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NIGHTLY VARIATIONS OF NONRADIAL OSCILLATIONS IN THE DELTA SCUTI STAR υ URSAE MAJORIS

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ABSTRACT

We obtained spectra of the rapidly rotating Delta Scuti star υ UMa with the Advanced Fiber Optic Echelle Spectrometer on five successive nights in 1993 April, at a cadence of one spectrum every 5 minutes over time periods averaging 4 hours on each night. Cross-correlations of the spectra with a template spectrum from a slowly rotating star of similar spectral type yielded the pattern of features propagating across the lines, averaged over all spectral lines recorded. The spacing of the features in wavelength and their speed of motion across the line profile depend on the azimuthal order m and frequency ν of propagating oscillation modes. Using a Doppler imaging analysis, we computed nightly $|m|$-ν diagrams; these show several resolved modes with effective azimuthal order m ranging from about 2 up to about 11, and frequencies between 130 and 170 μHz (i.e., periods between 2.1 and 1.6 hours). We identify the observed modes as propagating prograde modes; the corresponding retrograde modes are not observed. Viewed in a frame corotating with the star with rotation speed of 116 km s^{-1} as derived from these data, modes with $m \sim 7$ and with $m \sim 11$ have approximately the same frequency (70 μHz). However, their relative amplitude changes substantially from night to night, suggesting that (1) the coherence time of the modes is not longer than about 1 day, or (2) a possible coupling between modes of similar intrinsic frequencies causes an alternating pattern of modal amplitude, or (3) beats are being observed between unresolved modes of similar wavelength and frequency.

Subject headings: stars: individual (υ Ursae Majoris) — stars: oscillations — stars: variables (δ Scuti)

1. INSTRUMENT AND OBSERVATIONS

The Advanced Fiber Optic Echelle Spectrometer (AFOE) is a fiber-fed bench-mounted echelle spectrograph, coupled to the Tillinghast 1.5 m telescope at the F. L. Whipple Observatory. At the time of observation, the spectrograph configuration provided a resolution of 56,000, and a total coverage of 730 Å between 4960 and 6280 Å over 10 orders. The spectrum was recorded on a 2048 by 2048 pixel CCD detector, binned in the cross-dispersion direction down to a 2048 by 1024 format. The AFOE was designed for extreme radial velocity precision observations, and is described in Brown et al. (1994).

We observed the rapidly rotating Delta Scuti star υ Ursa Majoris (=HR 3888, =HD 84999) on five consecutive nights in 1993 April. Observations were made over 2.5 to 5 hours on each night, with a cadence of one spectrum every five minutes, yielding a total of some 190 spectra. In unblended strong lines, the rotationally broadened profiles clearly show "bumps" propagating from the blue side to the red side of the lines, as has already been reported by Walker, Young, & Fahlman (1987). The continuum signal-to-noise ratio of the spectra is only about 60 so that the bumps are not as clearly seen in individual lines as in the data discussed by Walker et al. but the large number of spectral lines observed presents highly redundant information, which may be combined to obtain useful information.

2. DATA REDUCTION AND ANALYSIS

The echelle spectrum extraction was carried out using a preliminary version of the AFOE standard reduction package which is still under development. Briefly, the raw frames were first corrected for bias and dark counts, then for scattered light. Each order was then extracted and flat fielded, and effects of cosmic rays eliminated.

In order to isolate the moving features, we first subtracted the mean spectrum for the corresponding night from each individual spectrum, and normalized the remainder to the mean spectrum. Then, for each order separately, we computed the cross-correlation function between each residual spectrum and a standard template spectrum. As a standard template spectrum we used a high signal-to-noise spectrum of a slowly rotating star (Procyon) of similar spectral type (F5 IV–V for Procyon vs. F2 IV for υ UMa), obtained with the same instrument in the same configuration. Finally, we computed a straight average of the cross-correlation functions over all the orders for a given spectrum to obtain a time-series of averaged cross-correlation profiles, $F_{cc}(v_{dop}, t)$ where v_{dop} is the Doppler displacement of wavelengths in the υ UMa profile. By computing the cross-correlation functions, the information from all the "bumps" moving across all spectral lines (including blended lines) has been combined into a single function of displacement from line center, thereby significantly increasing the signal-to-noise ratio of the moving features.

To characterize the position of the moving features, we computed the cross-correlation functions of the F_{cc} functions, and measured the offset, δV, of the peak closest to the zero lag. Figure 1 shows examples of such cross-correlations of the F_{cc} functions for two hours of observations. Also shown are the locations δV of the cross-correlation peaks closest to zero velocity difference.

For each night, we have measured δV for all possible positive time differences δt, using each υ UMa–Procyon cross-correlation function of that night in turn as a reference. The resulting dependence of δV as a function of δt is shown for each night in the left-hand side of Figure 2 (Plate L6).

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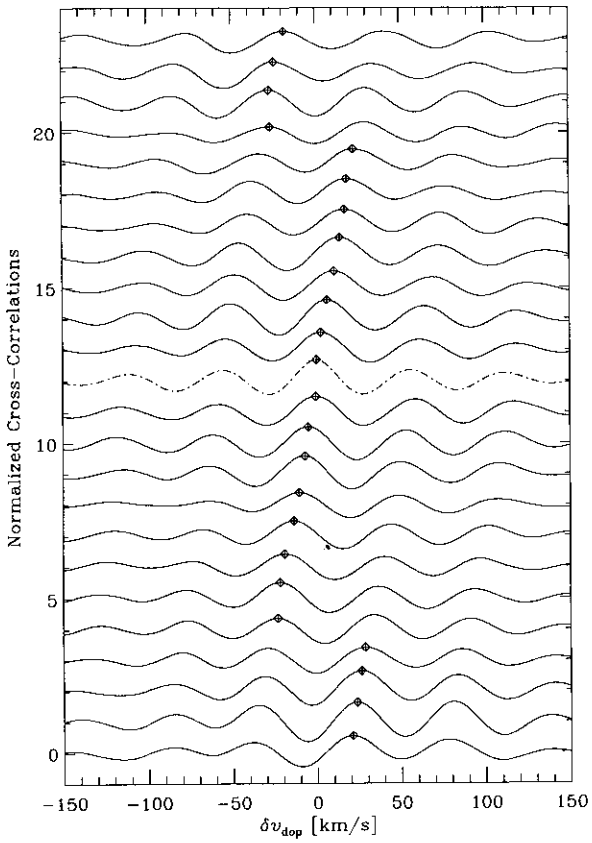

FIG. 1.—Plot of normalized cross-correlation of the F_{cc} functions for 2 hr of observations on 1993 April 11 (offset by integers for clarity). The υ UMa–Procyon cross-correlation function, F_{cc}, for the middle of the sequence was used as the reference profile; its cross-correlation with itself (i.e., autocorrelation) is shown dashed. Also shown are the locations δV of the peaks closest to zero velocity difference.

If the mode phase velocity in the rotating stellar reference frame were small compared to the rotational velocity (as assumed in Walker et al. 1987) such plots should present a simple "saw-tooth" profile whose slope, a_o, pattern period, ΔT, and peak to peak amplitude, $V_{pp} = a_o \Delta T$, are related to the rotation period, P_{rot}, the rotational velocity, v_{rot}, the inclination, i, and the azimuthal order, m, of the mode according to

$$P_{rot} = |m| \Delta T = |m| \frac{V_{pp}}{a_o} \quad (1)$$

and

$$|m| = \frac{2\pi(v_{rot} \sin i)}{V_{pp}} . \quad (2)$$

The quantity $v_{rot} \sin i$ was directly measured from the spectra by broadening the Procyon spectrum until it best matched the averaged υ UMa spectrum in the least-squares sense; we found $v_{rot} \sin i = 116 \pm 12$ km s^{-1} (a value that agrees very well with the value of 115 km s^{-1} compiled by Bernacca & Perinotto 1973).

This model may be pursued by fitting the quantities V_{pp} and a_o in the least-squares sense to the data presented in the left-hand side of Figure 2, allowing us to deduce values of $|m|$, P_{rot} and $R(\sin i)/R_\odot$ (since $v_{rot} = 2\pi R/P_{rot}$). Such an analysis yields values of $|m|$ that vary significantly from night to night ($|m| \simeq 13.6$, 4.2, 9.9, 5.0, 12.1 for the five consecutive nights, respectively). However, undermining this simple picture, the derived value of $R(\sin i)/R_\odot$ also varies significantly from night to night [$R(\sin i)/R_\odot \simeq 2.29$, 1.55, 1.84, 1.60, 1.93, respectively], as does P_{rot} ($P_{rot} \simeq 1.00$, 0.68, 0.80, 0.70, 0.84 days, respectively). We conclude that the simple model of a slowly propagating single mode is unable to explain the data. Also, direct inspection of the left-hand side of Figure 2 suggests that more than a single mode is present on most nights (with the exception of April 11), and that the mode characteristics vary significantly from night to night.

We have therefore carried out a more rigorous analysis, based on the "Doppler imaging" technique described by Kennelly, Walker, & Merryfield (1992). In this technique, the profiles describing the moving features are first remapped from Doppler space, v_{dop}, to longitude, ψ. Then a two-dimensional Fourier transform is computed to convert the resulting $\psi - t$ time-series into a two-dimensional $|m|$-ν power spectrum, where m is the azimuthal order and ν is the frequency in the observer's frame of reference.

If we assume that the line-of-sight velocity is dominated by the rotational velocity component and that the star is observed almost edge-on (i.e., $\sin i \simeq 1$), the remapping from Doppler space to longitude is given by

$$F_{cc}(v_{dop}) = F_{cc}[(v_{rot} \sin i) \sin(\psi)] . \quad (3)$$

Gray-scale plots of the remapped $F_{cc}(\psi, t)$ time-series are shown on the right-hand side of Figure 2.

Figures 3*a*–3*e* show the five resulting nightly $|m|$-ν power spectra obtained from Fourier transforming the $F_{cc}(\psi, t)$ time-series, and Figure 3*f* shows the average of the power spectra over the five nights.

3. RESULTS

The nightly $|m|$-ν diagrams show prominent power around $m = 2$ to 3, $m = 7$, and $m = 11$. Moving bumps with spacing corresponding to low m are not apparent at earlier stages in the analysis, and we suspect that this power may be an artifact of the reduction procedure; this matter is still under investigation. However, the power peaks around $m = 7$ and $m = 11$ do correspond to the moving bumps seen on the left side of Figure 2, and as expected they vary from night to night. Thus, on April 8 and 11, where a simple sawtooth pattern in Figure 2 (*left*) suggests one predominant mode, there is indeed a single predominant mode in the corresponding $|m|$-ν diagram, but at $|m| \simeq 7$ on April 8 and $|m| \simeq 11$ on April 11. Nights showing comparable amplitude of peaks at these two values of $|m|$ correspond to more complex behavior in Figure 2. Interestingly, the modal amplitude seems to alternate from night to night; namely, the $m \simeq 7$ mode amplitude dominates on April 8 and 10, while the $m \simeq 11$ mode dominates on April 9 and 11; both modes have comparable amplitude on April 7. The total power does not change significantly from night to night.

We estimated the rotational period, $P_{rot} = 1.217 \pm 0.30$ day, from our measured rotational velocity, $v_{rot} \sin i$, assuming $\sin i = 1$, and our best estimate of the radius. This radius ($R/R_\odot = 2.79 \pm 0.40$) was derived from an estimate of the effective temperature, $T_e = 7130 \pm 93$ (Smalley & Dworetsky 1993), the parallax, $\pi = 0.035 \pm 0.004$ (Jenkins 1952) and the apparent magnitude, $m_V = 3.80$ (Rufener 1976).

Any nonpropagating modes (for instance, a convection pattern that evolves slowly with respect to the rotational period) would satisfy $\nu = |m|/P_{rot}$ and would therefore lie on

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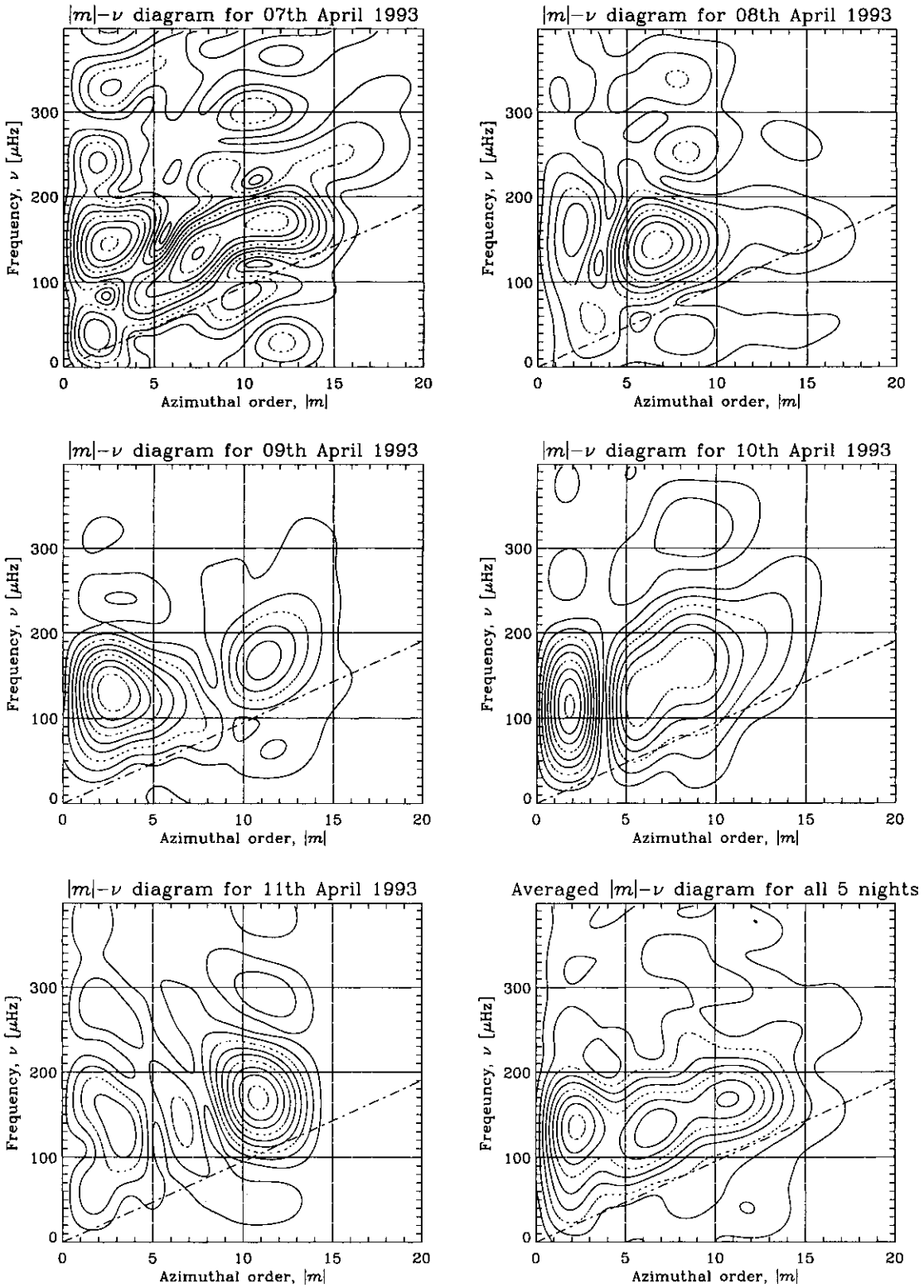

FIG. 3.—Nightly $|m|$-ν power spectra (*a*–*e*) and their average (*f*). The dot-dashed lines correspond to $\nu = |m|/P_{\rm rot}$, for $P_{\rm rot} = 1.217$ days.

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the dot-dash line plotted in Figure 3. However, the two dominant observed modes both lie about 70 μHz above this line.

We therefore conclude that we observed at least two propagating modes, both prograde, and both with a similar intrinsic frequency (i.e., the frequency seen in a frame rotating with the star) around 70 μHz (or a period around 4 hr). The corresponding retrograde modes are not observed.

We have also estimated the amplitude of the radial velocity perturbation required to reproduce the observed line profile distortion of the propagating features. This was done by computing a simple model in which a spherical harmonic function for the radial component of the mode velocity perturbation is superposed on a solid body rotational velocity pattern corresponding to $v = 116$ km s^{-1} and assuming $\sin i = 1$. Ignoring limb darkening, we computed a time series of synthetic line profiles by integrating the reference Procyon spectrum over the stellar disk, Doppler-shifted according to the line-of-sight velocity corresponding to the superposition of the solid body rotation and a sectoral mode for $l = m = 12$. The resulting synthetic profile was cross-correlated in the same way as the observed ones. The amplitude of the radial velocity oscillation mode was then adjusted to produce synthetic propagating features comparable in amplitude to the observed ones. The oscillation amplitude required to match the observed features is about 6.5 km s^{-1}.

4. CONCLUSIONS

Perhaps the most interesting result from these observations of υ UMa is the significant variation from night to night of the star's oscillation spectrum. In addition, the present data are incompatible with the simple assumption adopted by Walker et al. (1987) of a negligible phase velocity with respect to the rotational velocity (at least in the case of υ UMa).

Two modes ($m \simeq 7$ and $m \simeq 11$) have been identified, both prograde, and both with a similar intrinsic frequency of about 70 μHz. The corresponding retrograde modes are not observed. The variation of the nightly $|m|$-ν diagrams is dominated by an alternating amplitude between the two modes.

Our estimate of the oscillation amplitude (6.5 km s^{-1}), is close to what would be expected, given a photometric amplitude of 0.07 magnitudes (Danziger & Dickens 1967), and a typical ratio of radial velocity amplitude to photometric amplitude of about 92 km s^{-1} per magnitude (Breger 1979). This velocity amplitude is about 70% of the photospheric sound speed, given the effective temperature $T_e = 7130$ K. For an oscillation frequency of 70 μHz it corresponds to a displacement amplitude of about 15,000 km, or about 0.0075 of the stellar radius.

The presence of only a few modes of similar intrinsic frequency might be explained by a narrow overlap in frequency between the excitation mechanism bandwidth and the rich spectrum of possible modes. On the other hand, the absence of the corresponding retrograde modes suggests the presence of some interaction with the rotation that would impede the growth of retrograde modes (as might be caused by a strong increase of the rotation velocity with depth). Finally, the alternating modal amplitude suggests any of three possibilities: (1) the coherence time is not longer than about a day and the alternation of amplitudes is purely coincidental; (2) we are seeing the interactions of unresolved mode beating; or (3) the amplitude modulation is caused by some form of mode coupling.

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