WAVE PROPAGATION IN PULSATING STARS

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Abstract. Lissajous diagrams are used to detect phase lags between radial velocity curves associated with different ions. Present in many kind of variable stars, this effect provides an important tool to study the atmosphere dynamics.

1. Introduction

Although the internal structure of pulsating stars is usually well described, their atmosphere is not so easy to model, due to the large set of parameters required. For instance, the pulsation energy may be modulated because of non-adiabatic effects (photon losses). Therefore, the knowledge of the dynamical status of the photosphere is important, particularly considering the boundary conditions. Indeed, the wave can be totally reflected at the outer boundary of the star (stationary wave) or be partially transmitted to other physical regions (such as the chromospheres and the coronae). This latter case, involving running waves, can now be deduced from spectroscopic observations for many kinds of stars, spread all over the HR diagram.

In the β Cephei star β CMa, Van Hoof & Struve (1953) observed a difference between the variations of the radial velocity curves corresponding to metallic lines and those corresponding to Balmer ones. This particular differential behavior has been called the Van Hoof effect, and is connected to atmosphere stratification. This effect may have several explanations, among which the most important are:

- a phase lag due to the propagation time of the wave between the different line forming regions.
- a variation of the pulsation amplitude depending on the physical conditions in the line forming region.

Initially discovered in \( \beta \) Cephei stars, this effect may be generalized to other pulsating star classes, providing a new tool to evaluate the atmosphere dynamics.

2. Detection of the phase lag

The easiest way to determine whether a phase-lag exists or not is to plot the radial velocity curve associated with a given line as a function of that corresponding to another one (this is called a Lissajous diagram). Such a diagram provides two important pieces of information:

- if the resulting curve (a loop) shows a width larger than the corresponding error bar, then a phase-lag exists between the two variations.
- the way the loop is drawn indicates which variation is late compared to the other. Hence, if the wave propagates outward, the stratification as a function of time of the moving atmosphere may be deduced.

When the radial velocity curves are nearly sinusoidal, a phase-lag is easily determined by plotting the Lissajous diagram, which is in this case an ellipse (Mathias & Gillet 1993).

Moreover, if it is assumed that the mean atmosphere of a low-amplitude pulsating star may be described with a static model, contribution functions of the different lines considered may be estimated and thus the corresponding forming region. Then, the average velocity of the propagation wave through the different layers can be derived (Fig. 1).

3. Other variable classes

The progressive wave phenomenon should be present in all pulsating stars, except those which have particular boundary conditions that allow standing waves. Indeed, a phase lag has been detected in various stellar classes, such as RR Lyrae (Mathias et al. 1995) and the \( \delta \) Scuti star \( \rho \) Puppis (Mathias et al. 1997).

Concerning classical Cepheids, Wallerstein (1992) observed dynamical effects related to stratification. We studied the radial velocity curves measured from different lines of the prototype Cepheid \( \delta \) Cephei. The Lissajous curve is represented on Fig. 2.

4. Conclusions

In addition to the four variable classes mentioned above, one can add the Mira stars for which Gillet (1988) was able to follow the shock wave propagation determined using the H\( \alpha \) line.