Radial and Nonradial Pulsations as Probes of Stellar Physics
ASP Conference Series, Vol. 259, 2002
C. Aerts, T.R. Bedding, & J. Christensen-Dalsgaard, eds.

Tomography of the Atmosphere of the Mira Variable Z Oph[1]

A. Jorissen[2], M. Dedecker[3]

Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles, Belgium

B. Plez

GRAAL, Université de Montpellier II, France

R. Alvarez

Observatoire Royal de Belgique

D. Gillet

Observatoire de Haute Provence, France

A. B. Fokin

Institute for Astronomy of the Russia Academy of Sciences, Moscow, Russia

Abstract. The new tomographic technique devised by Alvarez et al. (2000) to explore the velocity field across the atmosphere of long-period variable stars (LPVs) is applied to the Mira variable Z Oph. The method cross-correlates the optical spectrum with numerical masks constructed from synthetic spectra and probing layers of increasing depths. This technique reveals that the line doubling often observed in LPVs around maximum light is the signature of the shock wave propagating in the atmosphere of these pulsating stars.

1. Line-doubling statistics among LPVs

It has been known for a long time that the brightness variations of long-period variable stars (LPVs) go along with spectral changes such as the doubling of the absorption lines around maximum light (e.g., Adams, 1941; Alvarez et al.,

---

[1]Based on observations made at Observatoire de Haute Provence, operated by the Centre National de la Recherche Scientifique, France

[2]Research Associate, Fonds National de la Recherche Scientifique, Belgium; e-mail: ajorisse@astro.ulb.ac.be

[3]Boursier F.R.I.A., Belgium

https://doi.org/10.1017/S0252921100016729 Published online by Cambridge University Press

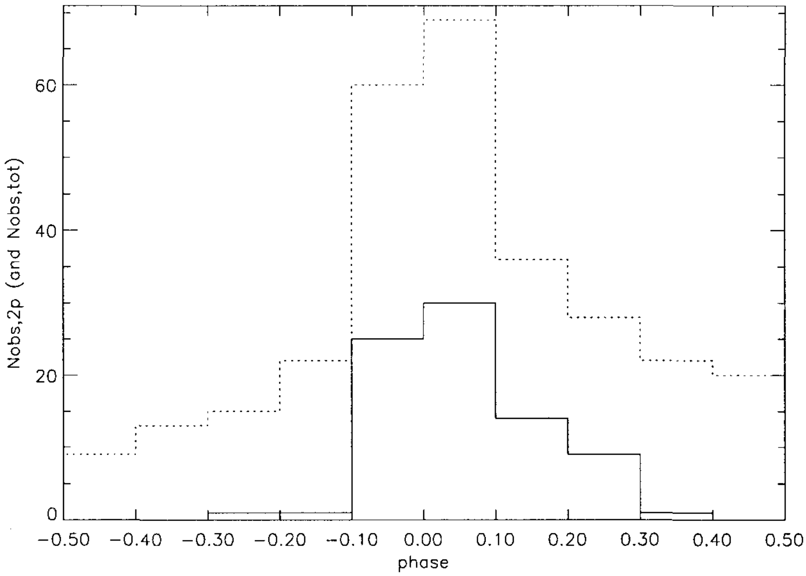

Figure 1. Statistics of the line-doubling phenomenon among 81 LPVs observed at the Haute-Provence Observatory (France) with the ELODIE spectrograph at various phases of their light cycle. Histograms are presented (i) for stars which exhibit a double or asymmetrical CCF (with a K0III template) and (ii) for the total set of observations (dashed line). See Alvarez et al. (2001b) for more details, and in particular for a discussion of possible selection effects against the detection of line doubling in LPVs with very late spectral types.

2001b and references therein). This phenomenon appears to be very common among LPVs, as shown in Fig. 1. To overcome the difficulty of studying the line profile in the very crowded optical spectra of LPVs, a cross-correlation technique has been used that correlates the observed spectrum with a spectral template mimicking a late-type giant (e.g., Queloz, 1995; Alvarez et al., 2001a). The shape of the resulting cross-correlation function (CCF) thus represents the *average shape of those lines in the observed spectrum that match the template.*

2. Tomography of the atmosphere of Z Oph

A new tomographic technique to probe the velocity field across the atmosphere of LPVs has been developed which sheds new light on the line-doubling phenomenon. The method, fully described in Alvarez et al. (2001a), cross-correlates the optical spectrum of LPVs with numerical masks constructed from synthetic spectra and probing layers of increasing depths. The CCF thus obtained reflects

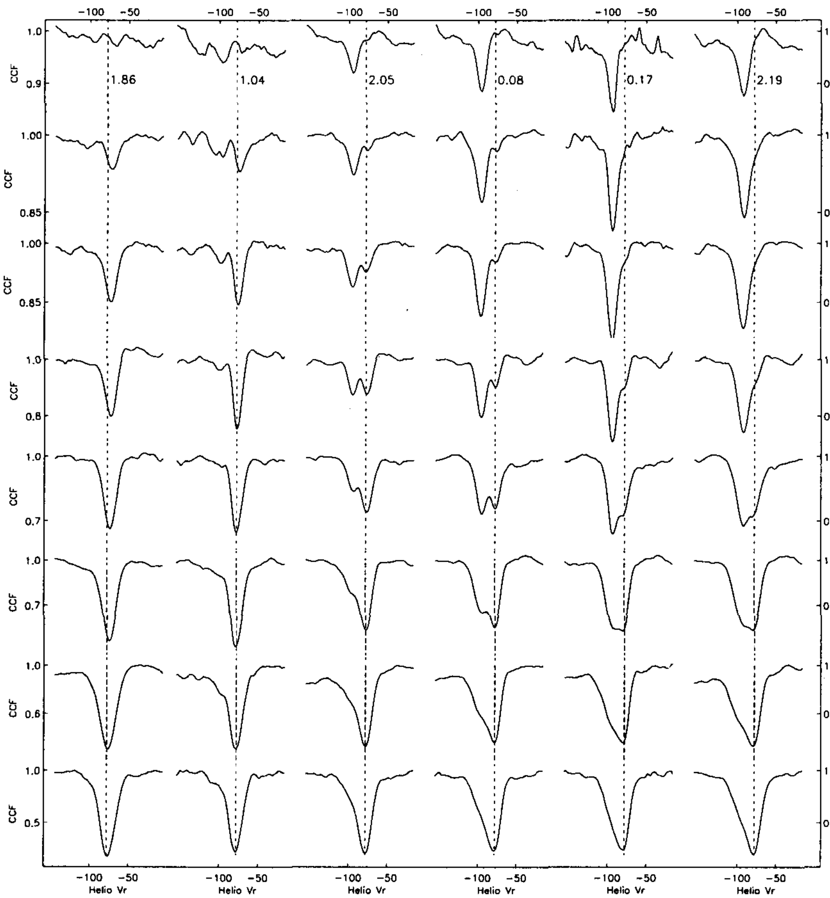

Figure 2. Sequence of CCFs probing layers of increasing depth (the bottom row corresponding to the uppermost layer) in the atmosphere of Z Oph (K3-M7, Mira with $P = 349$ d), at 6 different phases around maximum light, merging different light cycles, as indicated by the labels (see Table 3 of Alvarez et al., 2001b for a log of the observations). The CCFs were computed with the tomographic masks constructed from a synthetic spectrum with $T_{\rm eff} = 3500$ K, $\log g = 0.9$ (see Table 1 of Alvarez et al., 2001a). To guide the eye, a vertical dashed line has been drawn at a velocity of -78 km s^{-1}, corresponding to the red peak.

the average line shape and velocity in the layer probed by a given mask. The sequence of CCFs obtained with the different masks at a given phase thus reflects the evolution of the velocity field across the photosphere (vertical sequence in Fig. 2). It is clearly seen on Fig. 2 that the CCF changes from a single (red) peak in the uppermost layers (bottom row) to a double peak further inside (upper rows).

The tomographic method thus makes it possible to follow the temporal *as well as spatial* evolution of the line doubling. Fig. 2, which presents the sequences of CCFs for the Mira Z Oph obtained at six different phases around maximum light (see Alvarez et al., 2000 for a similar example involving the Mira RT Cyg), shows that line doubling occurs higher and higher in the atmosphere as time passes. In the last (rightmost) sequence (corresponding to phase 0.19), the innermost layer (top row) exhibits a single *blue* peak, indicating matter moving upward, while in the uppermost layers matter is still falling in (single *red* peak).

This behaviour is consistent with the passage of a shock wave across the photosphere, as first shown by Schwarzschild (1952) in the context of W Vir variables.

3. Future work

The major weakness of the method is that it offers no possibility so far to calibrate the respective depths of the layers probed, and hence to evaluate the velocity at which the shock propagates in the atmosphere. It is hoped that future observations combining spectroscopy and interferometry may help to perform such a calibration by deriving the stellar radius associated with the different masks.

References

Adams, W.S. 1941, ApJ, 93, 11

Alvarez, R., Jorissen, A., Plez, B., Gillet, D., & Fokin, A. 2000, A&A, 362, 655

Alvarez, R., Jorissen, A., Plez, B., Gillet, D., Fokin, A., & Dedecker, M. 2001a, A&A, 379, 288

Alvarez, R., Jorissen, A., Plez, B., Gillet, D., Fokin, A., & Dedecker, M. 2001b, A&A, 379, 305

Queloz, D. 1995 in New Developments in Array Technology and Applications, eds. A. Davis Philips, K. Janes, & A. Upgren, (Dordrecht: Kluwer), 221

Schwarzschild, M. 1952 in Transactions of the IAU, VIII, ed. P.T. Oosterhoff (Cambridge: Cambridge University Press), 811

https://doi.org/10.1017/S0252921100016729 Published online by Cambridge University Press