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NRP Modeling of the Line Profile Variations of λ Eri in the 1994 Campaign

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Abstract. We report attempts to model the observed line-profile variations (*lpv*) of λ Eri during a productive spectroscopic and photometric campaign in 1994 November. We find that none of the nonradial pulsation spheroidal modes with $m = -1$ — -3 could explain the *lpv* associated with the dominant 16.9 hr period since the horizontal velocity components and the temperature variations dominate the *lpv* for such modes. In contrast, certain tesseral toroidal modes can reproduce the observed *lpv* well both for the main 16.9 hr period and the 6.45 hr period.

1. Introduction

The *lpv* in λ Eri stars is suspected to play an important role in studying the Be phenomenon. However, it is controversial between the non-radial pulsations (NRP) hypothesis and the rotational modulations (Balona 1990, 1995, Gies 1996). To try to resolve it, we have organized international campaigns of λ Eri in 1994 February and November at Okayama, Rohzen, Crimea, Ondrejov, Haute Provence, ESO/CAT, Toledo, Atlanta, Brazil, Dominion (spectroscopy) and at Dodaira, Rohzen, SAAO, Valencia, UNAM, Mt. Hopkins (photometry) and at the Limber Observatory (polarimetry). In our preliminary report (Kambe et al. 1998), we found that at least two periods exist in more than four observing runs. Although many transient features are also observed in the star (Smith et al. 1989), we concentrate herein on modeling the periodic component of *lpv*, trying to see if they can be understood within the framework of the current NRP hypothesis. An extensive analysis of the campaign data will appear in a separate paper.

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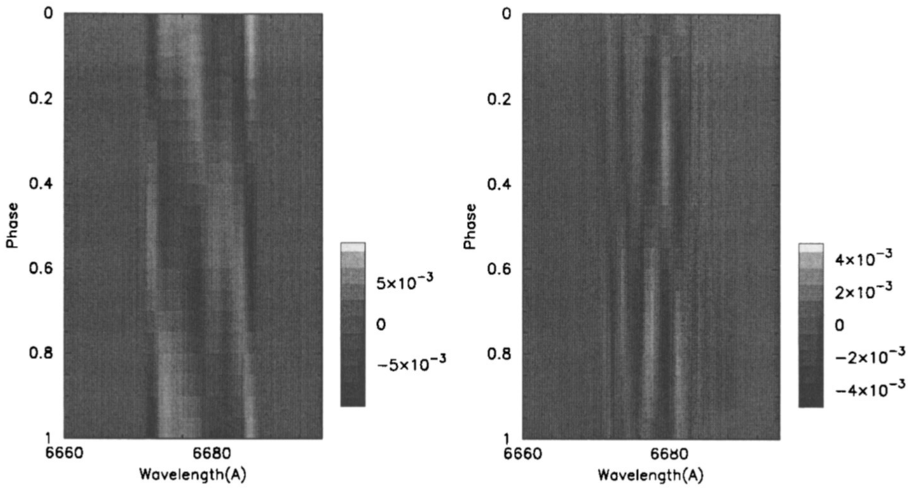

Figure 1. Each frequency component of the observed *lpv* in 1994 November; (a) for the 16.9 hr period; (b) for the 6.45 hr period.

2. Observed *lpv*

In Figure 1, we plotted the each frequency component of the observed *lpv* (HeIλ6678 line) for the well-known 16.9 hr period and the newly found 6.45 hr period during a productive campaign in 1994 November. The observed pattern (or bumps) of both frequency components is regular but very complicated, separating, merging, disappearing, and appearing at certain phases. This is in sharp contrast to the *lpv* in ζ Oph and ϵ Per in which bumps travel continuously from blue to red. Although the *lpv* pattern is not simple, it is a global pattern, which hints that NRP is the cause of the variations.

In this paper, we examine whether NRP can reproduce the observed features of the *lpv* mainly by comparing the observed and the theoretical gray maps. The method is primitive but still powerful since such features cannot be easily recognized by the period analyses commonly used.

3. Basic Stellar Parameters and *lpv* Calculations

For our models we used a value $T_{\rm pol}$ =24000K, which combined with $B-C$=−2.2, the HIPPARCOS parallax, gives a stellar radius of $R(\equiv R_{\rm eq})$=10.5$R_\odot$. The stellar mass is estimated to be 13$M_\odot$ from Schaller et al. (1992). Since the radius is too high for the main sequence B2IVe star, we also use the model with M=12$M_\odot$ and $R_{\rm eq}$= 7$R_\odot$ (Smith et al. 1991). However, the result is almost the same for both models. We also assume the inclination angles is 45° $\sim$ 90°.

We use the BRUCE code (Townsend 1997) to calculate the *lpv*'s caused by spheroidal modes. BRUCE is a linear NRP code and implements the velocity, temperature, and geometric perturbations computed from rotationally modified eigenfunctions by Lee & Saio (1986, 1990). Here, we assume NRP are adiabatic.

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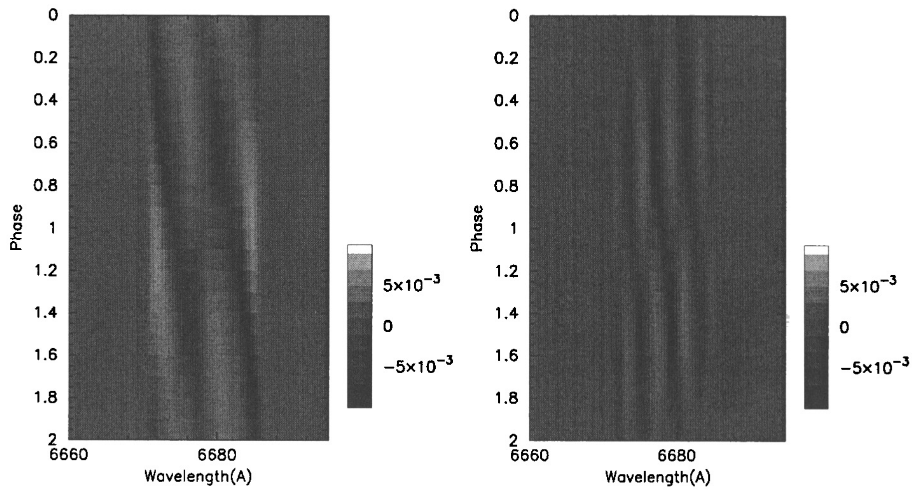

Figure 2. The example of toroidal modes which reproduce similar *lpv* to those observed; (a) l=5, m=2 mode for the 16.9 hr period; (b) l=9, m=5, for the 6.45 hr mode. In these cases, an inclination angle of 45° is assumed.

We used a Kurucz model atmosphere (1994 CD-ROMs) and SYNSPEC code (Hubeny 1988) for the line synthesis of He I λ6678.

For the toroidal modes, we modified the Kambe & Osaki (1988) code so that it can calculate the *lpv* due to tesseral toroidal modes.

4. Results

Although the observed *lpv* can be explained by the radial velocity component of l=4, m=−2 mode as suggested by Kambe et al. (1998), it requires a radial velocity amplitude of 50 km s^{-1}. In addition, for low-frequency modes, the horizontal velocity components and the temperature perturbations dominate the *lpv* and their features are quite different from the observed ones. In fact, the bumps travels continuously from blue to red when temperature perturbations are important for the *lpv*. The situation is basically the same for m=−1 and m=−3 modes which have slightly shorter pulsation periods ($\gtrsim$ 15 hr) and thus smaller k values (2 – 3).

Kambe & Osaki (1988) showed that some toroidal modes can reproduce the observed *lpv* about as well as spheroidal modes can. For this data set we found that some m=2, 3 tesseral toroidal modes could reproduce *lpv* similar to the observed variations with the 16.9 hr period (*e.g.*, l=5, m=2, V_{tor}= 150 kms^{-1}; Fig. 2a). [Note in this example that the detailed pattern is still different between the observed *lpv* and and the theoretical models.] The complicated *lpv* with a period of 6.45 hr could also be reproduced by the tesseral modes (*e.g.*, l=9, m=5; Fig. 2b).

5. Summary and Discussion

In λ Eri, it is unlikely that spheroidal modes can explain the observed *lpv* with a period of 16.9 hr since the temperature and horizontal velocity perturbations will dominate the *lpv*. In contrast, tesseral toroidal modes are found to be capable of explaining the observed *lpv*.

Toroidal modes with small m can naturally explain why the observed periods are close to the rotation period in many λ Eri stars $[\sigma_{obs} = (\frac{2}{l(l+1)} - 1)m\Omega_{rot}]$. The other observed features like the doubling of the periods (by switching $m = 1 \Leftrightarrow m=2$) and the existence of relatively small number of modes can be understood by toroidal modes. The modes are also promising in that they have small, if any, temperature perturbations. [However, to explain the observed photometric variations, the eigenfunctions with higher order correction terms by rotation may be taken into account.]

It is one of drawbacks against the toroidal mode hypothesis that no convincing excitation mechanism is found so far. The Be phenomenon may not be directly explained by the toroidal modes since they are retrograde. At present, it is not clear whether there is any relation among the periodic variations, the transient features, and the high energetic phenomenon (magnetic activities?) in Be stars (Smith & Polidan 1993, Smith et al. 1997). However, we would like to emphasize here that the toroidal modes are one way of explaining the observed global and periodic variations.

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