

Two new rapidly oscillating Ap stars: HD 60435 and HD 203932

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Accepted 1984 January 22. Received 1984 January 20; in original form
1983 November 28

Summary. The discovery of two new rapidly oscillating Ap stars is announced. HD 60435 is the largest amplitude rapidly oscillating Ap star yet discovered with a peak-to-peak variability of $\Delta B \leq 15.7$ mmag; HD 203932 is the smallest with $\Delta B \leq 2.4$ mmag. A qualitative description of the complex frequency pattern in HD 60435 is given based on 56 hr of observations obtained on 16 nights. A frequency analysis of 29 hr of observation of HD 203932 obtained on 12 nights shows the presence of one frequency, $f = 10.09724 \pm 0.00012 \text{ hr}^{-1}$ ($P = 5.94222 \pm 0.00007 \text{ min}$) with a semi-amplitude of 0.65 mmag. A list of the nine known rapidly oscillating Ap stars with references is given.

1 Introduction

The rapidly oscillating Ap stars are cool magnetic Ap stars which oscillate with periods between about 6 to 14 min and with peak-to-peak light variations of $\Delta B < 0.016$ mag. Their oscillations are accurately modelled as high overtone non-radial p -modes of low degree (l small) with the axis of oscillation aligned with the magnetic axis (the oblique pulsator model, Kurtz 1982). Both the high overtone and the orientation of these oscillations are surprising and hence present interesting theoretical problems.

Dolez & Gough (1982) suggested that the oscillation modes in the rapidly oscillating Ap stars do not rotate synchronously with the magnetic field. They reconcile this with the oblique pulsator model by suggesting that growth and decay times are short for these modes and only modes which are currently aligned with the magnetic field are excited to observable amplitudes. They suggest maximum growth rates for periods near 10 min.

Shibahashi (1983a, b; Cox 1984) has suggested that magnetic overstability leads to oscillating convective motions near the magnetic poles which excite high overtone global oscillations. This model naturally explains the coincidence of the pulsation and magnetic axes and the high overtones of the oscillations. It also serendipitously provides an additional source of rotational light variation and hence may help explain a long standing problem in the magnetic Ap stars, e.g. see Bonsack's (1979) discussion of HR 1217. A disadvantage of this model is that it introduces a new excitation mechanism within a known instability strip.

Table 1. The rapidly oscillating Ap stars

HD	HR	Name	$b-y$	m_1	c_1	β	P min	ΔB mmag	Refer- ence	H_e (G)	Reference	Spectral type	Reference
24712	1217	—	0.183	0.212	0.634	2.744	6.14	14.5	1, 2	+ 300 to + 1200	13	A5p	23
60435	—	—	0.132	0.234	0.843	—	12.6	15.7	3	—	—	Ap Sr (Eu), Fp SrEu	24, 25
83368	3831	—	0.146	0.203	0.796	2.827	11.67	10.2	1	— 700 to + 700	14	Ap SrEuCr ¹	26, 25
							5.835						
101065	—	—	0.448	0.368	—0.014	2.641	12.14	14.6	4, 5, 6	— 2200	15	Controversial	27
128898	5463	α Cir	0.152	0.195	0.760	2.831	6.825	4.8	7, 8, 9	— 300 (variable)	16, 17, 18	Ap SrEu(Cr), Ap SrEu	24, 25
137949	—	33 Lib	0.188	0.321	0.584	2.833	8.27	2.8	1	+ 1400 to + 1800	19	Fp SrCrEu	25
201601	8097	γ Equ	0.147	0.238	0.760	2.819	12.5	2.8	10, 11	+ 500 to — 800	20, 21, 22	FOp	23
203932	—	—	0.169	0.196	0.736	2.814	5.94	2.4	3	—	—	Ap SrEu	25, 28
217522	—	—	0.289	0.215	0.487	2.701	13.72	4.2	12	—	—	Ap (Si)Cr ² , Fp SrEu	26, 25
												1. Strong Sr.	
												2. May be Eu rather than Si.	

References

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|-----------------------------------|-------------------------------------|---------------------------------|
| 1 Kurtz (1982) | 11 Weiss (1983a) | 21 Bonsack & Pilachowski (1974) |
| 2 Kurtz & Seeman (1983) | 12 Kurtz (1983b) | 22 Scholz (1979) |
| 3 This paper | 13 Preston (1972) | 23 Hoffleit (1982) |
| 4 Kurtz (1980) | 14 Thompson (private communication) | 24 Houk & Cowley (1975) |
| 5 Kurtz (1981) | 15 Wolff & Hagen (1976) | 25 Bidelman & MacConnell (1973) |
| 6 Weiss & Kreidl (1980) | 16 Wood & Campusano (1975) | 26 Houk (1978) |
| 7 Kurtz, Allen & Cropper (1981) | 17 Borra & Landstreet (1975) | 27 Kurtz & Wegner (1979) |
| 8 Kurtz & Balona (in preparation) | 18 Borra & Landstreet (1980) | 28 Houk (1982) |
| 9 Weiss & Schneider (1984) | 19 Wolff (1975) | |
| 10 Kurtz (1983a) | 20 Babcock (1958) | |

Table 2. Journal of *B* observations of HD 60435

Date (1983)	JD 2 440 000 +	<i>t</i> hr	<i>N</i>	σ mmag
February 17/18	5383	3.49	590	5.6
February 18/19	5384	2.83	480	4.8
February 19/20	5385	4.99	819	3.4
February 20/21	5386	1.23	176	2.8
February 21/22	5387	5.24	830	3.5
March 15/16	5409	4.18	697	4.1
March 16/17	5410	4.99	837	2.7
March 18/19	5412	4.13	677	4.2
March 19/20	5413	4.77	784	3.3
March 20/21	5414	1.00	168	3.8
March 21/22	5415	4.23	673	4.7
March 29/30	5423	3.36	435	3.6
April 01/02	5426	3.32	458	2.8
April 02/03	5427	2.06	329	3.0
April 03/04	5428	3.22	497	2.7
April 04/05	5429	3.55	508	3.8
	Σ	56.59	8958	(3.7)

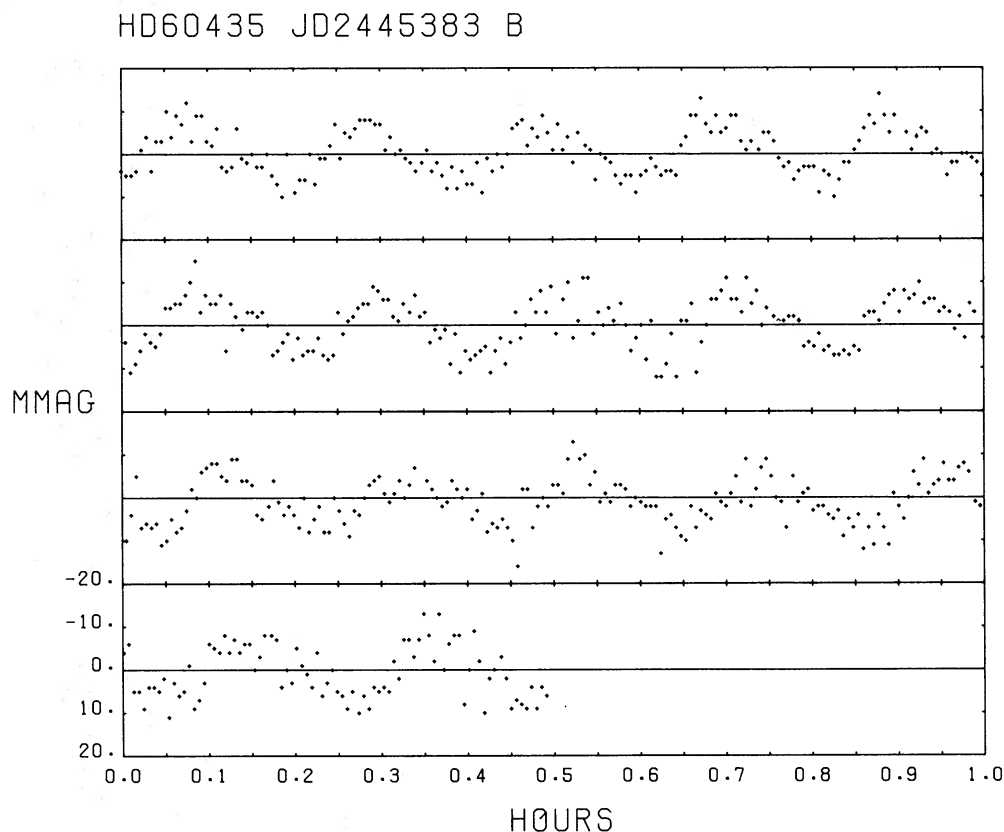


Figure 1. The *B* light variations of HD 60435 on JD 2445383. Each panel of this light curve is 0.04 mag high and 1 hr long. The panels should be read from left to right, top to bottom, to show one continuous 3.49 hr light curve. Thus, the right hand border of each panel is identical in time with the left border of the panel just beneath it. The solid horizontal line through the middle of the light curve represents the mean magnitude for the night. Each point represents a 20-s integration. The 12-min oscillations are obvious. The non-sinusoidal shape caused by the 6-min oscillations is noticeable.

Observationally, it is important to discover and study many rapidly oscillating Ap stars to see what the range of their behaviour is. In this paper the discovery of two new rapidly oscillating Ap stars is presented, which brings the total number of members of this group to nine. Table 1 lists these nine stars along with their Strömgren photometric indices (Vogt & Faundez 1979; Hauck & Mermilliod 1980; Weiss 1983b), pulsation periods, peak-to-peak maximum B light variations, and magnetic-field strengths. There are no obvious correlations of period or amplitude with any of the other stellar characteristics.

Rotational periods are known for only two of these stars, HD 24712 ($P = 12.4564$ day, Kurtz & Seeman 1983) and HD 83368 ($P = 2.8519$ day, Kurtz 1982). Rotational light variations are known to be small in HD 137949 (ΔV and $\Delta B < 0.005$ mag, Kurtz 1982), HD 217522 ($\Delta B < 0.005$ mag, Kurtz 1983b), and HD 201601 ($\Delta B < 0.01$; Wolff & Morrison 1973; Kurtz 1983a). There are also indications that mean light variations are small in HD 101065 (Heck, Manfroid & Renson 1976; Przybylski 1978). There are small mean light variations in HD 60435 which are reported in the next section of this paper. The mean light variations of HD 128898 and HD 203932 are unstudied.

2 HD 60435

High speed photometric observations of HD 60435 were obtained on 16 nights from 1983 January to April with the People's Photometer attached to the 0.5-m telescope of the South African Astronomical Observatory (SAAO) and with the University of Cape Town photo-

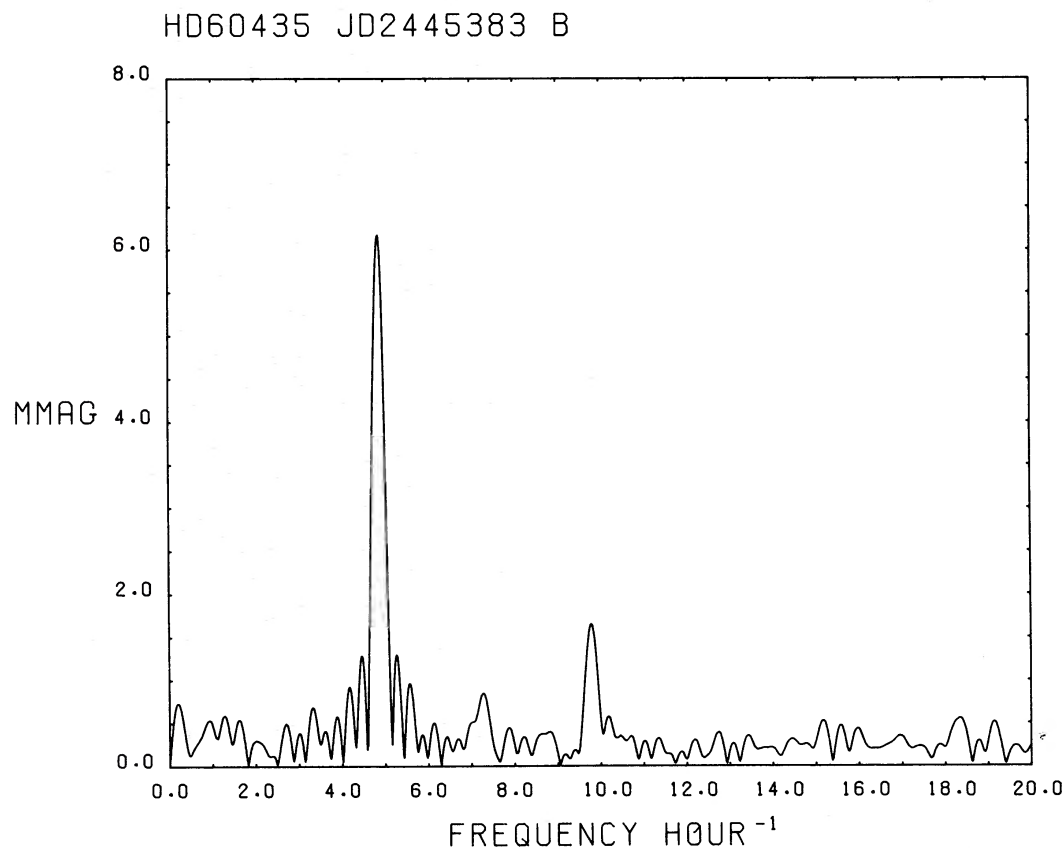


Figure 2. The amplitude spectrum of the light curve presented in Fig. 1. The amplitude here and throughout this paper is semi-amplitude A as in $A \cos(\omega t + \phi)$. It is therefore, half the peak-to-peak variation. Both the 12- and 6-min periods can be seen here.

meter attached to the SAAO 0.75-m telescope. All observations were made using continuous 20-s integrations through a Johnson *B* filter. Table 2 lists the nights on which observations were obtained, the Julian dates of those nights, the duration of the observations in hours, the number of 20-s integrations obtained, and the standard deviation of one observation with respect to the mean of the night. The data were corrected for mean extinction and for sky transparency variations with periods longer than 2 hr.

HD 60435 was tested for light variations because of its spectral classification of Ap SrEu (Bidelman & MacConnell 1973; Houk & Cowley 1975) and relatively large $b-y = 0.132$ index. All of the rapidly oscillating Ap stars yet discovered are cool magnetic Ap stars (typically with SrCrEu peculiarities) as can be seen in Table 1. The first night that this star was observed showed it to be the largest amplitude rapidly oscillating Ap star yet discovered. Fig. 1 shows the light curve for that night and Fig. 2 shows an amplitude spectrum of that light curve. The oscillations in this star are primarily at a period of about 12 min but also at a period near 6 min. This is similar to the behaviour of HR 3831 (Kurtz 1982) which means that a complete frequency solution may yield i , the rotational inclination of the star, β , the magnetic obliquity, and P_{rot} , the rotational period.

The data available for HD 60435 are inadequate for a complete frequency solution so this presentation is limited to a short description of the fascinating behaviour of this star. During the first week that HD 60435 was observed, JD 2445383 – 5387, it began by oscillating with frequencies of 4.9 hr^{-1} and 9.7 hr^{-1} at respective semi-amplitudes of 6.2 mmag and 1.7 mmag. These amplitudes dropped steadily until they were undetectable and then the low-frequency peak reappeared, but not the high frequency peak. During the second week of observations, JD 2445409 – 5415, no variations were detectable for three nights. The amplitude then rose to 3.4 mmag at a frequency of 5.1 hr^{-1} . The errors are sufficiently low to argue that this frequency is different from the 4.9 hr^{-1} frequency observed earlier. No higher frequency oscillations were detected. During the third week of observations, JD 2445423 – 5429, only the low-frequency oscillations were present at low amplitude. A more detailed quantitative

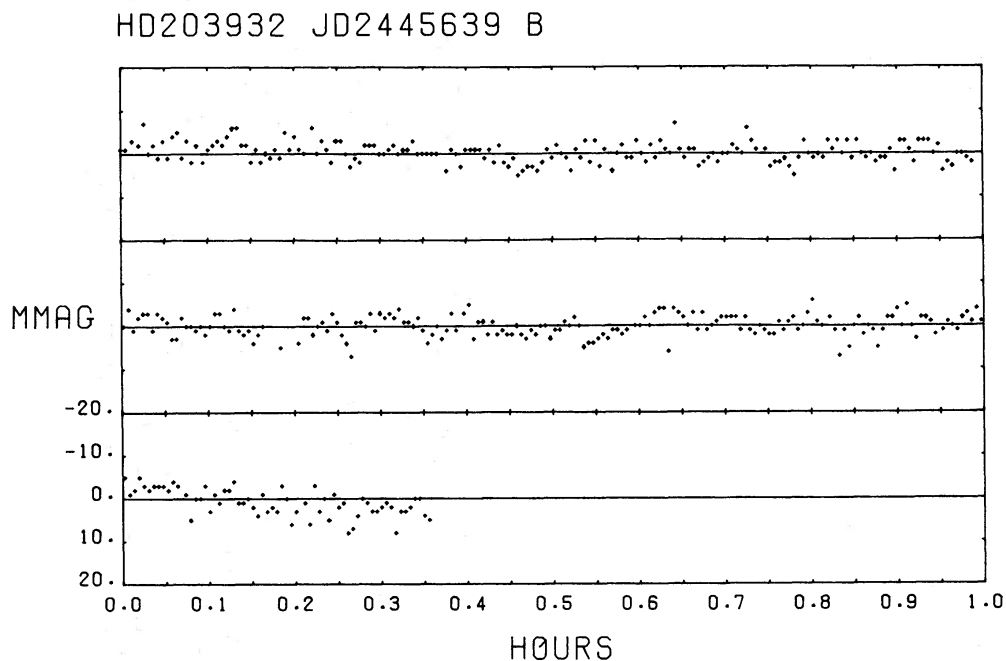


Figure 3. The *B* light curve of HD 203932 on JD 2445639. The 6-min oscillations were at the largest amplitude detected on this night.

HD203932 JD2445639 B

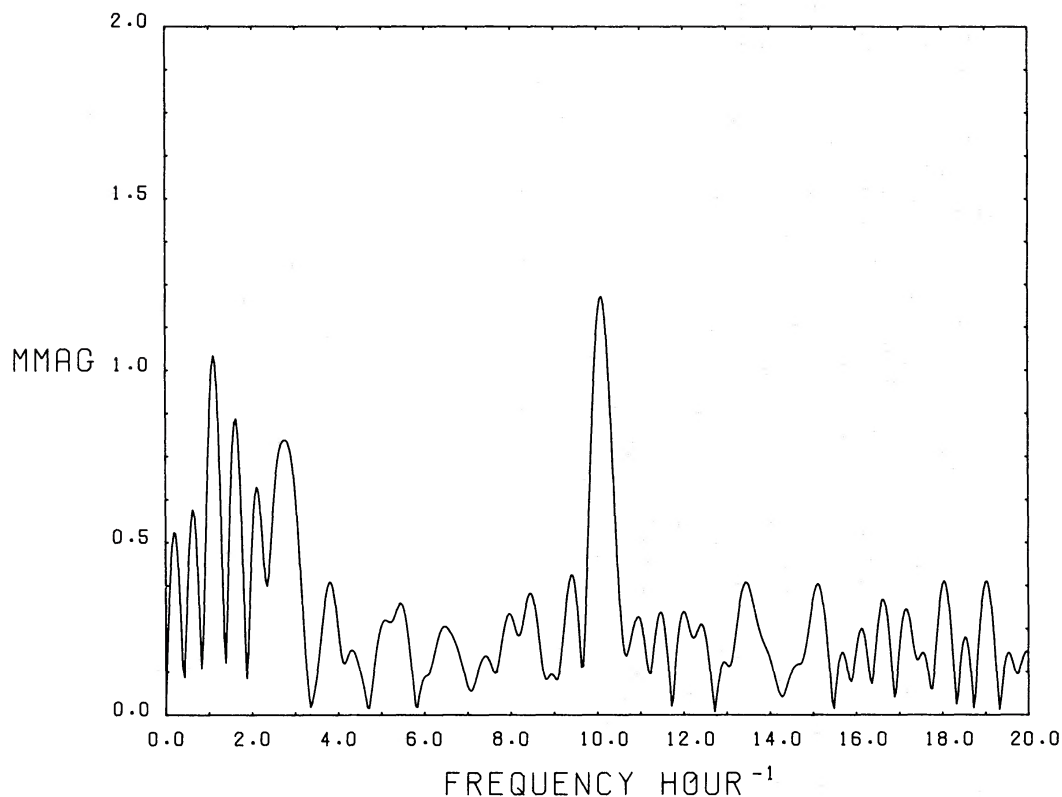


Figure 4. The amplitude spectrum of the light curve presented in Fig. 3.

description of these data will be made in the future when more observations have been obtained.

The mean magnitude of HD 60435 was observed each night by observing the comparison star HD 59994AB (A2m–A5–A7, Houk & Cowley 1975) for 100-s before and after the high speed observations of HD 60435. The mean *B* magnitude of HD 60435 varies by at least 0.01 mag, but no period can be determined from the data. Observers of rotational light variations in Ap stars are encouraged to put this star on their observing program. The mean light level should be calculated by averaging continuous integrations over one 12-min pulsation cycle.

Table 3. Journal of *B* observations of HD 203932.

Date (1983)	JD 2 440 000 +	<i>t</i> hr	<i>N</i>	σ mmag
August 07/08	5554	3.04	541	2.6
August 08/09	5555	0.85	151	1.7
August 10/11	5557	1.43	218	2.9
August 11/12	5558	2.17	385	2.8
August 12/13	5559	2.22	392	2.1
August 15/16	5562	5.99	1002	3.4
October 01/02	5609	4.70	832	2.7
October 25/26	5633	2.14	369	2.9
October 26/27	5634	0.98	176	2.4
October 27/28	5635	2.55	450	2.8
October 30/31	5638	1.13	198	2.5
November 00/01	5639	2.36	409	2.5
	Σ	29.56	5123	(2.8)

3 HD 203932

HD 203932 was tested for light variations for the same reason as HD 60435: HD 203932 is classified as Ap SrEu (Bidelman & MacConnell 1973; Houk 1982) and has a relatively large value of $b-y = 0.169$ and relatively small value of $\beta = 2.814$ which indicate a low temperature for an Ap star. From the first night of observation of this star variations in the data with a period near 6 min were noticeable at the telescope. HD 203932 is, however, the lowest amplitude rapidly oscillating Ap star yet found. Fig. 3 shows the light curve obtained on JD 2445639 where variations with a period of about 6 min and a semi-amplitude of 1.2 mmag can be seen by the discerning reader. Fig. 4 is an amplitude spectrum of the light curve shown in Fig. 3.

High speed photometric observations of HD 203932 were obtained on 12 nights from 1983 August to November in the same manner described for HD 60435. All observations were made with the People's Photometer attached to the SAAO 0.5-m telescope. Table 3 gives a journal of the observations.

The data were frequency analysed using the technique of Fourier analysis of unequally spaced data (Deeming 1975) with modifications suggested by O'Donoghue (1981) and O'Donoghue & Warner (1982) which greatly reduce computing time. Analysis of the data on a nightly basis, in weekly subsets, and as a whole, show that there is only one frequency present above the noise level. That frequency is $f = 10.09724 \pm 0.00012 \text{ hr}^{-1}$ ($P = 5.94222 \pm 0.00007 \text{ min}$) where the estimated error is the Gaussian half-width of the central

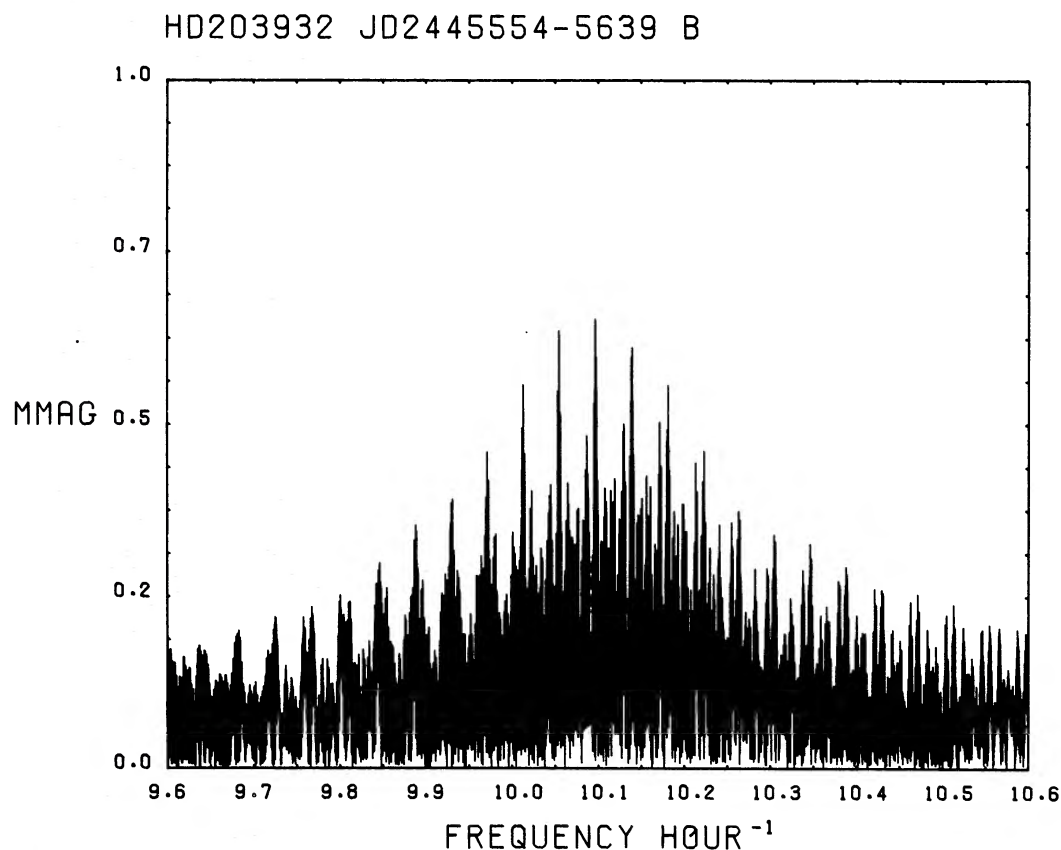


Figure 5. A high resolution amplitude spectrum of the entire data set of HD 203932 showing the peak at $f = 10.09724 \text{ hr}^{-1}$. The noise level at higher and lower frequencies than these shown in this plot is at about 0.20 mmag.

HD203932 JD2445554-5639 B

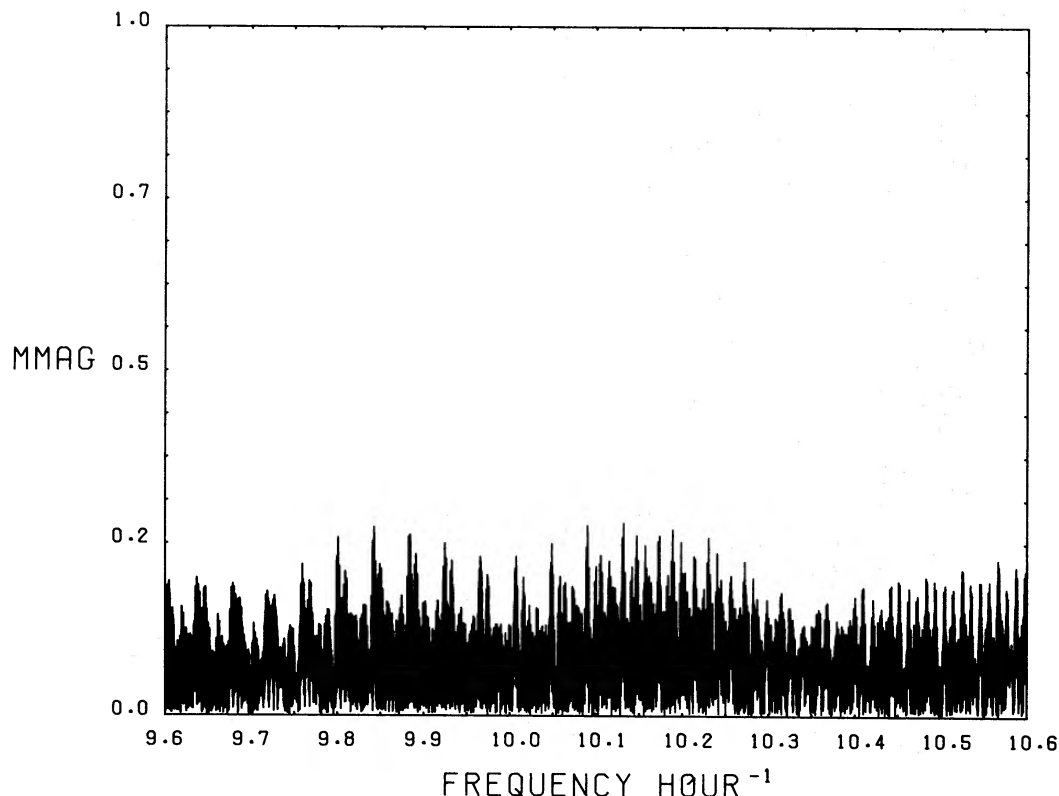


Figure 6. A high resolution amplitude spectrum of the entire data set after the frequency $f = 10.09724 \text{ hr}^{-1}$ has been removed from the data. No significant peaks can be seen above the noise level. This is also true outside of the frequency range shown.

peak. In the absence of contamination of this peak by secondary frequencies, this error is overestimated; the centroid of the peak and hence the frequency can be determined to higher accuracy.

Fig. 5 shows an amplitude spectrum of the entire data set which clearly demonstrates the frequency at $f = 10.09724 \text{ hr}^{-1}$. When that frequency is removed from the data the amplitude

Table 4. Fit of $f = 10.09724 \text{ hr}^{-1}$ to the data.

JD 2440 000 +	A mmag	ϕ
5554	0.58 ± 0.16	-2.4 ± 0.3
5555	0.37 ± 0.20	-1.9 ± 0.5
5557	1.01 ± 0.28	-1.1 ± 0.3
5558	0.93 ± 0.20	-1.6 ± 0.2
5559	0.93 ± 0.14	-2.1 ± 0.2
5562	0.62 ± 0.15	-1.4 ± 0.3
5609	0.68 ± 0.13	-1.2 ± 0.2
5633	0.65 ± 0.21	-1.9 ± 0.3
5634	0.19 ± 0.26	-2.8 ± 1.4
5635	0.76 ± 0.18	-1.5 ± 0.2
5638	0.56 ± 0.25	-2.7 ± 0.4
5639	1.21 ± 0.17	-2.0 ± 0.1
5554-5639	0.66 ± 0.05	-1.70 ± 0.08

The parameters given in this table fit the relation:

$$\Delta B = A \cos [2\pi f(t - t_0) + \phi] \text{ where } t_0 = \text{JD } 2445\,000.00000.$$

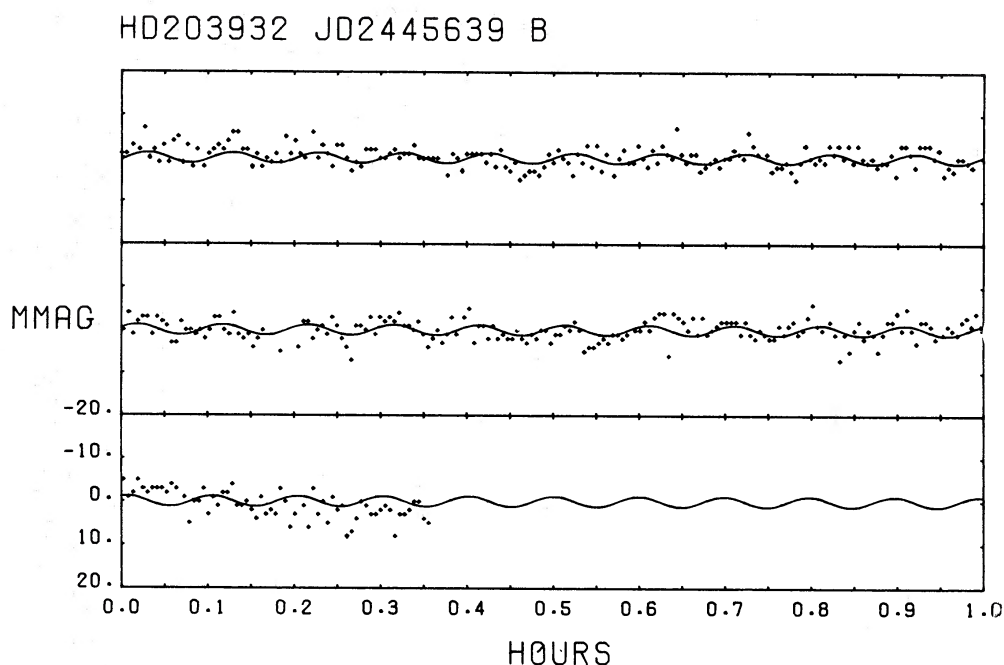


Figure 7. The *B* light curve of HD 203932 on JD 2445639 with the frequency $f = 10.09724 \text{ hr}^{-1}$ ($A = 0.66 \text{ mmag}$, $\phi = -1.70$) determined from the entire data set fitted. This light curve can be compared with the same light curve without the fitted frequency shown in Fig. 3.

spectrum of the residuals shown in Fig. 6 indicates that no secondary frequencies are present with semi-amplitudes greater than 0.22 mmag .

Nevertheless, there is an indication that the amplitude of oscillation in HD 203932 is modulated. Table 4 shows the results of a least squares fit of $f = 10.09724 \text{ hr}^{-1}$ to each night of data and to the whole data set. The amplitude of oscillation on JD 2445639 differs by more than 3σ from the amplitude determined from the entire data set. The amplitude modulation could be caused by either secondary oscillation frequencies or rotational amplitude modulation in an oblique pulsator. I suspect from the present data that the secondary frequency or frequencies are just below the noise level in Fig. 6. This means that a concerted observing effort, especially with a telescope larger than the one used to obtain the data presented here (to reduce scintillation noise) would probably detect such frequencies.

In Fig. 7 the frequency with the amplitude and phase derived from the entire data set is fitted to the light curve obtained on JD 2445639. The fitted curve may make it easier for the reader to see the variations in the data. Comparison of Figs. 7 and 3 is useful.

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