ASTEROSEISMOLOGY OF β CEPHEI

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Abstract. We discuss the oscillation features of β Cephei, which is a magnetic star in which the magnetic axis seems to be oblique to the rotation axis. We interpret the observed equi-distant fine structure of the frequency spectrum as a manifestation of a magnetic effect on an eigenmode, which would be a radial mode in the absence of the magnetic field. Besides these frequency components, we interpret another peak in the frequency spectrum as an independent quadrupole mode. By this mode identification, we deduce the mass, the evolutionary stage, the rotational frequency, the magnetic field strength, and the geometrical configuration of β Cephei.

Since many of the β Cephei-type stars show multi-periodic pulsations, it is expected that a lot of information can be extracted from the pulsations of these stars. Telting et al. (1997) investigated the line-profile variability of β Cephei in detail by means of an extensive data set of high-resolution, high S/N spectra obtained at the Observatoire de Haute Provence during one month, and deduced that the variations show periodicity with at least five frequencies. Three frequencies among them are separated from the main frequency $f_1 = 5.250$ day^{-1} by $-2/6$ day^{-1}, $-1/6$ day^{-1}, and $+1/6$ day^{-1}, respectively. Hence, we regard the four peaks (and the small peak at $f_1 + 2/6$ day^{-1}) as part of a frequency quintuplet with equal spacing. The central frequency f_1 has been identified as the radial pulsation mode. Besides the variations in the luminosity and in the velocity field, a magnetic field has been detected and the field strength seems to vary with a period of 6 or 12 days (Rudy & Kemp 1978). Furthermore, the UV-wind lines of this star reveal a periodic variation with a 6 or 12 day period (Henrichs et al. 1993). Hence we conclude that the magnetic field of β Cephei is oblique to the rotation axis, and that the star rotates with a period of 6 or 12 days. We interpret the quintuplet fine structure found by Telting et al. (1997) as a manifestation of a magnetic perturbation of a radial mode. We assume that the dominant component of the magnetic field is dipolar, and that the effect of the magnetic field on the oscillations is stronger than that of the rotation of the star. Being influenced

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by such a strong magnetic field, the eigenmode, which would be a pure radial mode in the absence of a magnetic field, is deformed to have an axially symmetric quadrupole component, whose symmetry axis coincides with the magnetic axis. Hence, the eigenfunction is characterized by means of a superposition of the spherical harmonic with $\ell = m = 0$ and that of $\ell = 2$ and $m = 0$ with respect to the magnetic axis (Shibahashi 1994). The aspect angle of the pulsation axis varies with the rotation of the star. Therefore, the contribution of the quadrupole component of the eigenfunction to the apparent variation changes with time and produces a quintuplet fine structure with an equal spacing of the rotation frequency in the power spectrum. Hence we conclude that the star is rotating with a period of 6 days rather than 12 days. The relative ratios of the side-peak amplitudes to the central peak amplitude depend on the strength of the magnetic field. On the other hand, the relative ratios among the side-peak amplitudes are dependent on the geometrical configuration of the star, — that is, the angle between the magnetic axis and the rotation axis, β, and the angle between the rotation axis and the line of sight, i. By analyzing the amplitude ratios, we estimate $\tan\beta \tan i \simeq 3$. The factor $\tan\beta \tan i$ can be independently estimated from the variation in the magnetic field strength, and the result is consistent with the estimation from the pulsation power spectrum.

The second highest peak $f_2 = 5.380$ day^{-1} in the power spectrum has been identified by Telting et al. (1997) as a mode with $\ell = 2$. We assume that f_2 belongs to a quadrupole axisymmetric mode with respect to the magnetic axis. The magnetically induced fine structure of this mode is undetectable, since the amplitude of the f_2 component is much smaller than the one of the radial component. Since we have two independent frequencies, f_1 and f_2, we can identify the evolutionary stage of the star. The candidates are (i) a $\sim 18M_\odot$ star at the middle of the hydrogen core-burning phase, (ii) a $\sim 12M_\odot$ star near the turning point, (iii) a $\sim 9M_\odot$ star at the late stage of the hydrogen core-burning phase. The oscillation mode f_1 is identified as the radial fundamental mode in the case (i) or (iii). On the other hand, it is identified as the radial first harmonic in the case (ii). Case (i) seems unlikely because of the high mass required. Though case (ii) cannot be ruled out, we think case (iii) is more likely because the radial fundamental mode is more easily excited. The radius of the star for case (iii) is estimated from the stellar evolution calculation as $R \simeq 6.5R_\odot$. Since $2\pi/\Omega = 6$ day and $V_e \sin i \simeq 25$ km/s, this means $i = 30°$. Combining this with $\tan\beta \tan i \simeq 3$, we obtain $\beta \simeq 80°$. We have calculated the theoretically expected power spectra and compared them with the observations. A magnetic field strength of 800 G and the geometrical configuration described in the above lead to a reasonable fit.

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