SPECTRAL VARIATIONS OF THE RAPIDLY OSCILLATING Ap STAR HD 60435

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ABSTRACT. The peculiar F star HD 60435 exhibits broadband light oscillations of low amplitude with periods between 15 and 4 minutes. Photographic spectra obtained in January/February 1985 using the University of Toronto 0.6 m telescope on Las Campanas, Chile, reveal that the star also undergoes slow spectral variations like those observed in many Ap stars. The data further suggest that Sr II maximum may coincide with maximum amplitude of light oscillations. According to the oblique pulsator model (Kurtz 1982) for such variables, this implies that Sr II is concentrated near at least one of the magnetic poles of HD 60435.

I. INTRODUCTION

Rapid photometric variations have been convincingly detected in 11 cool peculiar A-F stars to date, mostly by Kurtz (e.g. 1982, 1984). The observed periods range from about 15 to 4 minutes; typical amplitudes are less than $0\overset{m}{.}01$ in Johnson B or V. The oscillation amplitudes are modulated, usually with timescales of days. For stars whose magnetic field variations have been determined, these modulation periods are identical to the magnetic periods, and are phased such that maximum oscillation amplitude occurs during peak field strength.

Kurtz (1982) has accounted for most of the observed properties of the rapid variations through his oblique pulsator hypothesis, which itself is an extension of the oblique rotator model. (That model, in which Ap stars possess dipole magnetic fields inclined to their rotation axes, has been very successful in explaining their long-term magnetic, spectroscopic, and photometric variations.) According to this picture, a rapidly oscillating Ap star is an oblique rotator which is also pulsating nonradially, but with the pulsation poles aligned with the magnetic axis instead of the rotation axis. The periods are indeed consistent with high-overtone noneradial p-modes, and the model readily explains the observed relation between the apparent magnetic field strength and oscillation amplitude (as well as other empirical features, such as fine structure in the Fourier spectra).

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HD 60435 is an F0p star (V = 9.0) which has one of the richest oscillation spectra yet analysed among the rapidly oscillating Ap stars. Kurtz (1984) first detected periods near 12 and 6 minutes in this star. Coordinated multi-site observations by Matthews et al. (1985) confirmed the presence of the "12-min" oscillations, and uncovered additional periods near 15 and 4 min. Additional photometry obtained a year later (Matthews et al. 1985a) showed these oscillations to be part of a pattern of frequencies spaced by roughly 55 μHz - and half that value - which might be expected for a spectrum of overtones of p-modes with even and odd degree (ℓ = 2, and 1,3).

The amplitude of the "12-min" oscillations varies with a timescale of about 8 days. Fourier spectra of the light curves also show fine splitting of peaks (predicted by the oblique pulsator model) which can account for beating with that period. Long-term photometric monitoring of HD 60435 by Matthews et al. (1985, 1985a) has yielded a light curve with a period of approximately 7.7 days (presumed to be the rotation and magnetic period of the star). All of these results are consistent with the oblique pulsator hypothesis.

A sample light curve of the rapid oscillations of HD 60435, and the corresponding Fourier amplitude spectrum, are shown in Figure 1.

In the absence of magnetic field measurements of this relatively faint star to refine tests of the oblique pulsator interpretation, spectroscopic data can supply another independent determination of the star's rotation, and perhaps some indirect information about the magnetic field geometry. As a first step, we decided to obtain several low-dispersion photographic spectra of HD 60435, in conjunction with simultaneous or contiguous rapid photometry. These would determine:

a) if the star is a spectrum variable, and if so, to what degree;

In the event of sufficiently strong variations...

b) a rough estimate of the variation period (or timescale) for comparison with previous results; and

c) any correlations between the line strength variations and the modulation of the rapid oscillations.

II. OBSERVATIONS

A dozen spectra were exposed using the U. of Toronto 0.6 m telescope and classification spectrograph (Las Campanas, Chile) during 31 January to 11 February 1985, by RWS and JMM, at a dispersion of 67 Å/mm. (The spectra were recorded on baked IIa-O plates; a typical exposure was about two hours long.

Coincident with these observations, rapid photometry of HD 60435 was performed by JMM, using the U of T telescope and the 0.9 m telescope of the Cerro Tololo Inter-American Observatory. (These measurements were part of a larger campaign undertaken by Matthews et al. (1985a).) The observations consisted of continuous 20-second integrations through a B filter. No comparison star was employed, but on nights of stable sky transparency, the star's rapid coherent oscillations can be distinguished from the slower random variations in the atmospheric aerosol extinction (see Figure 1).

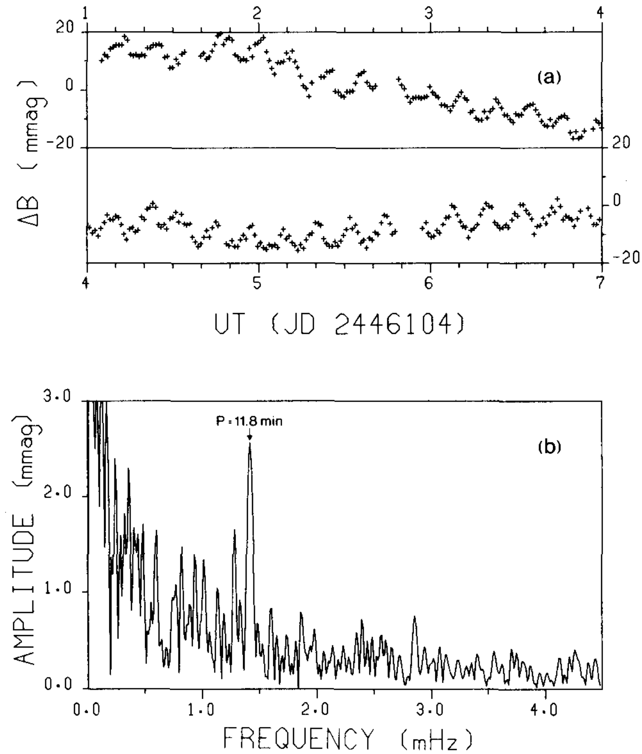

FIGURE 1. a) A light curve of HD 60435. Each point represents a 60-s integration through a B filter, using the CTIO 0.9 m telescope. b) A Fourier spectrum of the data in a). The power present at low frequencies is attributed to slow incoherent changes in sky transparency.

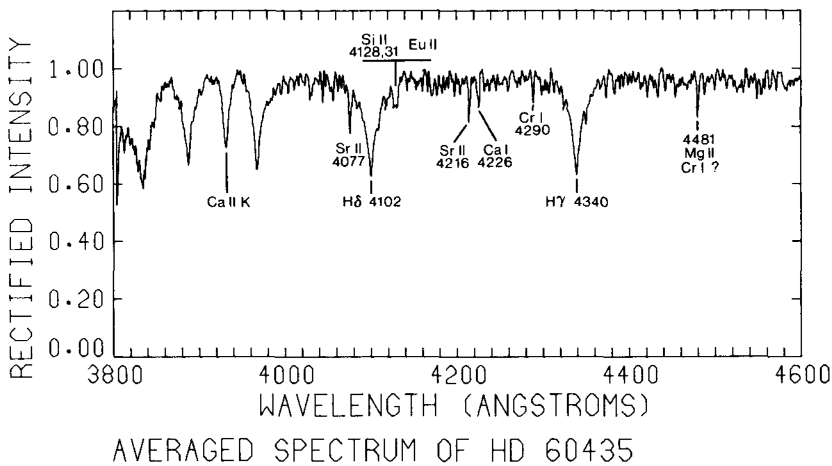

FIGURE 2. A plot of the average of the 12 digitized photographic spectra of HD 60435.

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III. RESULTS

The photographic spectra were digitized using the PDS microdensitometer of the U of T. A tracing of the average of all 12 spectra is presented in Figure 2. The appearance of this spectrum agrees with an F0p(SrCr) classification for HD 60435. A few of the strongest lines are labelled. (Many lines which are apparent upon visual inspection of the plates appear as 'noise' in the continuum of the tracing.)

To display variations in line strengths, each individual spectrum was divided by the average spectrum of Figure 2. In the divided spectra, lines weaker than average will appear as 'bumps' in the continuum, while stronger lines are seen as depressions. The divided spectra are plotted in Figure 3. On some spectra (e.g. 3 Feb), there are indications that the photometric properties of the plate are non-uniform, and hence, the line strength information from those is suspect. However, on others (e.g. 31 Jan, 9 Feb), there is little doubt that the line strength changes are genuine. The constancy of the Hγ and Hδ lines was taken as an indicator of the reliability of the scan features.

Beside each spectrum in Figure 3 is an estimate of the B amplitude of the "12-min" oscillation of HD 60435, derived from the amplitude spectrum of the light curve from each night of observation (e.g. see Figure 1b for the night of 8 Feb).

To show the relation between the oscillation and spectroscopic variation even more clearly, the values of $R_\lambda/R_c - 1$ were determined for the Sr II λ4215 line in the ratioed spectra shown in Figure 3. Figure 4 is a plot of these values as a function of the time of observation. The values of ΔB are also plotted there. The lines drawn through the points are meant only to suggest the occurence of variations, and to indicate a correlation between the spectral and photometric variability.

A few limited conclusions may be drawn from the data in Figures 3 and 4:

a) HD 60435 is a spectrum variable, although a rather mild one.

b) A comparison of the relative line strengths and oscillation amplitudes suggests that Sr II is strongest at times of maximum photometric amplitude. On nights when Sr II λ4215 is noticeably stronger than average, the measured B amplitudes were $\gtrsim$ 2.0 mmag. On 8 Feb, when the amplitude reached its peak value ($\tilde{2.5}$ mmag) over the 12-day interval, the Sr II λ4077 line was also stronger than average. That line shows no marked deviation from average on any other night.

c) Variations of the λ4481 line are also apparent. In addition to the Mg II doublet, there is also a Cr I line at this wavelength; however, the observed variation shows no obvious correlation with the photometric modulation.

In the context of the oblique pulsator model, result b) implies that Sr II may be concentrated at one magnetic pole of HD 60435.

Unfortunately, the S/N ratio of these spectra is too low to permit any more specific conclusions based on these data. The preliminary findings are encouraging enough to prompt further spectroscopic investigations of HD 60435, at higher resolution and S/N. Two of the authors (JMM and WHW) are currently planning such an observing programme.

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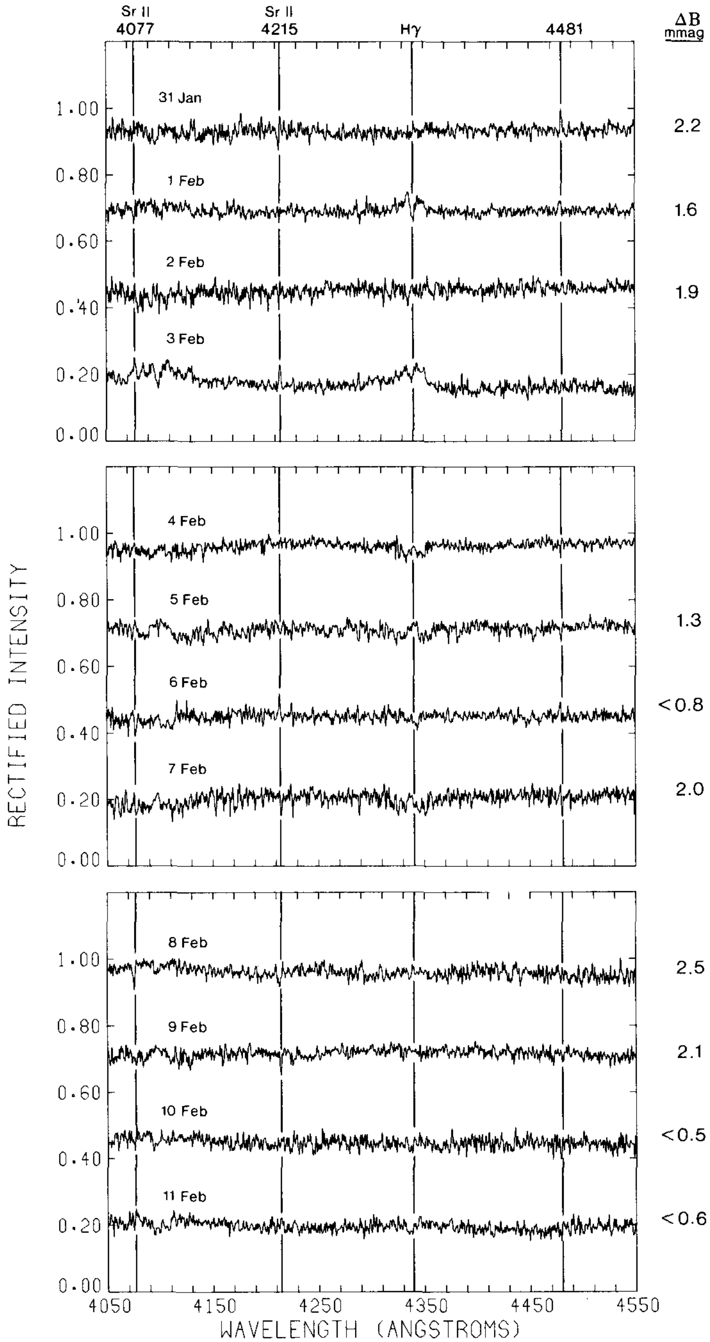

FIGURE 3. The 12 individual spectra, divided by the average spectrum of Figure 4. On the right are the corresponding B amplitudes of the "12-min" oscillation measured on those nights.

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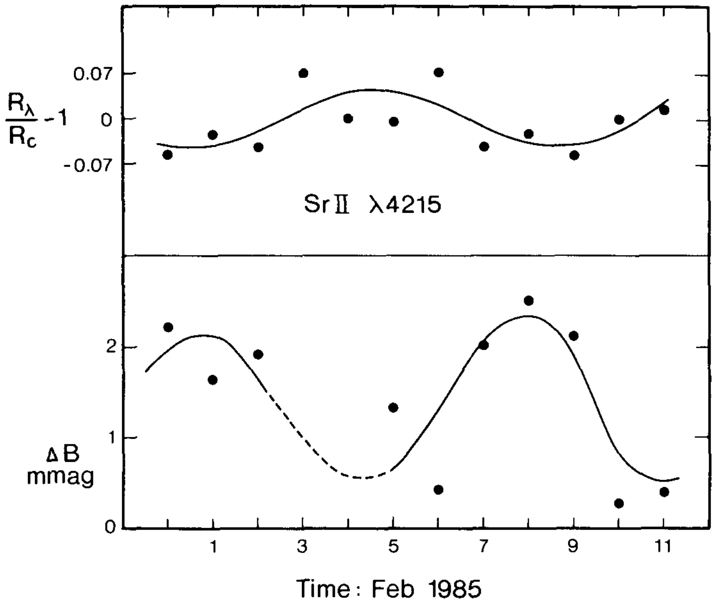

FIGURE 4. The variations of the Sr II λ4215 line strength and of ΔB (the amplitude of the light variability) plotted against time. The curves are fits by eye to both sets of data.

DISCUSSION

RAMADURAI: Is there any limit to the magnetic field strength at all? You said there are no observations yet, but is it possible to put some limits?

WEHLAU: No; there is no information at all and we have made tentative arrangements to see whether there is a magnetic field or not. It is a 9th magnitude star. The measurement requires observing time on a large telescope in the southern hemisphere.

RAMADURAI: How strong are the abundance anomalies in this star? Is it in the same range as for Ap stars?

WEHLAU: It is clearly an Ap star with Sr, Cr anomaly. However, the spectra show it to be only a mild spectrum variable, so that higher resolution spectra are required to study the spectrum variability.

G.S.D. BABU: Since this magnetic field is not yet observed, do you think the application of Kurtz's model for explaining the rapid oscillation is justified?

WEHLAU: Yes, I think that is quite correct. We really do need to get magnetic information in order to see what is going on. HD 60435 shows the features typical of the rapid oscillator. The oblique pulsator model appears to explain these features for other rapid oscillators, so, it seems appropriate to use it for this star as well; still it would be very desirable to measure the magnetic field and to test the applicability of the oblique pulsator model.

G.S.D. BABU: Is any spectrophotometry done for this star?

WEHLAU: No.