star. This is to distinguish such light variations from the rapid pulsational variability which occurs on a time-scale of minutes.

HD 6532 is a Rapidly Oscillating Ap star with periods near 6.94 min discovered by Kurtz & Kreidl (1985). They found that the amplitude spectrum of the rapid oscillations in this star showed three frequencies which were not equally spaced, but they pointed out that aliasing problems made their frequency analysis insecure and that one or more of their frequencies may have been incorrectly identified. They also found a rotational period for HD 6532 of $P_{\rm rot}=1.7858$ day from its mean light variations.

In order to suppress the daily aliasing problem in HD 6532, Kurtz & Cropper (1987) observed HD 6532 for 90 hr contemporaneously from the South African Astronomical Observatory and Mount Stromlo and Siding Spring Observatory in 1985. They found that the rapid light variations in HD 6532 could be described completely by an equally spaced frequency triplet with a frequency splitting of $\Delta f=5.952\pm0.004\,\mu$Hz. They also found from their mean light observations the same rotation period of $P_{\rm rot}=1.7886\pm0.0005$ day as found by Kurtz & Kreidl corresponding to a rotation frequency of $f_{\rm rot}=6.471\pm0.002\,\mu$Hz which is clearly not equal to the pulsational frequency splitting.

Kurtz (1986) pointed out that if the frequency splitting and rotational frequency in HD 6532 are really not the same, then the oblique pulsator model is not applicable, but rather the pulsation frequencies should be interpreted as rotationally perturbed m-modes. He further pointed out, however, that before such a conclusion should be reached it is important to be certain of the rotation period. The study of the mean light variations undertaken by both Kurtz & Kreidl (1985) and by Kurtz & Cropper (1987) used HD 6491 as the only comparison star.

HD 6491 is an F2IV/V star (Houk 1982) with $V=8.141$ and Strömgren colours of $b-y=0.244$, $m_1=0.165$, $c_1=0.633$ (Olsen 1983) and $\beta=2.716$ (Hauck & Mermilliod 1985). Both the colours and spectral type place this star outside of the observed δ Scuti instability strip (Breger 1979) and make it a good candidate for use as a constant comparison star. The use of a single comparison star for a variable star study is not a foolproof procedure, however, unless the comparison star has been proved constant in an independent study. Neither Kurtz & Kreidl (1985) nor Kurtz & Cropper (1987) provided that proof for HD 6491 because their observations were primarily concerned with the rapid oscillations in HD 6532 and only secondarily with the mean light variations; the technique of high-speed photometry which they were employing did not easily lend itself to proper, full-scale studies of the mean light variations.

Because of this we have undertaken a standard differential photometric study of the mean light variations in HD 6532 using HD 6491 and HD 7259 as comparison stars. HD 7259 is classified as F5IV by Houk (1982) and has Strömgren colours of $b-y=0.310$, $m_1=0.157$, $c_1=0.500$ and $\beta=2.652$ (Hauck & Mermilliod 1985). At the request of Dr D. Brown we also included the He-weak magnetic variable HD 5737 (HR 280 α Scl) in this study in order to try to determine its rotation period.

We discovered that HD 6491 is a variable star and hence was not suitable for the mean light studies of Kurtz & Kreidl (1985) and Kurtz & Cropper (1987); we discovered that HD 6532 has a rotation period of $P_{\rm rot}=1.9455\pm0.0019$ day or a rotation frequency of $f_{\rm rot}=5.949\pm0.006\,\mu$Hz which is equal to the frequency splitting found by Kurtz & Cropper (1987) in the amplitude spectrum of the rapid oscillations in this star. Our results for HD 5737 indicate that there is probably some photometric variability in this star, particularly in V, but that the variations are so small that our results are inconclusive.

2 Observations

Observations were obtained on 35 nights from 1986 June to November using the 'New Photometer' attached to the 0.5-m telescope of the South African Astronomical Observatory (SAAO) at Sutherland. The New Photometer is a single-channel system using a Hamamatsu R943 GaAs tube. We used 40-s integrations through *U, B, V, R* and *I* filters on each star followed by 5-s integrations through the same filters on the sky. We observed in the sequence HD 7259, 6491, 6532, 5737, 6491, 7259. The observations were placed on the standard system using E-region standards and were corrected for dead-time losses, sky background and extinction. All observations were obtained through 30 arcsec or larger apertures. Observations of HD 5737 were made through a 1 mag neutral density filter since the Hamamatsu tube can only accommodate counting rates up to 400 000 s^{-1}. HD 7259 was taken to be our constant standard and the other stars' observations were reduced to differential magnitudes with respect to HD 7259. Where the HD 7259 magnitudes differed by more than 1 mmag over the time it took to go through the observing sequence, we used linear interpolation of the HD 7259 magnitudes to obtain the differential values for the other stars. The results of these observations are presented in Tables 1, 2 and 3.

Table 1. Differential mean photometry of HD 6532.

HJD	ΔV	ΔB	ΔU	ΔR	ΔI
6595.6599	1.898	1.609	1.674		
6596.6673	1.900	1.601	1.661		2.316
6597.6553	1.902	1.619	1.680		2.323
6601.6454	1.903	1.609	1.675		2.321
6603.6543	1.902	1.604	1.671		2.326
6614.6385	1.909	1.609	1.637		
6614.6670	1.908	1.607	1.641		
6630.5843	1.901	1.619	1.675		2.321
6631.5620	1.905	1.598	1.658		2.322
6633.5461	1.902	1.598	1.659		2.330
6641.5455	1.899	1.602	1.660		2.310
6642.5033	1.902	1.607	1.670		2.314
6643.5305	1.900	1.597	1.657		2.319
6644.4647	1.901	1.606	1.667		2.312
6644.6734	1.908	1.596	1.657		2.331
6645.5265	1.912	1.611	1.668		2.316
6649.5350	1.908	1.599	1.649		2.318
6650.4710	1.914	1.597	1.655		2.332
6650.6605	1.919	1.593	1.653		2.341
6654.4677	1.915	1.599	1.647		2.333
6654.6521	1.913	1.591	1.645		2.328
6655.5611	1.910	1.603	1.647		2.323
6658.5089	1.918	1.594	1.650		2.337
6712.3876	1.898	1.612	1.675	2.108	2.316
6713.4476	1.902	1.606	1.672	2.111	2.321
6723.4643	1.909	1.600	1.636	2.115	2.321
6724.5102	1.918	1.599	1.647	2.136	2.343
6725.4937	1.904	1.601	1.641	2.119	2.326
6729.3394	1.906	1.596	1.636	2.122	2.321
6729.5266	1.913	1.603	1.643	2.134	2.335
6730.3927	1.923	1.595	1.645	2.138	2.334
6739.3302	1.893	1.614	1.658	2.124	2.326
6740.2899	1.917	1.594	1.640	2.132	2.336
6740.5281	1.911	1.594	1.656	2.123	2.323
6741.2795	1.902	1.599	1.649	2.114	2.314
6744.3056	1.912	1.595	1.642	2.127	2.328
6745.2885	1.907	1.618	1.673	2.124	2.320
6745.5097	1.896	1.607	1.671	2.108	2.314
6750.2869	1.907	1.599	1.658	2.114	2.322
6750.4627	1.906	1.606	1.656	2.118	2.320
6751.2861	1.901	1.608	1.670	2.118	2.318
6751.4716	1.908	1.609	1.662	2.120	2.324
6752.3093	1.905	1.597	1.656	2.116	2.320

Note: the differential magnitudes given in this table are in the sense mag(HD 6532) – mag(HD 7259).

Table 2. Differential mean photometry of HD 6491.

HJD	ΔV	ΔB	ΔU	ΔR	ΔI
6595.6588	1.593	1.490	1.499		
6595.6637	1.595	1.493	1.505		
6596.6628	1.596	1.499	1.504		1.707
6596.6717	1.599	1.500	1.505		1.710
6597.6507	1.601	1.509	1.515		1.717
6597.6595	1.604	1.506	1.513		1.714
6601.6409	1.597	1.497	1.509		1.707
6601.6494	1.598	1.499	1.510		1.708
6603.6501	1.602	1.503	1.515		1.709
6603.6585	1.604	1.507	1.512		1.715
6614.6325	1.602	1.503	1.498		
6614.6443	1.601	1.501	1.502		
6614.6620	1.599	1.501	1.501		
6614.6740	1.602	1.503	1.504		
6630.5803	1.592	1.495	1.507		1.706
6630.5883	1.594	1.495	1.504		1.711
6631.5579	1.603	1.504	1.514		1.710
6631.5661	1.605	1.508	1.513		1.713
6633.5420	1.610	1.510	1.522		1.717
6633.5503	1.609	1.509	1.517		1.714
6641.5409	1.608	1.511	1.519		1.715
6641.5499	1.610	1.511	1.519		1.711
6642.4991	1.608	1.508	1.520		1.717
6642.5076	1.613	1.517	1.518		1.716
6643.5262	1.602	1.507	1.515		1.712
6643.5347	1.608	1.507	1.513		1.715
6644.4605	1.599	1.501	1.512		1.708
6644.4690	1.603	1.502	1.513		1.710
6644.6696	1.589	1.484	1.498		1.700
6644.6771	1.592	1.487	1.499		1.702
6645.5306	1.600	1.500	1.513		1.708
6649.5307	1.603	1.500	1.512		1.714
6649.5451	1.599	1.498	1.509		1.705
6650.4668	1.602	1.500	1.509		1.712
6650.4805	1.603	1.504	1.509		1.707
6650.6565	1.608	1.511	1.521		1.716
6650.6698	1.610	1.511	1.521		1.712
6654.4635	1.588	1.498	1.508		1.708
6654.6478	1.590	1.492	1.503		1.708
6654.6616	1.591	1.490	1.503		1.708
6655.5564	1.599	1.496	1.507		1.717
6655.5711	1.599	1.501	1.506		1.704
6658.5044	1.598	1.498	1.510		1.709
6658.5241	1.601	1.497	1.509		1.710
6712.3787	1.592	1.495	1.505	1.653	1.707
6712.3915	1.595	1.494	1.500	1.653	1.706
6713.4434	1.586	1.488	1.498	1.648	1.705
6713.4554	1.591	1.491	1.500	1.650	1.708
6723.4600	1.596	1.492	1.501	1.656	1.704
6723.4733	1.595	1.498	1.505	1.658	1.710
6724.5066	1.606	1.516	1.510	1.665	1.717
6724.5182	1.608	1.516	1.514	1.669	1.714
6725.4897	1.606	1.514	1.517	1.669	1.718
6725.5021	1.608	1.516	1.515	1.667	1.714
6729.3359	1.603	1.505	1.508	1.663	1.712
6729.3471	1.606	1.505	1.505	1.663	1.709
6729.5230	1.603	1.507	1.510	1.667	1.728
6729.5344	1.609	1.507	1.514	1.667	1.717
6730.3890	1.605	1.510	1.511	1.667	1.712
6730.4011	1.602	1.502	1.510	1.661	1.703
6739.3261	1.607	1.509	1.516	1.665	1.709
6739.3386	1.603	1.511	1.516	1.660	1.709
6740.2859	1.603	1.502	1.504	1.655	1.710
6740.2982	1.603	1.502	1.510	1.662	1.712
6740.5246	1.606	1.494	1.499	1.658	1.703
6740.5357	1.597	1.498	1.505	1.651	1.707
6741.2761	1.589	1.493	1.498	1.654	1.703
6741.2868	1.599	1.496	1.499	1.655	1.700
6744.3020	1.604	1.504	1.507	1.662	1.712

Table 2–*continued*

HJD	ΔV	ΔB	ΔU	ΔR	ΔI
6744.3134	1.603	1.502	1.512	1.662	1.711
6745.2849	1.605	1.513	1.513	1.665	1.718
6745.2960	1.606	1.505	1.516	1.663	1.714
6745.5061	1.593	1.492	1.501	1.654	1.711
6745.5170	1.600	1.495	1.505	1.652	1.717
6750.2834	1.609	1.509	1.519	1.660	1.713
6750.2946	1.604	1.512	1.518	1.664	1.716
6750.4591	1.604	1.501	1.513	1.661	1.705
6750.4703	1.604	1.503	1.514	1.661	1.706
6751.2826	1.602	1.493	1.509	1.663	1.711
6751.2935	1.602	1.500	1.506	1.662	1.709
6751.4681	1.594	1.490	1.501	1.652	1.710
6751.4791	1.595	1.487	1.500	1.655	1.710
6752.3059	1.596	1.497	1.506	1.658	1.706
6752.3167	1.595	1.494	1.500	1.655	1.707

Note: The differential magnitudes given in this table are in the sense mag(HD 6491) – mag(HD 7259).

Table 3. Differential mean photometry of HD 5737.

HJD	ΔV	ΔB	ΔU	ΔR	ΔI
6649.5403	0.141	0.484	0.842		0.738
6650.4760	0.141	0.486	0.845		0.735
6650.6654	0.144	0.487	0.849		0.744
6654.4728	0.144	0.491	0.849		0.743
6654.6572	0.140	0.490	0.850		0.745
6655.5667	0.146	0.489	0.851		0.750
6658.5146	0.142	0.482	0.844		0.744
6712.3830	0.139	0.486	0.842	0.447	0.748
6713.4514	0.140	0.489	0.843	0.444	0.749
6723.4687	0.146	0.499	0.831	0.457	0.757
6724.5141	0.147	0.498	0.836	0.458	0.754
6725.4979	0.147	0.497	0.843	0.461	0.759
6729.3431	0.145	0.488	0.828	0.454	0.750
6729.5303	0.153	0.498	0.847	0.470	0.764
6730.3970	0.147	0.488	0.827	0.449	0.743
6739.3344	0.151	0.500	0.846	0.462	0.758
6740.2942	0.149	0.496	0.837	0.458	0.751
6740.5317	0.156	0.497	0.850	0.462	0.751
6741.2829	0.144	0.487	0.834	0.454	0.747
6744.3091	0.148	0.491	0.834	0.458	0.754
6745.2921	0.150	0.495	0.840	0.461	0.757
6745.5132	0.146	0.490	0.845	0.457	0.758
6750.2905	0.146	0.493	0.835	0.456	0.752
6750.4663	0.148	0.494	0.844	0.462	0.755
6751.2896	0.147	0.487	0.829	0.456	0.751
6751.4750	0.145	0.487	0.836	0.458	0.756
6752.3128	0.145	0.486	0.829	0.455	0.709

Note: The differential magnitudes given in this table are in the sense $\Delta V = V(\mathrm{HD\,5737}) - V(\mathrm{HD\,7259})$, $\Delta B = B(\mathrm{HD\,5737}) - B(\mathrm{HD\,7259}) - 1$, $\Delta U = U(\mathrm{HD\,5737}) - U(\mathrm{HD\,7259}) - 2$, $\Delta R = R(\mathrm{HD\,5737}) - R(\mathrm{HD\,7259})$ and $\Delta I = I(\mathrm{HD\,5731}) - I(\mathrm{HD\,7259})$. All observations of HD 5737 were obtained through a neutral density filter; by observing the comparison star HD 7259 both with and without the neutral density filter we found that its density as a function of wavelength is $D_V = 0.952 \pm 0.001$, $D_B = 0.949 \pm 0.002$, $D_U = 0.933 \pm 0.002$, $D_R = 0.946 \pm 0.003$ and $D_I = 0.938 \pm 0.001$.

3 Frequency analysis of HD 6532

The differential mean magnitudes listed in Table 1 were frequency-analysed using a faster algorithm (Kurtz 1985b) of Deeming's (1975) Discrete Fourier Transform. Each of the colours was analysed individually; we will illustrate the analysis with the V data.

Fig. 1 shows the amplitude spectrum of the mean V data. The highest peak lies at $f_1=1.0277$ day^{-1}. This is clearly the frequency which best fits the data, but we must assess whether it correctly represents variations in the V data or whether it may be an artefact of our incomplete data set.

Horne & Baliunas (1986) give the 'False Alarm Probability' for finding a peak in a power spectrum at a signal-to-noise of z as

$$F=1-(1\text{-}e^{-z})^N \quad (1)$$

where N is the number of Fourier frequencies searched. N is not rigorously defined for unequally spaced data so for our purposes here we take the separation between independent frequencies to be $1/\Delta T$ where ΔT is the time-span of the data set. The Nyquist frequency is also not rigorously defined for unequally spaced data. Our sampling frequency is mostly once-per-night, but on nine nights we obtained two points with several hours separation. The Nyquist frequency for data sampled once-per-day would be 0.5 day^{-1}, but we are confident that with our several-hour sample time on many nights we can meaningfully search for frequencies up to 4 day^{-1}. The highest peaks in all of the amplitude spectra presented in this paper lie in the 0–2 day^{-1} range so we will only present amplitude spectra in this range.

If we thus take our working Nyquist frequency to be 4 day^{-1} and the separation between independent frequencies to be $1/\Delta T$ with $\Delta T=156.6$ day, then $N=626$ for the HD 6532 V data. Looking at Fig. 1, one might naïvely judge the noise to be about 3 mmag which means that for the

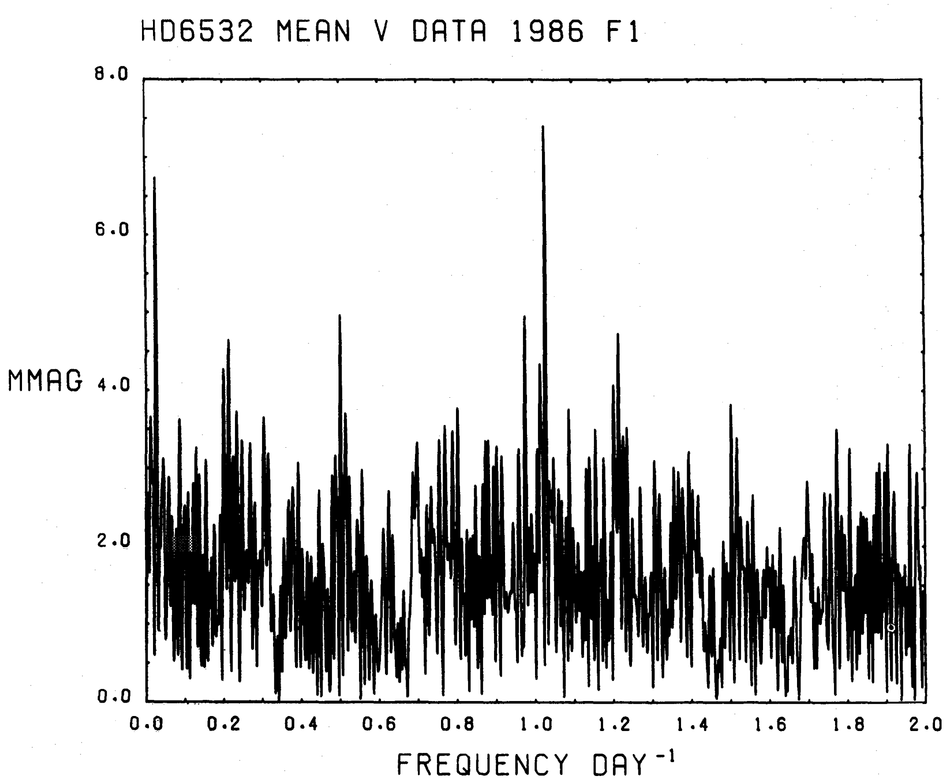

Figure 1. An amplitude spectrum of the HD 6532 mean V data in the frequency range 0–2 day^{-1}. The highest peak is at $f_1=1.028$ day^{-1}.

1.0277 day^{-1} peak with an amplitude of 6.3 mmag $z=(6.3/3)^2=4.4$ (remember that z is the signal-to-noise in power and Fig. 1 is an amplitude spectrum). From equation (1) we then find that the False Alarm Probability is $F=0.9996$; i.e. it is virtually certain that in a frequency analysis where 626 independent frequencies are searched, some frequency peak will stand out at a signal-to-noise of 2:1 in the amplitude spectrum.

This does not mean that we believe that the peak at 1.0277 day^{-1} is Fig. 1 is an artefact of our analysis, however. The problem here is to assess correctly the noise level in Fig. 1. This problem is exacerbated by the extremely complex spectral window pattern for these data; at frequencies near to zero the spectral window pattern is asymmetrical due to the spill-over of the window pattern from negative frequencies. Fig. 2 shows the spectral window for the V data for an injected tracer signal with a frequency of 1.0277 day^{-1} and an amplitude of 6.3 mmag. This window pattern was calculated by creating an artificial data set sampled at exactly the times of observations given in Table 1, but with a noise-free sinusoid of the frequency and amplitude given above. The complexity of the window pattern is apparent in Fig. 2 and will become even more apparent below.

Fig. 3 shows the amplitude spectrum of the V data after $f_1=1.0277$ day^{-1} has been prewhitened from the data. The highest peak here is at $f_2=0.5138$ day^{-1}, half of $f_1=1.0277$ day^{-1}. However, f_2 looks even less convincing than f_1 if one repeats the False Alarm Probability arguments above. In fact, there are two peaks of nearly equal height at f_2; the lower peak is the +1 day^{-1} alias of the negative counterpart of f_2. This is shown in Fig. 4 which is the spectral window pattern for an injected tracer signal with a frequency of 0.5138 day^{-1} and an amplitude of 4.4 mmag.

Prewhitening the data by both f_1 and f_2 gives the amplitude spectrum shown in Fig. 5. In our opinion this amplitude spectrum shows the true noise in the data which we conservatively

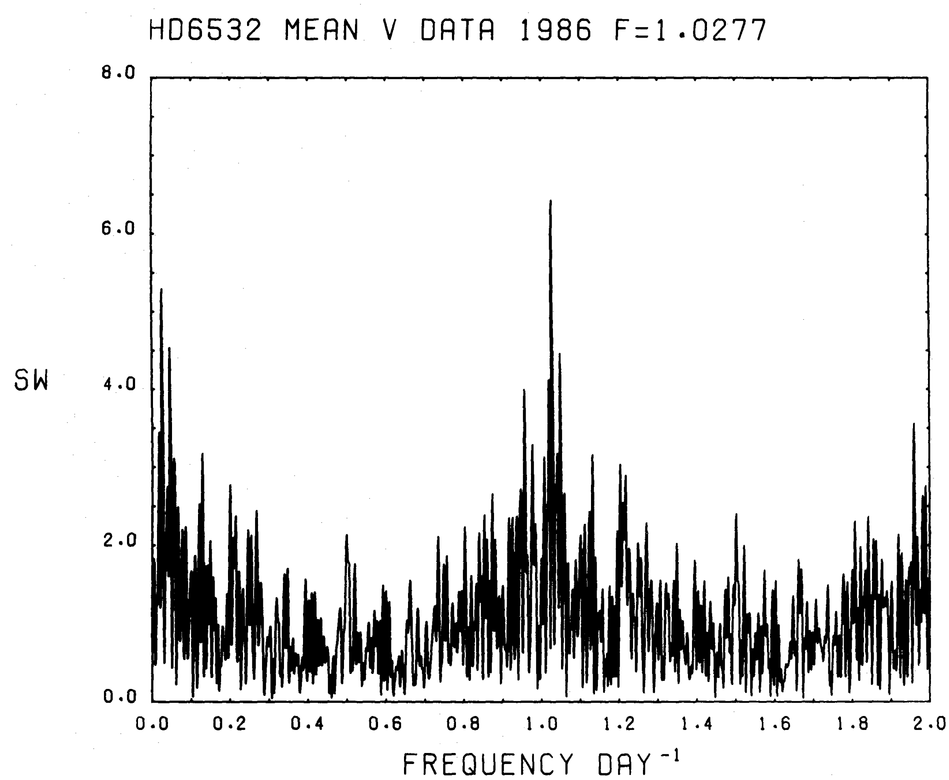

Figure 2. The spectral window for a pure, noise-free sinusoid of frequency $f=1.0277$ day^{-1} with an amplitude of $A=6.3$ mmag sampled at the times of observation of the HD 6532 V data. This shows some of the complexity of the window pattern which is partially due to the 'spill-over' of the aliases of the peaks in the negative amplitude spectrum.

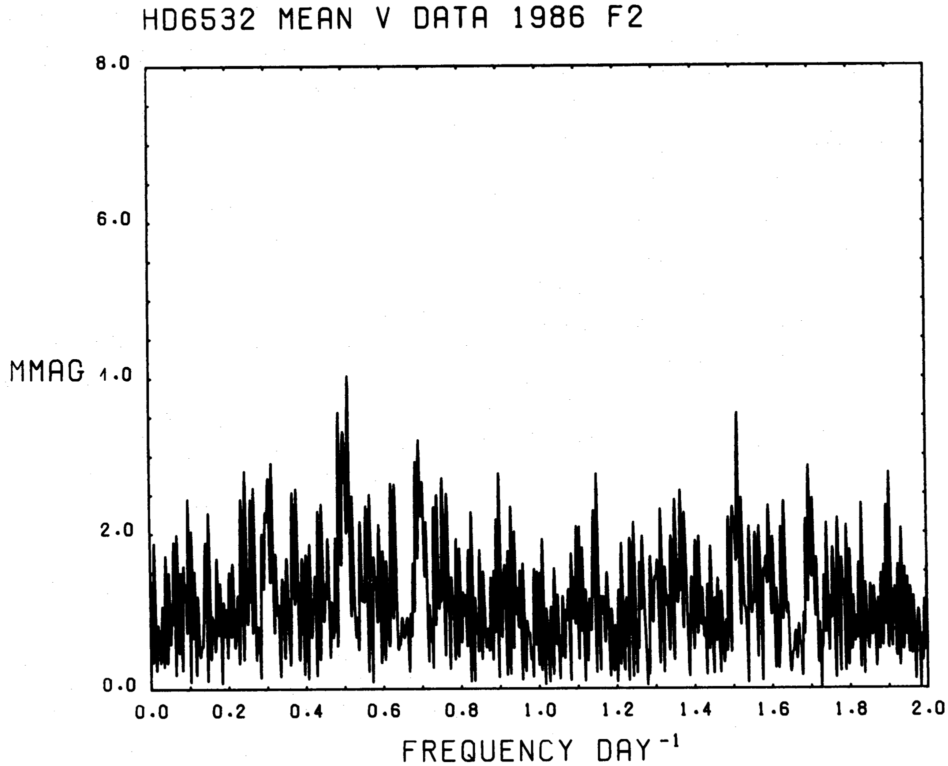

Figure 3. An amplitude spectrum of the HD 6532 mean V data after prewhitening by $f_1=1.0277$ day^{-1}. The highest peak here occurs at $f_2=0.5138$ day^{-1}, half of f_1. There are two peaks near f_2; the lower frequency sidelobe is the $+1$ day^{-1} alias of the negative counterpart to f_2 at -0.5138 day^{-1}.

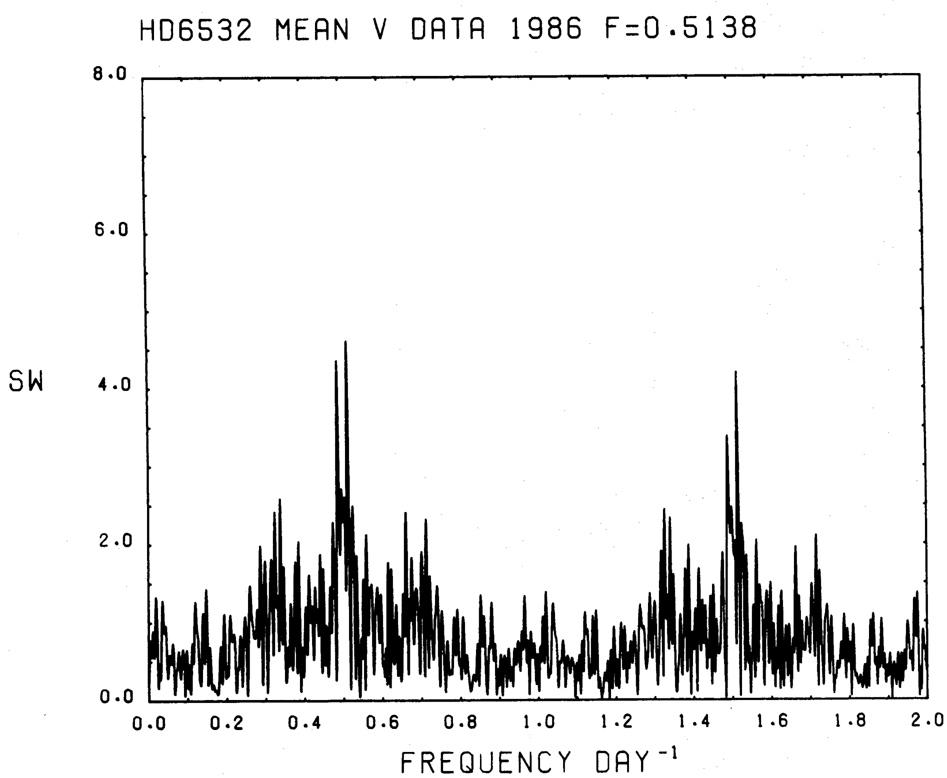

Figure 4. The spectral window for a pure, noise-free sinusoid of frequency $f=0.5138$ day^{-1} with an amplitude of $A=4.4$ mmag sampled at the times of observation of the HD 6532 V data. This diagram highlights the complexity of the spectral window for frequencies near to 0.5 day^{-1} in data with 1-day gaps. The peak just to the left of $f_2=0.5138$ day^{-1} is the $+1$ day^{-1} alias of $-f_2$.

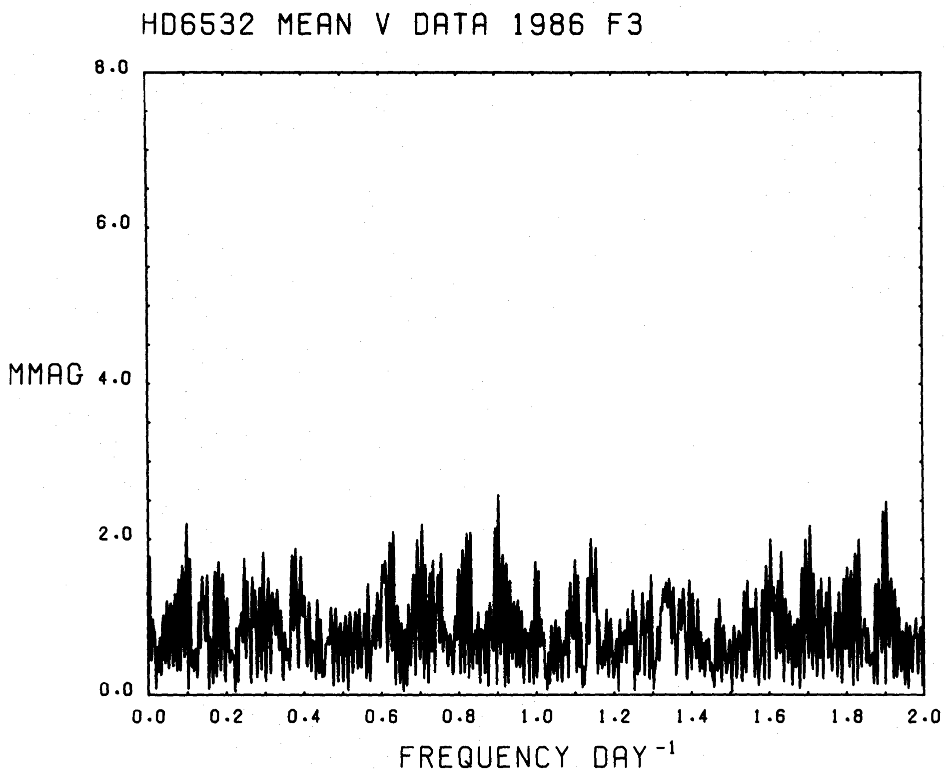

Figure 5. An amplitude spectrum of the HD 6532 *V* data after prewhitening by f_1 and f_2. In our opinion this amplitude spectrum represents the true noise level in the data. From arguments given in the text we expect to find some peaks in a pure noise spectrum at a signal-to-noise of 2:1; we therefore conservatively estimate the noise level in this figure to be at 1.5 mmag.

estimate to be 1.5 mmag (remember that we are virtually guaranteed a peak with a 2:1 signal-to-noise by previous arguments). If we then return to the original False Alarm Probability calculation, but now use a noise of 1.5 mmag, we find that for f_1, $z=(6.3/1.5)^2=17.6$ and $F=1.3\times10^{-5}$. That is, f_1 has almost no chance of being an artefact of our analysis and, as long as we have not selected an alias, it is the frequency of the variations in the *V* data.

Our frequency analyses of the *U, B, R* and *I* data give similar results to the above analysis of the *V* data: in *U, R* and *I* the highest peak is at f_1 and the second highest peak is at f_2; in *B* the highest peak is at f_2 and the second highest peak is at f_1. We have fitted f_1 and f_2 to each colour using a non-linear least-squares program and we find that the frequencies determined for f_1 and f_2 all lie within 1σ of the mean values for all five data sets of $\langle f_1\rangle=1.0280\pm0.0006$ day^{-1} and $\langle f_2\rangle=0.5140\pm0.0005$

Table 4. Parameters of the linear least-squares fit of $f_{rot}=0.5140$ day^{-1} and its first harmonic $f=1.0280$ day^{-1} to the HD 6532 data.

	A_0 mag	A_1 mmag	ϕ_1	A_2 mmag	ϕ_2	σ mmag
U	1.656	7.2±1.2	−2.39±0.17	12.4±1.1	1.62±0.11	5.71
B	1.602	7.7±0.9	−1.57±0.11	3.8±0.8	1.78±0.26	4.12
V	1.907	4.4±0.7	2.02±0.16	6.3±0.7	−1.65±0.13	3.33
R	2.122	6.4±1.6	2.34±0.26	8.7±1.5	−1.74±0.21	5.02
I	2.324	6.2±1.0	2.29±0.16	6.7±1.0	−1.76±0.17	4.52

The last column is the standard deviation of one observation with respect to the fit of the parameters to the data. Because of the contribution of the rapid oscillations to σ, it is a slight overestimate of the errors of our observations. t_0=JD 2446630.000.

day^{-1}. We then fitted those mean values to each colour individually by linear least-squares using the relation

$$\Delta m = A_0 + A_1 \cos\,[2\pi f_1(t-t_0)+\phi_1] + A_2 \cos\,[2\pi f_2(t-t_0)+\phi_2] \quad (2)$$

where t_0=JD 2440000.0000. The parameters derived from those fits are given in Table 4 and they are shown as solid lines in the phase diagram in Fig. 6. In addition to fitting equation (2) with its fundamental and first harmonic frequencies to the data, we fitted the fundamental, first and second harmonic frequencies to the data; only for the U data was the amplitude of the second harmonic significant so we do not present those fits here.

It is clear from Fig. 6 that HD 6532 has a double-wave mean light curve with maxima and

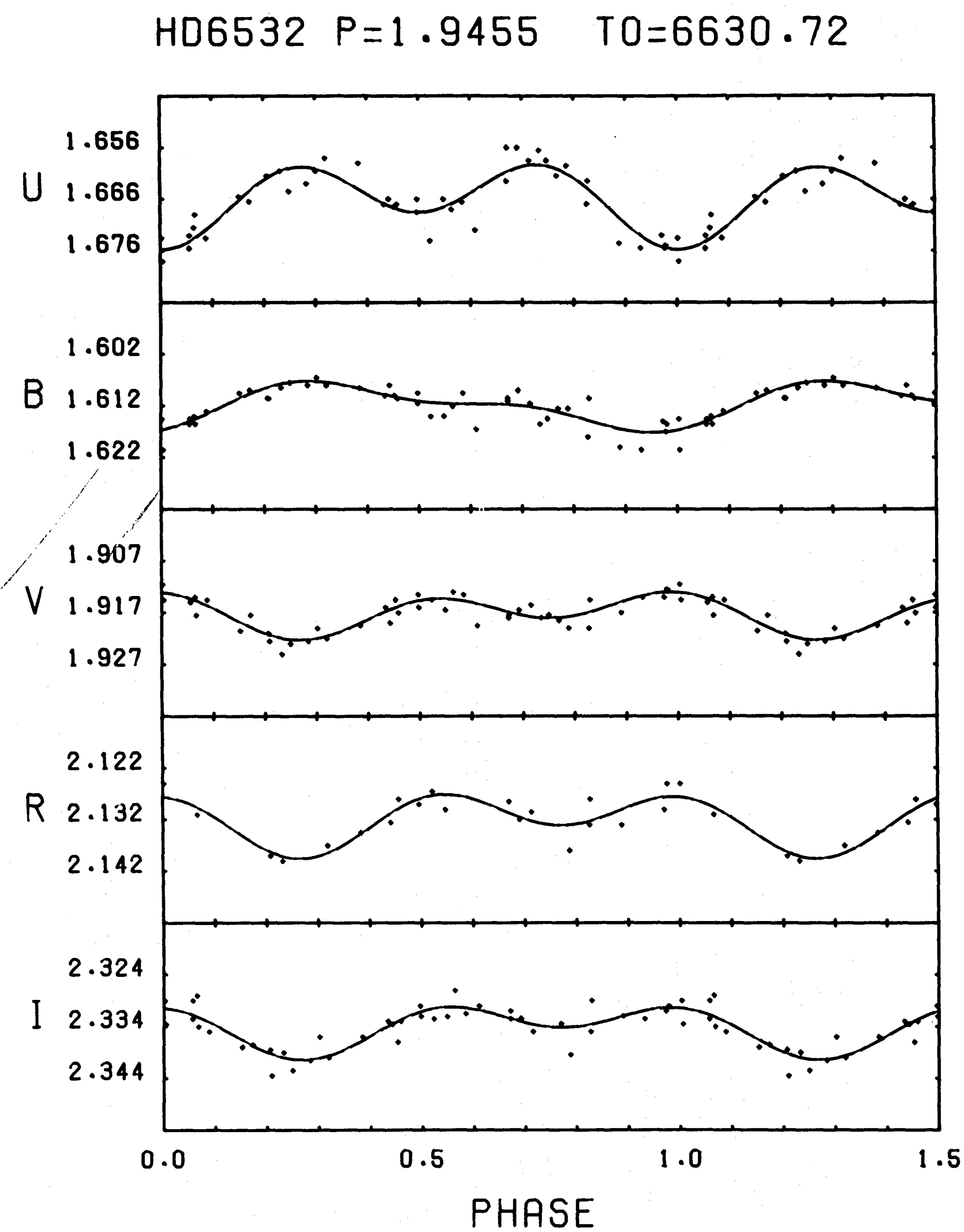

Figure 6. A phase diagram for the HD 6532 mean differential data using f_2=0.5140±0.0005 day^{-1} (P=1.9455±0.0019 day) for the rotation period of the star. The magnitudes are the differential magnitudes given in Table 1. The double-wave nature of the light variations is evident in this figure indicating that f_2=0.5140 day^{-1} is the correct rotational frequency and not f_1=1.0280 day^{-1}. The reason that f_1 dominates the amplitude spectra in this star is that the differences of the primary and secondary minima are not large. The anti-phase behaviour of U with respect to V, R and I with B in an intermediate state is common in Ap stars.

minima being in anti-phase for U and V with B being in an intermediate state. This is common in the mean light curves of Ap stars (see e.g. Mathys & Manfroid 1985). Thus the correct rotational frequency for HD 6532 is $f_2=0.5140\pm0.0005$ day^{-1} which gives a rotational period of $P_{rot}=1.9455\pm0.0019$ day. This is equal to the frequency splitting seen in the amplitude spectrum of the rapid oscillations in this star (Kurtz & Cropper 1987). The reason Kurtz & Kreidl (1985) and Kurtz & Cropper (1987) obtained a different rotation period for HD 6532 was that they used HD 6491 for a comparison star and HD 6491 is variable.

The residuals to the fits of f_1 and f_2 to the HD 6532 data given in the last column of Table 4 are slight overestimates of the intrinsic errors in our observations. This is because we have made no attempt to remove the effects of the 6.94-min oscillations on our observations. The amplitude of the rapid oscillations in HD 6532 can be as large as 4 mmag peak-to-peak in Johnson B (it is probably less in V and about the same in U based on the behaviour of other Rapidly Oscillating Ap stars – see Kurtz 1982). Our 40-s integrations span about 10% of a single oscillation and hence may for individual observations include systematic effects approaching 2 mmag. The total contribution of this effect to the residuals given in Table 4, however, is probably less than 1 mmag. We therefore estimate that our observational errors are about 0.5 to 1.0 mmag less (depending on the colour) than those given in Table 4.

The ephemeris for HD 6532 is

$$\text{HJD (mean light extremum)}=2446630.72+1.9455\pm0.0019\ \text{E}. \qquad (3)$$

4 Frequency analysis of HD 6491

We frequency-analysed the HD 6491 given in Table 2 in the same way as for HD 6532 above. In the case of HD 6491 we found that the phase of the frequency with the highest peak in the

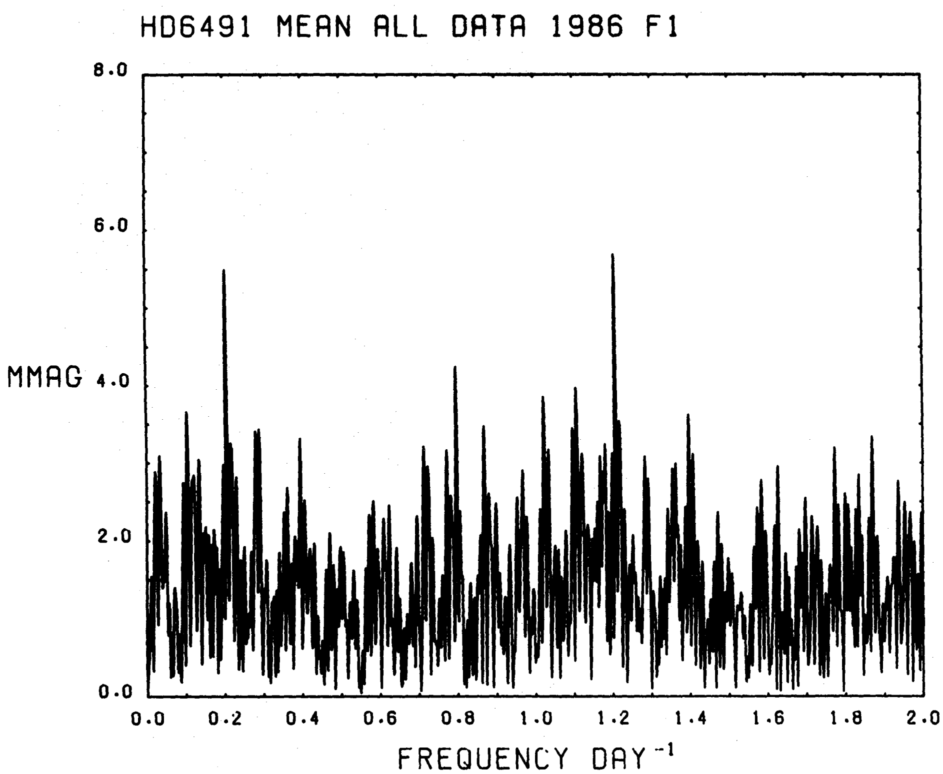

Figure 7. An amplitude spectrum of all of the HD 6491 data after the mean has been removed from the magnitudes of each colour individually. The highest peak is at $f_1=1.20713$ day^{-1}, but the alias of that peak at $f=0.20544$ day^{-1} is nearly as high.

amplitude spectrum is the same at all wavelengths so we could obtain a better signal-to-noise ratio by analysing all the data simultaneously. It is that analysis which we present here.

Fig. 7 shows the amplitude spectrum of all of the HD 6491 data after the zero point was removed from each colour individually. The highest peak occurs at $f_1=1.20713$ day^{-1} with an alias nearly as high at 0.20544 day^{-1}. When we prewhiten the data by f_1 we get the amplitude spectrum shown in Fig. 8 in which the highest peak lies at $f_2=1.11940$ day^{-1}. After prewhitening by f_1 and f_2 we get the amplitude spectrum shown in Fig. 9 which we consider to be noise.

A non-linear least-squares fit of f_1 and f_1 and f_2 simultaneously to all of the HD 6491 data gives the parameters listed in Table 5. Following the arguments given above for HD 6532, we conservatively estimate the noise in Fig. 7 to be 1.5 mmag. Thus for $f_1=1.20713$ day^{-1} with an amplitude of 6.1 mmag we find that $z=16.54$ and $F=4.1\times10^{-5}$. It is virtually certain, therefore, that f_1 is not an artefact and that HD 6491 is a variable star. It is not certain, however, that we have correctly selected f_1 since its -1 day^{-1} alias at 0.20544 ± 0.00017 day^{-1} provides almost as good a fit to the data. Fig. 10 shows the fit of $f_1=1.20713\pm0.00017$ day^{-1} ($P=0.82841\pm0.00012$ day) and Fig. 11 shows the fit of the $-$day^{-1} alias of $f_1=0.20544\pm0.00017$ day^{-1} ($P=4.868\pm0.004$ day) to the data.

For $f_2=1.11940$ day^{-1} with an amplitude of 3.25 mmag we find that $z=4.69$ and $F=0.9968$ indicating that the probability of finding some peak with the amplitude of f_2 is near certainty. The reason that we have pursued this argument about f_2, however, is that it is coincident with the frequency derived for HD 6532 by Kurtz & Kreidl (1985) and independently by Kurtz & Cropper (1987) when they used HD 6491 as the comparison star for HD 6532. The probability of a false alarm at a *particular* frequency is simply $F_p=e^{-z}$ which in this case is $F_p=e^{-z}=0.009$. That is, it is very unlikely that a $z=4.69$ peak should occur within one Fourier frequency of the frequency

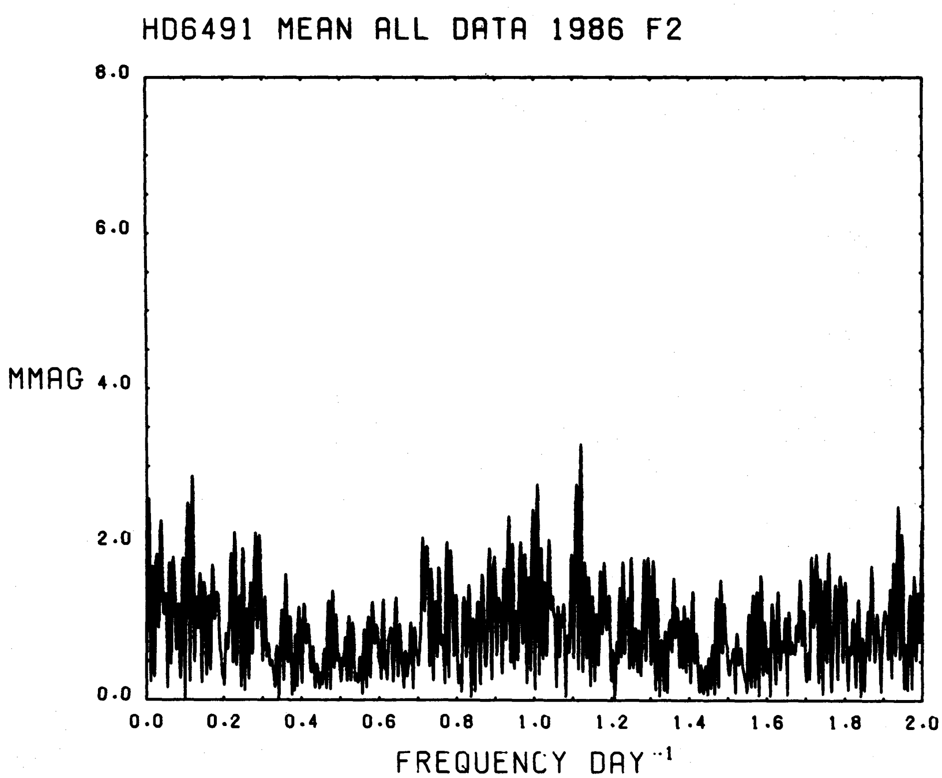

Figure 8. An amplitude spectrum of all of the HD 6491 data after prewhitening by $f_1=1.20713$ day^{-1}. The highest peak here is at $f_2=1.11940$ day^{-1} which coincides with the frequency found by Kurtz & Kreidl (1985) and Kurtz & Cropper (1987) when using HD 6491 as a comparison star for HD 6532. The chance of finding a peak of this height at that particular frequency is only $F_p=0.009$.

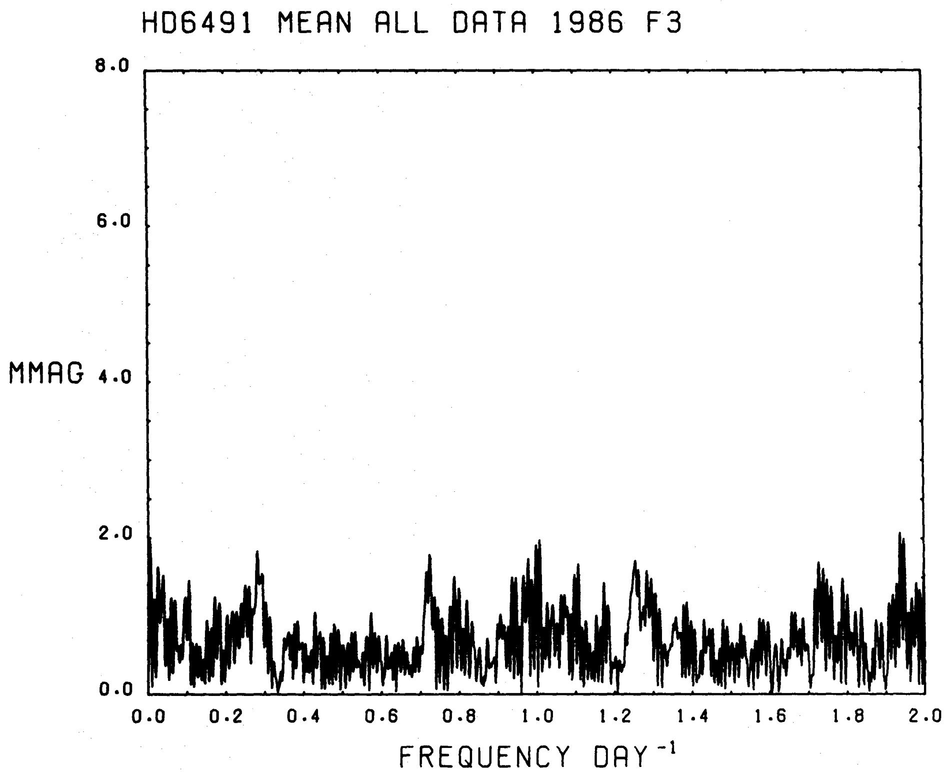

Figure 9. An amplitude spectrum of the HD 6491 data after prewhitening by f_1 and f_2. In our opinion this amplitude spectrum represents the true noise level in the data. As in Fig. 5 we conservatively estimate the noise level in this figure to be at 1.5 mmag.

Table 5. Parameters of the non-linear least-squares fit of f_1 only and f_1 and f_2 simultaneously to the HD 6491 data.

	f mHz	A mmag	ϕ radians	σ mmag
f_1	1.02713±0.00016	6.1±0.4	−0.73±0.08	4.66
f_1	1.20699±0.00014	6.24±0.31	−0.61±0.07	
f_2	1.11940±0.00027	3.25±0.31	0.07±0.14	4.07

t_0=JD2446630.0000.

found for HD 6532 in those previous studies. This leaves f_2 as a curiosity; there is no way to determine its reality with only the data available.

It is possible that HD 6491 is an ellipsoidal variable (for a review of the ellipsoidal variables, see Morris 1985). If so, then it should show a double-wave light curve which would mean that its rotational period is either $P_{\rm rot}=2$ (0.82841 day)=1.65682 day or $P_{\rm rot}=2$ (4.868 day)=9.736 day. We have found that there is no significant amplitude at any of the harmonics or sub-harmonics of f_1 indicating that the data are represented to within the errors by a single sinusoid. Thus, if HD 6491 is an ellipsoidal variable, the maxima and minima are equal to within the errors in the data.

Another possibility for the variability in HD6491 is that it may be an RS CVn (spotted) star [see Hall (1976) for a review of these stars]. There are RS CVn stars with primary stars as early as F2, the spectral type of HD 6491; the prototype of the class, RS CVn itself, has a primary which has a

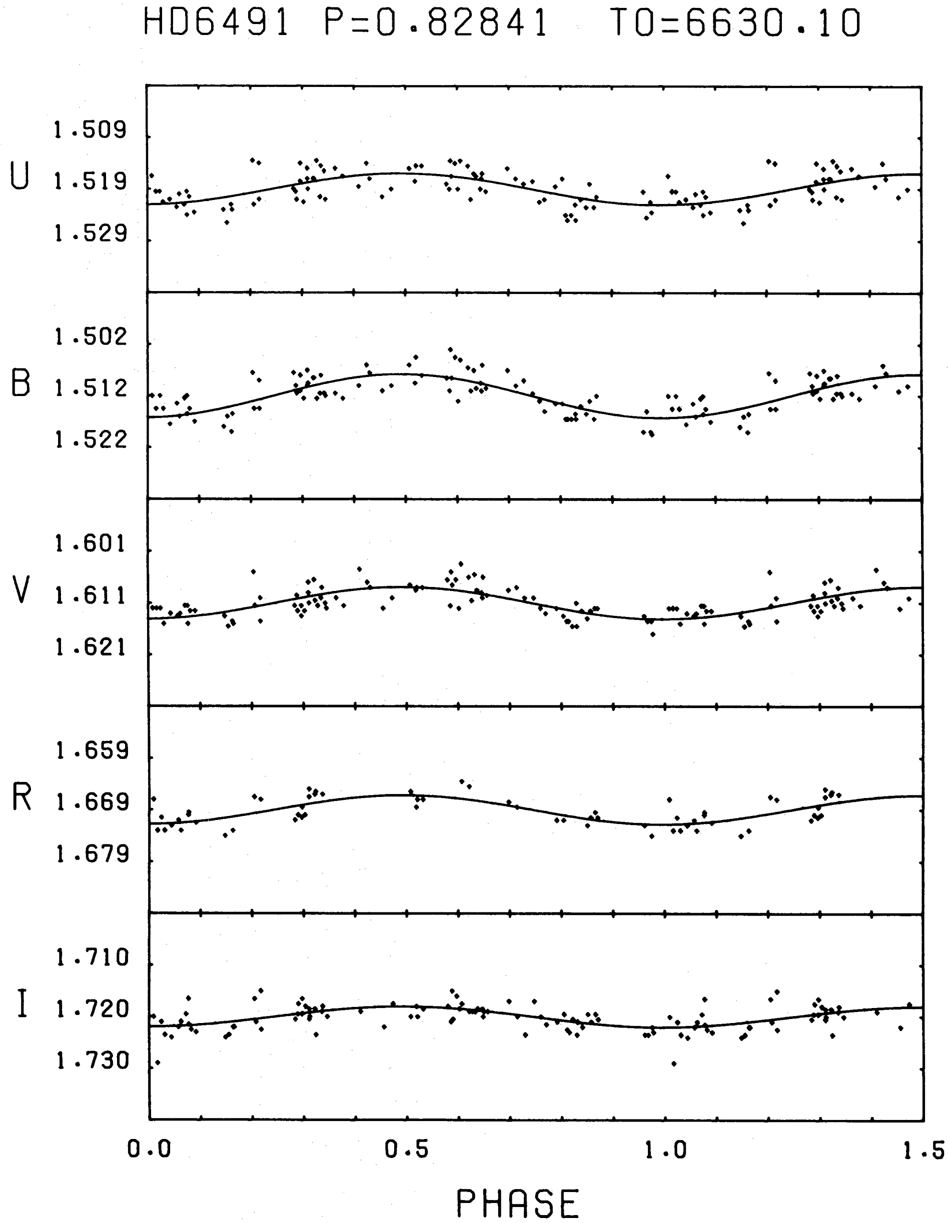

Figure 10. A phase diagram for the HD 6491 mean differential data using f_1=1.20713±0.00017 day^{-1} (P_{rot}=0.82841±0.00012 day) for the rotation period of the star. The magnitudes are the differential magnitudes given in Table 1.

spectral type of F4 IV/V. If HD 6491 is an RS CVn star, then the second period found in our frequency analysis, f_2=1.11940 day^{-1}, might be real and associated with the spot drift which is observed in these stars.

We obtained 6.7 hr of continuous high-speed photometric observations of HD 6491 on four nights in 1986 October using the St Andrews Photometer attached to the 1-m telescope of the South African Astronomical Observatory at Sutherland. A frequency analysis of these data indicates that there is no variability in HD 6491 greater than 1 mmag at periods of 6 hr or less, i.e. those associated with δ Scuti pulsation. We can therefore rule out the possibility that our frequency analysis missed a period shorter than 4 day^{-1} because of our sampling interval.

A radial velocity and spectroscopic study of HD 6491 is called for if the true nature of the variability of this star is to be determined.

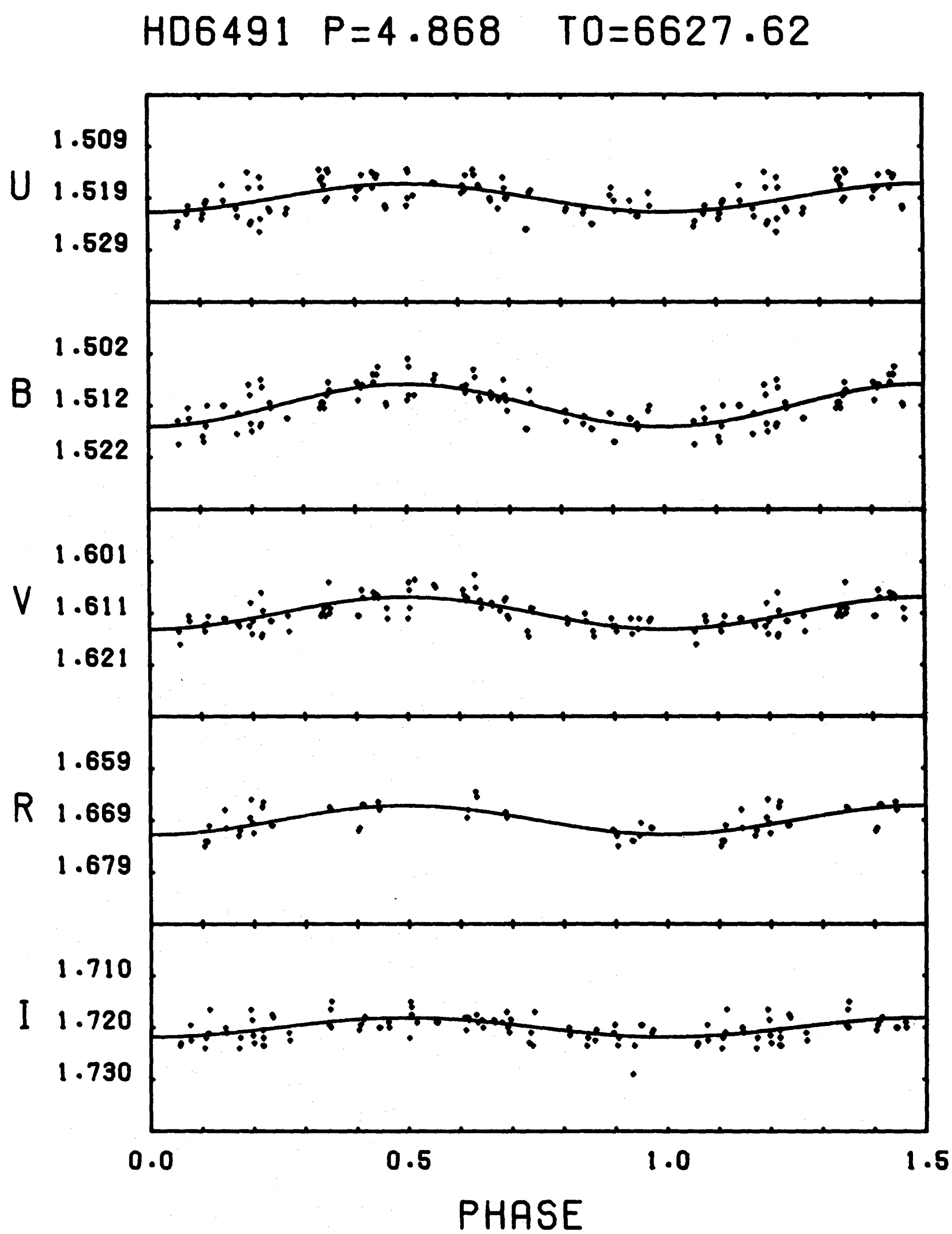

Figure 11. A phase diagram for the HD 6491 mean differential data using the -1 day^{-1} alias of f_1 at f=0.20544±0.00017 day^{-1} ($P_{\rm rot}$=4.868±0.004 day) for the rotation period of the star. The magnitudes are the differential magnitudes given in Table 1.

The ephemeris for HD 6491 is

$$\text{HJD (minimum brightness)}=2446630.10+0.82841\pm0.00012\ E \qquad (4)$$

or

$$\text{HJD (minimum brightness)}=2446627.62\pm4.868\pm0.004\ E \qquad (5)$$

5 Frequency analysis of HD 5737

HD 5737 is the prototype of the Ti–Sr sub-class of the He-weak stars. A polarity-reversing magnetic field was discovered in this star by Borra, Landstreet & Thompson (1983) who could not select an unambiguous period for the magnetic variations; they illustrated their data with a trial period of 19.35 day. Pedersen (1979) suggested a period of ~24 day based on 16 observations of the He line strength obtained over a time-span of 65 day. Shore, Brown & Sonneborn (1987)have found that HD 5737 shows evidence of a magnetically controlled stellar wind.

Further study of this interesting star is hampered by our lack of knowledge of its rotation period. Shore *et al.* (1987) suggest that mean light observations of HD 5737 should be studied for variations which might allow the determination of P_{rot}. We added HD 5737 to the present observing program at their request in order to try to do this.

We frequency-analysed the data given in Table 3 in the same manner as in the above analyses of HD 6532 and HD 6491. Unfortunately, no unambiguous peaks stand out above the noise in the

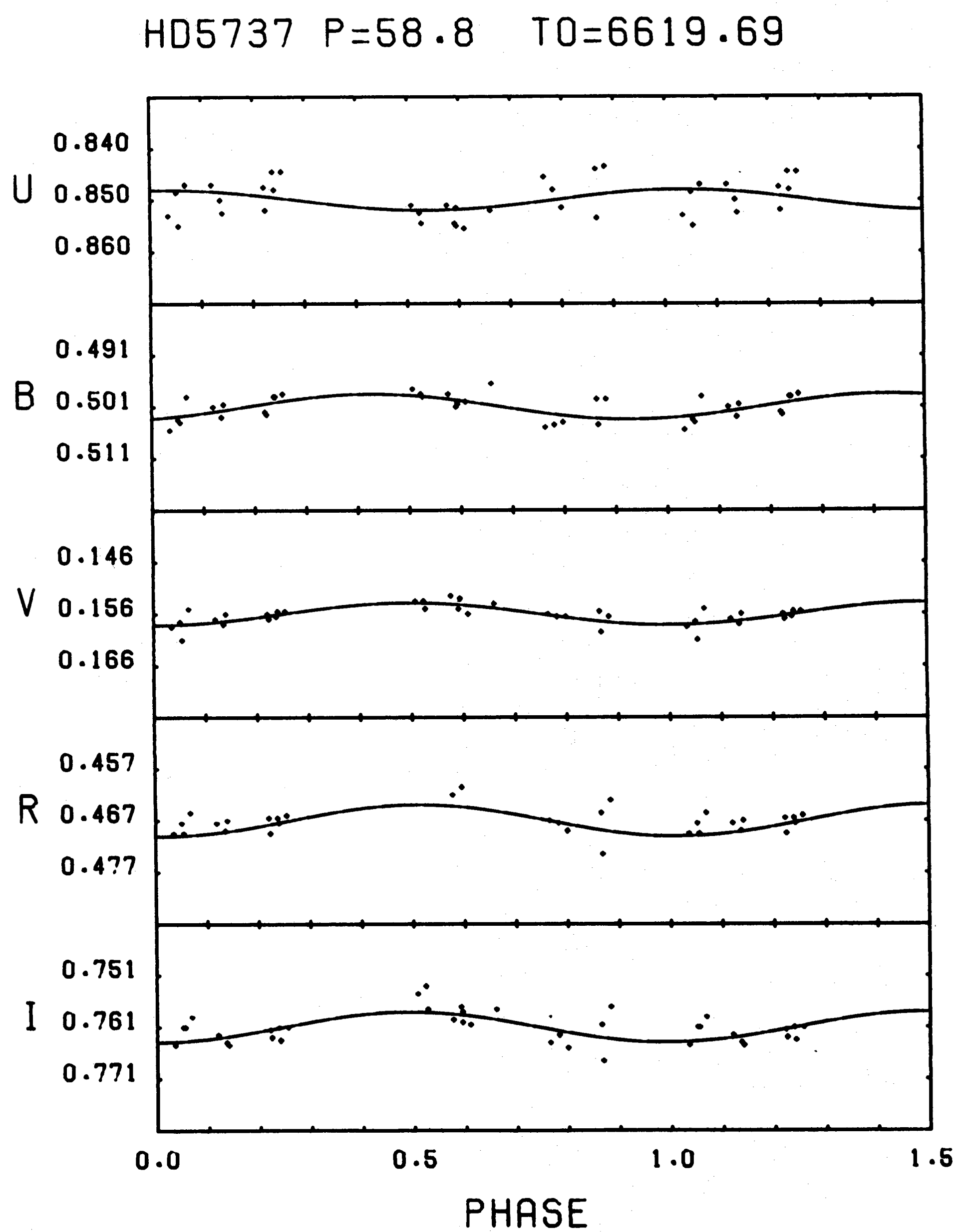

Figure 12. A phase diagram of the HD 5737 mean differential magnitudes showing the fit of the 58.8-day period to the data. This period is only marginally significant, although it seems likely that there is some photometric variation in these data.

Table 6. Parameters of the linear least-squares fit of f=0.017 day^{-1} (P=58.8 day) to the HD 5737 data.

	A_0 mag	A_1 mmag	ϕ_1	σ mmag	σ_2 mmag
U	0.840	4.0±2.0	−0.45±0.46	5.71	7.33
B	0.491	5.0±1.2	−2.94±0.21	3.91	4.97
V	0.146	4.3±0.8	2.92±0.15	2.47	3.91
R	0.457	6.2±1.0	2.84±0.23	4.57	5.64
I	0.751	5.9±1.6	2.96±0.23	5.16	6.60

t_o=JD 2446630.0000. The last column, σ_2, is the standard deviation of one observation about the mean. The column before that, σ, is the standard deviation of one observation with respect to the fit of f=0.017 day^{-1} to the data. That these errors are close to the errors in our observations is evidence that there is photometric variability in HD 5737.

amplitude spectra of the data. Our best fits occur for periods of 0.98 day or 58.8 day, but both are at best only marginally statistically significant. Fig. 12 illustrates the fit of the 58.8-day period. We have tested Borra *et al.*'s (1983) seven magnetic observations and find that they are fitted by the 58.8-day period to an accuracy of σ=167 G per observation, not a great deal more than the observational errors they quote. This is not to say that we believe that the 58.8-day period is correct, but rather that long periods may have to be considered in future studies of this star.

The standard deviations per observation for the HD 5737 data are given in the last column of Table 6. These values are somewhat larger than the residuals to the fit of the derived frequencies to the HD 6532 data given in Table 4 which we consider to be a slight overestimate of our observational errors. A least-squares fit of the 58.8-day period to the HD 5737 data is given in Table 6. The residuals to this fit are comparable to those in Table 4 and hence give some support to the notion that there is some real photometric variation in the HD 5737 data. On the other hand, these numbers also point out that future photometric studies of HD 5737 need to strive for 1 mmag accuracy to improve on the present study. That sort of accuracy can be achieved in a dedicated study which should probably be confined to one filter. Our observations indicate that the best filter to use is Johnson V, Strömgren y or some other filter with a central wavelength nearly the same as these two where the apparent variations are largest.

Acknowledgments

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