Doppler Imaging of Stellar Oscillations: Multi-Site Observations of Epsilon Cephei

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Abstract. We investigate the oscillation properties of ϵ Cep using a series of specialized techniques designed to extract and analyze time variations in absorption line profiles. To obtain the necessary temporal coverage for this investigation, multi-site observations were collected at 3 sites (China, France, Arizona) all equipped with high-resolution échelle spectrographs. From these observations, we find evidence for a very rich spectrum of modes in ϵ Cep.

1. Introduction to Epsilon Cephei

Epsilon Cephei is a bright, rapidly-rotating, multi-periodic δ Scuti star. As such, this star is an interesting candidate for stellar seismology studies, as information about the star's structure could potentially be derived from its oscillation properties. In particular, low- and high-degree nonradial modes ($\ell = 0$ to 20) could be detected as line-profile variations in spectroscopic time-series observations.

Based on photometric and parallax observations, we have identified ϵ Cep as an $M = 1.8 \pm 0.2 M_\odot$ main sequence star about halfway through its main hydrogen-core burning stage. The rotation period of the star is estimated to be $\Omega \sin i = 0.94 \pm 0.04$ days (where i is the unknown inclination of the star).

2. Multi-Site Observations of Epsilon Cephei

In 1997 September, we observed ϵ Cep with the goal of obtaining continuous, high-resolution, spectroscopic observations lasting several days. Three sites par-

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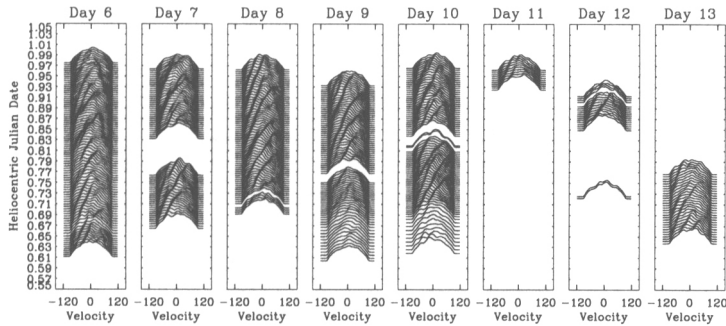[8] Currently at Atmospheric and Environmental Research, Inc., Cambridge, MA.

Figure 1.   The time-series of broadening functions derived from the FLW observations of ϵ Cep using the Doppler Deconvolution technique. The profiles are plotted as a function of Doppler shift and time relative to HJD 2450 700 and have been normalized to unit area. Patterns of variation owing to the oscillations of the star can be seen as bumps which travel through the profiles.

ticipated in the ϵ Cep campaign: the Xinglong Observatory in China (XLG), the Observatoire d'Haute Provence in France (OHP), and the Fred Lawrence Whipple Observatory in Arizona (FLW). Each site was equipped with a high-resolution ($R \simeq 40\,000$) échelle spectrograph providing an overall coverage between 3300 and 7000 Å. The observations were very successful. Exposure times were kept under 10 minutes and yielded signal-to-noise values of 100 to 300. By combining the data sets, a frequency resolution of 0.144 cycles day^{-1} was achieved and the amplitude of the aliases in the Fourier window function that result from regular gaps in the coverage were significantly reduced.

3.   Analysis Techniques

A series of specialized techniques were used to extract and analyze the patterns in the ϵ Cep échelle data. These techniques are described in greater detail by Kennelly et al. (1998).

3.1.   Doppler Deconvolution of Line-Profile Variations

We used the Doppler Deconvolution method to obtain a measure of the line-profile variability of ϵ Cep. The procedure was as follows.

- Derive a model of the intrinsic spectrum of the star $\psi(v)$ from the time-averaged observed spectrum $\bar{\phi}(v)$ and the rotational broadening function $R(v)$: i.e., solve $\bar{\phi}(v) = R(v) * \psi(v)$. A synthetic spectrum generated from a model atmosphere was used as the initial guess.

- Model the observed spectra $\phi(v, t)$ as the convolution of the derived narrow-line intrinsic spectrum $\psi(v)$ and a time-dependent broadening function $B(v, t)$: i.e., solve $\phi(v, t) = B(v, t) * \psi(v)$. The rotational broadening function was used as a first guess.
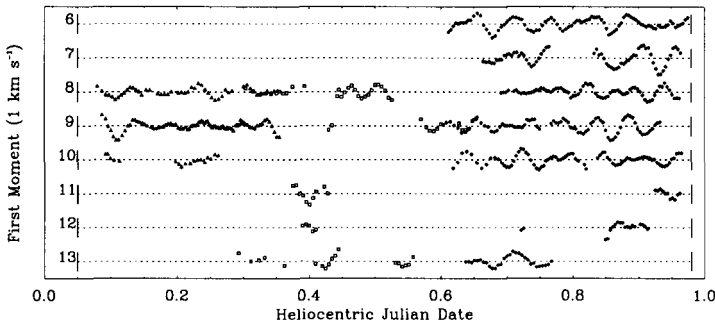
Figure 2. The variation in the first moment of the ϵ Cep broadening functions. The figure shows the results from XLG (triangles), OHP (squares), and FLW (diamonds) as a function of HJD for each day of observation. The amplitude of the axes represents 1 km s^{-1}. In the few instances where observations from different sites overlap, agreement between the measurements is very good.

The resulting time-series of broadening functions provides a very accurate measure of the patterns of line-profile variability. Fig. 1 illustrates the results obtained at FLW. To study the low-degree modes of oscillation ($\ell \leq 3$), we analyzed the variation in the first three moments of the broadening function profiles (Fig. 2). To study higher-degree modes, the Fourier-Doppler Imaging technique was used.

3.2. Fourier-Doppler Imaging

We used the Fourier-Doppler Imaging technique to decompose the patterns of line-profile variation into Fourier components that could be more readily interpreted in terms of modes and frequencies. The procedure was as follows.

- Remap the time-variable component of the broadening function $\tilde{B}(v,t)$ from velocity to "Doppler space", i.e., $\tilde{B}(v,t) \rightarrow \tilde{B}(\phi,t)$, using the relation $\phi_i = \sin^{-1}(v_i/v\sin i)$.

- Compute the two-dimensional Fourier transform of $\tilde{B}(\phi,t)$ and corresponding amplitude spectrum.

The resulting two-dimensional Fourier spectrum is illustrated in Fig. 3.

3.3. Two-Dimensional Frequency Analysis

Finally to identify the dominant modes and frequencies, we fit sinusoids to the residual broadening functions, using a two-dimensional frequency analysis. The procedure was as follows.

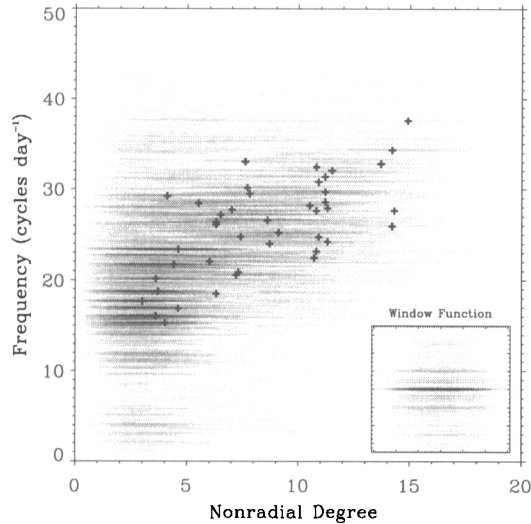- Identify a peak from the two-dimensional amplitude spectrum.

Figure 3. The two-dimensional Fourier amplitude spectrum and frequency analysis of ϵ Cep. The spectrum was computed using the Fourier-Doppler Imaging technique by transforming the time-variable component of the broadening functions in Doppler space and time. The window function for the spectrum is illustrated as an inset. The frequencies identified by the two-dimensional frequency analysis are indicated as crosses.

- Use the nonlinear Levenberg-Marquardt least-squares method to determine the frequencies, amplitude, and phase.

- Subtract the fitted function from the data and calculate the amplitude spectrum of the residuals.

- Identify additional frequencies and repeat the fitting procedure

The measured frequencies are indicated as crosses in Fig. 3. Modes with degrees ranging up to $\ell = 15$ have been identified. We find that the frequencies tend to increase with nonradial degree. This can be explained as a contribution owing to the rotation of the star if the observed modes are prograde and have similar frequencies in the corotating frame.

References

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