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EVIDENCE FOR GLOBAL OSCILLATIONS IN THE K2 DWARF EPSILON ERIDANI

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ABSTRACT

We have obtained evidence of global p-mode oscillations in the K2 V star ε Eri (HD 22049), based on observed time variations in the Ca II H and K emission lines. Power spectra of time series of Ca II intensity measures reveal a number of peaks, spaced at about 86 and 172 μHz. The 172 μHz spacing is significantly larger than the corresponding spacing (136 μHz) observed for solar p-mode oscillations but is in excellent agreement with predictions for a star of the known radius of ε Eri ($R/R_\odot \approx 0.81$). The amplitude of the oscillations seen in the H and K flux of this chromospherically active star is much larger than in the Sun. Peak power in the H and K fluctuations occurs at periods near 10 minutes, in contrast to predictions of peak oscillation amplitude near 4 minutes for a K2 dwarf.

Subject headings: Ca II emission — stars: chromospheres — stars: individual — Sun: oscillations

I. INTRODUCTION

The search for stellar analogs for the solar "5-minute" oscillation has been under way for several years (e.g. Traub, Mariska, and Carleton 1978; Baliunas *et al.* 1981; Smith 1982, 1983), stimulated in part by the great success of current solar oscillation investigations. Many of the important results of solar oscillation studies have been derived from observations in disk-integrated sunlight—that is, observations of the Sun as a star. These reveal the frequencies of acoustic, or p-modes of oscillation of low angular degree, $l = 0, 1, 2,$ or 3 (cf. Christensen-Dalsgaard and Gough 1980). The same techniques should be applicable to other stars as well. Unfortunately, the observed amplitude per mode of the disk-integrated solar velocity oscillations (the usually measured quantity) is less than 0.3 m s^{-1} (Grec, Fossat, and Pomerantz 1983), which is beyond the range of conventional capabilities for differential radial velocity measurements on even bright stars.[3]

Solar "5-minute" oscillations are also visible in the intensities of the Ca II H and K lines, which show the same spectrum of spatial and temporal fluctuations seen in the familiar "κ-ω" diagram of velocity oscillations (Kneer and von Uexküll 1983). Scaling the few percent amplitude of the spatially resolved Ca II K intensity fluctuations (Jensen and Orrall 1963) by the ratio of the disk-integrated velocity amplitude of low-degree modes (~ 0.3 m s^{-1}) to the spatially resolved velocity amplitude (~ 0.3 km s^{-1}; Leighton, Noyes, and Simon 1962), one estimates the disk-integrated intensity amplitude of solar low-degree p-modes in Ca II to be only a few times 10^{-5}. However, the H and K lines are greatly enhanced in chromospherically active stars, and it is possible that the chomospheric response to the p-mode oscillation is enhanced as well. Indeed, preliminary indications of chromospheric oscillations in the active-chromosphere K2 dwarf ε Eri were reported by Baliunas *et al.* (1981). Furthermore, statistically significant moment-to-moment fluctuations in the H and K flux of ε Eri were noted in the data reported by Vaughan *et al.* (1981). Therefore we have obtained several continuous 6 hr observations of this star in search of evidence for p-mode oscillations.

II. OBSERVATIONS AND ANALYSIS

The observations were made using the HK Photometer on the 60 inch (1.5 m) telescope at the Mount Wilson Observatory on four different nights. The quantity measured, S, is proportional to the chromospheric emission in nominally 1 Å bands centered on H and K, normalized to the emission in 20 Å "continuum" bands to the red and violet of H and K (Vaughan, Preston, and Wilson 1978). Data were obtained as 60 s integrations at intervals of about 67 s, over a 6 hr period of time. The data for the first night, 1982 October 13, are plotted in Figure 1a. While the data appear quite noisy, there is a hint of oscillatory behavior with period near 10 minutes. The autocorrelation function (Fig. 1b) reflects this through a marginally significant peak near 10 minutes.

In the Sun, the oscillations were discovered because their power exhibits a rather broad peak at 5 minutes, but their character as global p-mode oscillations was demonstrated only later by observing their normal mode structure. Similarly, stellar p-mode oscillations would be indicated, not by the presence of peaked power near a particular period, but by the appearance of multiple peaks in the power spectrum, regularly spaced in frequency. Specifically, the globally averaged p-mode spectrum contains peaks of power at $\nu = \Delta\nu_0[n + \frac{1}{2}l + \varepsilon] + \cdots$, where n is the number of nodes in the radial direction, l is the degree of the Legendre polynomial describing the mode structure at the surface, and ε is a small correction term. In this equation

$$\Delta\nu_0 = \left[2\int_0^R dr/c(r)\right]^{-1},$$

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[3] However, see *Note added in proof*.

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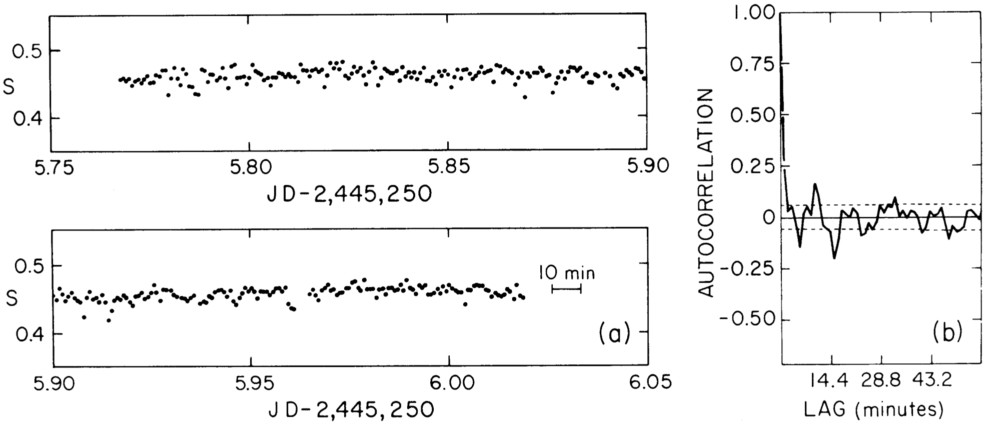

FIG. 1.—(*a*) Sky-corrected HK flux index *S*, observed at 67 s intervals for 6 hr on 1982 October 13. (*b*) Autocorrelation function of the data set in Fig. 1*a*; the dashed lines give 1 σ error estimates for the peaks in the autocorrelation function (see Baliunas *et al.* 1983).

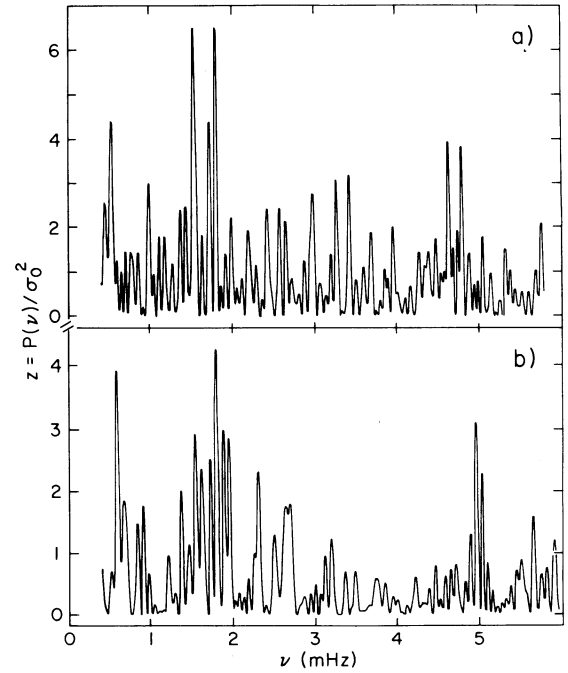

FIG. 2.—(*a*) Power spectrum of the data of 1982 October 13 (Fig. 1*a*). (*b*) Power spectrum from the data of 1983 November 29. In both spectra power is plotted in units of the variance σ^2 of the data, listed in Table 1.

where $c(r)$ is the sound speed in the interior and R is the stellar radius. As already stated, only modes with $l = 0, 1, 2$, or 3 survive surface cancellation effects to any significant degree. Thus the peaks in the p-mode power spectrum should have nearly uniform spacing of $\Delta\nu_0/2$, with peaks of even order alternating with peaks of odd order.

For the Sun, $\Delta\nu_0$ is observed to be about 135 μHz, very close but not quite identical to values predicted from solar interior models (Ulrich and Rhodes 1983). Calculations performed by J. Christensen-Dalsgaard (1984, personal communication) indicate that for stars of similar age on the lower main sequence, $\Delta\nu_0 R/R_\odot \approx$ constant, approximately independent of spectral type. For the zero-age main sequence, $\Delta\nu_0 R/R_\odot \approx 145$ μHz, while for stars evolved to the age of the Sun, $\Delta\nu_0 R/R_\odot \approx 137$ μHz. For ε Eri, Lacy (1977) has determined $R/R_\odot = 0.81$, with an uncertainty of about 10%. The star ε Eri is older than the zero-age main sequence, but younger than the Sun, judging by its Ca II emission and rotation rate (Vaughan *et al.* 1981). Therefore, we would expect for ε Eri that 169 $\mu\text{Hz} < \Delta\nu_0 < 179$ μHz.

Figure 2*a* illustrates the power spectrum of the 6 hr of data obtained on 1982 October 13, calculated according to the method of Ferraz-Mello (1981). Data pertinent to the observations and the power spectrum are given in Table 1. The three prominent peaks at $\nu = 1542$, 1732, and 1803 μHz, corresponding to $P \approx 10$ minutes, are related to the weakly visible quasi-periodic oscillations with 10 minute periods seen in the raw data. The two highest peaks both have power P, measured in terms of the variance σ^2 of the data, given by $z = P/\sigma^2 = 6.5$. This power corresponds to that of a pure cosine wave of amplitude 0.006 times the mean value of the S index for ε Eri on the night of the observation.

Whether there is a preferred spacing of the individual peaks in the power spectrum may be explored by calculating its normalized autocorrelation function in frequency space, following a similar treatment of solar data (Scherrer *et al.* 1983). The autocorrelation function for the 1982 October 13 data is shown in Figure 3*a*. The first subsidiary peak may be identified with the spacing $\Delta\nu_0/2$ and the second with $\Delta\nu_0$; we see that $\Delta\nu_0 \approx 170$ μHz, in very good agreement with predictions. The three high peaks in the power spectrum of Figure 2*a* may then be interpreted as global p-modes described by (in order of increasing frequency) $2n + l = k$, $k + 2$, $k + 3$, where k is an integer whose precise value is unknown but is close to $1542/85 \approx 18$.

We may estimate the statistical significance of the individual peaks in the power spectrum of Figure 2*a*, using the false alarm probability described by Scargle (1982). This is the probability that somewhere in the power spectrum of a random Gaussian data set with the same variance as the observed data, a peak would occur with height equaling or exceeding the highest peak observed. For the data in Figure 2*a* the false alarm probability for the highest peak, with $z = 6.5$, is about 21%. The probability of two or more peaks in a random data set with the same variance exceeding this value, as they do in the spectra of Figure 2*a*, is estimated using Scargle's methods

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TABLE 1

DATA FOR ε ERIDANI OBSERVATIONS INDICATING p-MODE OSCILLATIONS

Parameter	1982 Oct 13	1983 Nov 29
Time range (JD-2,445,000)	255.768–256.019	667.707–667.937
No. of data points, N_0	321	290
Variance $\sigma^2 = \langle(\Delta s/s)^2\rangle$	0.938×10^{-4}	1.222×10^{-4}
Significant power spectrum near P = 10 minutes (in μHz)	1542	1540
	—	1615
	1732	1721
	1803	1795
	—	1883
	—	1949

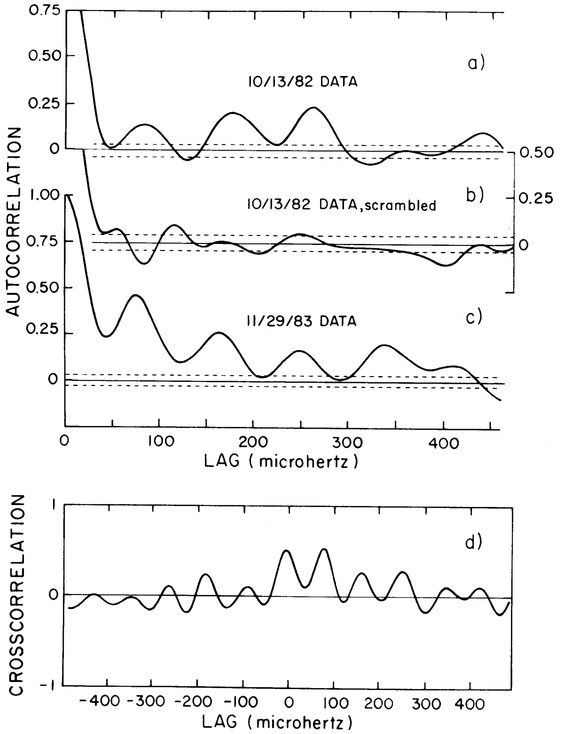

FIG. 3.—(a) Autocorrelation of the power spectrum of Fig. 2a. In this and the two panels immediately below, the dashed lines give 1 σ error estimates (see Baliunas *et al.* 1983), and the range of the power spectrum over which the autocorrelation function is calculated is 0.25 mHz $< \nu <$ 6 mHz. (b) Autocorrelation of the power spectrum obtained from random scrambling of the data set of Fig. 1a. (c) Autocorrelation of the power spectrum of Fig. 2b. (d) Cross correlation of the power spectra of Figs. 2a and 2b, in the range 1.2 mHz $< \nu <$ 2.9 mHz.

to be 2.6%. While this probability is relatively small, it is by itself not convincing. However, the suggestive spacing of the three highest peaks led us to make a deeper study.

First, we scrambled the observed data points, by randomly reassigning them to the actual observation times. This reassignment preserves the window function and the variance of the data but destroys any periodic signals which might be present. In 10 trials, calculation of the power spectrum and its autocorrelation function (cf. Fig. 3b) never produced the periodicity in the autocorrelation (or height of autocorrelation peaks) seen in the actual data (Fig. 3a). In some scrambled cases (cf. Fig. 3b) there appeared a weak periodicity in the autocorrelation function at a period corresponding to the sidelobe spacing $1/T = 46$ μHz, caused by the finite observing interval T. Standard apodization techniques were successful in reducing these sidelobe peaks, without affecting the peaks in the true data. However, in order to derive the maximum frequency resolution of the data strings, we calculated the power spectra and autocorrelation functions in Figures 2 and 3 using unapodized data.

A further test of the reality of the detection would be provided by a repeat detection of peaks at the same spacing and same absolute frequencies. A second run on 1983 October 22 produced no detectable signal. On these dates, the S index for ε Eri was $S = 0.60$, nearly the highest value ever recorded for this star since 1966 (cf. Wilson 1978). It is possible that the extraordinarily high activity level on the star at this time caused the amplitude of the oscillation signal in the H and K lines to decrease, or the level of stochastic fluctuations to increase, so the nondetection of the oscillation in our second run does not in itself negate the apparent detection in the first run.

A third observation was obtained on 1983 November 29; relevant data are included in Table 1. This observation once again yielded power spectra with evenly spaced peaks near a period of 10 minutes (Fig. 2b). We note that (a) the spacing of the peaks, indicated by Figure 3c, is essentially the same as for the 1982 October 13 data; and (b) the three most significant peaks in the 1982 October 13 data coincide in absolute position, to well within the resolution of the data ($1/T \approx 50$ μHz), with three of the prominent peaks in the 1983 November 29 data (see Table 1). The mean frequencies of these three peaks are 1541 ± 5 μHz, 1727 ± 5 μHz, and 1799 ± 5 μHz, where the quoted uncertainties are $2^{-1/2}$ times the average of the three differences between the measured positions.

To investigate the source of the frequency differences listed in Table 1, we created artificial data with known frequencies, and power equal to that of the observed peaks, combined with noise whose variance equaled that of the observational data. The rms deviation of the measured spectral peaks from their true values was about 10 μHz. Thus the differences quoted above could be due entirely to the low signal-to-noise ratio of the data.

The power in the highest peak in the November 29 power spectrum, measured in units of the variance of the spectrum, is $z_{\max} = 4.28$. The probability of a peak with this or greater power occurring somewhere in the power spectrum of random noise with the same variance is high (0.87). The probability of a peak of this height being the highest *and* coinciding with the highest peak of the 1982 October 13 data to within the 50 μHz resolution, as in fact occurred, is only 0.002, and the probability of coincidence to a few μHz (Table 1) is even smaller. Again, scrambling of the data caused the preferred spacing of the peaks to disappear, so that the autocorrelation function of the scrambled power spectrum shows no clear repetitive subsidiary peaks like those in Figure 3c.

Figure 3d shows a cross correlation between the power spectra of Figures 2a and 2b. There is very significant modulation at a period of 86 μHz, as measured by least squares fitting of the seven peaks in the range (-300 μHz $< \Delta\nu <$ 300 μHz). This period should correspond to $\Delta\nu_0/2$, so that $\Delta\nu_0$ =

172 μHz. The shift in frequency, measured as the offset from zero of the central peak in Figure 3*d*, is only 6 μHz, again insignificant compared to the resolution of the data ($1/T = 50$ μHz, where $T = 1.99 \times 10^4$ s is the shorter of the two observations).

The frequency splitting $\Delta\nu_0 = 172$ μHz is our best estimate of the basic *p*-mode splitting. With this value of $\Delta\nu_0$, the rms deviation of the nine spectral peaks listed in Table 1 from a linear fit with slope $d\nu/dn = \Delta\nu_0$ is 8.4 μHz, in good agreement with the rms deviation of 10 μHz estimated above to be caused by noise in the data.

A fourth night of observations of ε Eri was obtained on 1983 December 29. These data fail to show the oscillation, in spite of the fact that observing conditions were good, and the value of the *S* index for the star was normal. It appears that either the amplitude of the phenomenon is time variable, or that our sensitivity to *p*-mode oscillations is sufficiently marginal that they are not always detectable.

In both spectra illustrated in Figure 2, other peaks occur near 5 mHz. These are not, however, reproduced in position in the two spectra and are of relatively lower statistical significance. The isolated peaks near 0.6 mHz ($P \approx 28$ minutes) occur at approximately the same frequency in both spectra and could be due to some unknown instrumental periodicity. Such an explanation, however, would seem unlikely to explain the regularly spaced sequence of peaks listed in Table 1.

III. DISCUSSION

The observations reported here need confirmation, even though we regard the coincidence of two separate measurements of frequencies of the highest spectral peaks, and of $\Delta\nu_0$, to be rather suggestive. If the data do reflect global *p*-mode oscillations with $\Delta\nu_0 = 172$ μHz, the following points should be emphasized.

1. The frequency $\Delta\nu_0$ is remarkably close to the predictions based on scaling from solar models to a star with the independently determined radius of ε Eri. This increases the confidence in the detection. It also suggests that radii of similar stars may be determinable by oscillation measurements, with an accuracy of a few percent or better. In addition, the measurement of individual *p*-mode frequencies can in principle provide important, and perhaps unique, information on depth-averaged structures or even dynamics in the interior.

2. The fractional amplitude of the oscillation modes seen in the H and K lines in ε Eri is of the order of a few times 10^{-3}. This is approximately two orders of magnitude larger than that expected for the Sun. It implies either that the velocity oscillations in the photosphere are extremely high in amplitude compared to their counterparts in the Sun, or that the response of the chromospheric emission to a given amplitude of photospheric velocity oscillations is much higher than for the Sun. Such behavior could be related to the extremely high level of mean chromospheric emission in ε Eri compared to the Sun.

3. The period of peak power, observed to be near 10 minutes on each of two nights, differs from the prediction that peak power should occur at about 4 minutes (Christensen-Dalsgaard and Frandsen 1983). These predictions are based on an assumed coupling of convective and oscillatory modes, but there is a great deal of uncertainty about the nature of the coupling mechanism. If the period of peak power can be measured for many stars, the data should give us better insights into the detailed excitation mechanism of solar and stellar oscillations.

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Note added in proof.—Very recently, Fossat *et al.* (1984, *ESO Messenger*, No. 36, p. 20) have reported the detection of "5 minute" velocity oscillations in α Cen using an optical resonance spectrometer.

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