Mem. S.A.It. Vol. 77, 180

Memorie della

Modelling NIR molecular lines for Miras

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Abstract. The atmospheric structure of Mira variables is considerably influenced by pulsation. Molecular absorption lines in the near-infrared (NIR), especially second overtone CO lines, show therefore a characteristic behaviour in time-series of high-resolution spectra. We computed synthetic CO line profiles based on a new dynamic model atmosphere and derived radial velocities (RVs) from the Doppler shifted lines. For the first time, we could quantitatively reproduce observations of the very typical, discontinuous RV curves.

Key words. Stars: late-type – Stars: AGB and post-AGB – Stars: atmospheres – Stars: carbon – Infrared: stars – Line: profiles

1. Probing atmospheric kinematics

Mira variables are luminous late-type giants, representing stars of low- to intermediate mass in the late evolutionary stage called Asymptotic Giant Branch (AGB). Due to the low effective temperature (<3500 K), molecules can form efficiently in the outer layers and dominate their spectral appearance. Towards the end of their evolution, such stars become unstable against radial pulsations. Eventually, this leads to the condensation of dust grains in the cool atmospheres and stellar winds develop.

High-resolution spectroscopy in the NIR has proven to be a valuable tool to investigate atmospheric kinematics. RVs derived from the wavelength shifts of spectral lines provide clues on the gas velocities throughout the extended, dynamic atmosphere. In the past, CO lines of the Δv=3 vibration–rotation bands at $\lambda\approx1.6\,\mu$m have been used to study deep photospheric layers in Miras, which are heavily affected by the pulsation. As the emerging shock front passes through the region of line formation, it leads to a very characteristic behaviour of the CO line profiles (line doubling around phases of maximum luminosity) and results in discontinuous, S-shaped RV curves during the lightcycle (e.g. Hinkle et al. 1984).

In Fig. 1 (left), a compilation of observational data (extracted from FTS spectra) is shown, suggesting a similar picture for all Miras, independent of their parameters (spectral type, period, metallicity, etc.). Realistic atmospheric models should reproduce this.

2. Modelling line profiles and synthetic radial velocities

Dynamic model atmospheres are needed to reproduce the complex phenomena within the outer layers of Mira variables. Recently, we presented synthetic line profiles based on models from Höfner et al. (2003). A special radiative transfer code was applied, which also takes

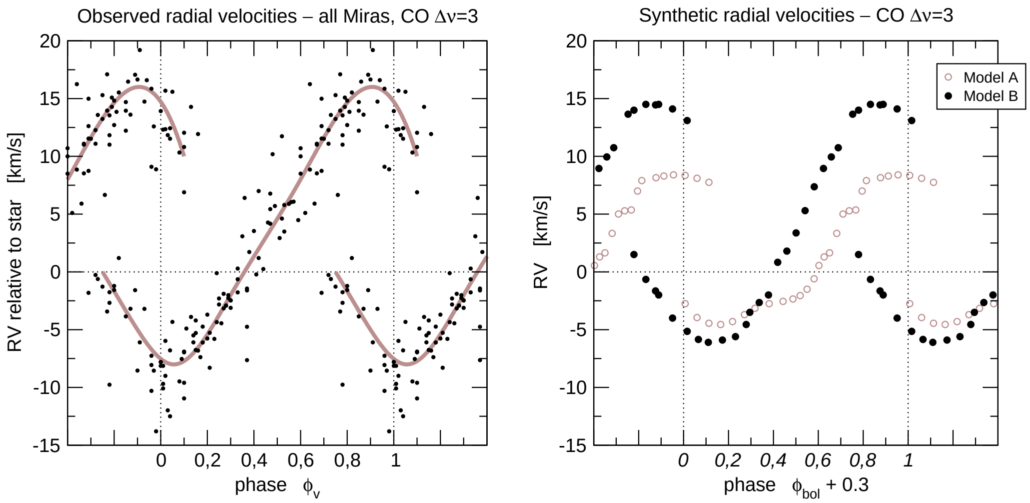

Fig. 1. *Left:* RV curves of second overtone CO lines for a sample of typical Miras (data taken from Lebzelter & Hinkle 2002). The grey, thick line was fit to guide the eye. *Right:* RV curves for the same lines as derived from model calculations (R=70.000). Model A was used in Nowotny et al. (2005a,b,c), while Model B is an improved version, which yields more realistic results, especially a comparable velocity amplitude of ΔRV=20.6 km$\cdot$s^{-1}.

velocity effects into account. Results can be found in Nowotny et al. (2005a,b,c). It could be shown, that state-of-the-art models can qualitatively reproduce the behaviour (line profiles, RVs) of spectral lines originating at different depths.

Still, some differences remained compared to observations. For CO Δv=3 lines the line splitting appears too weak and the extracted velocity amplitude ΔRV too low (cf. Sect. 6.2. in Nowotny et al. 2005c). Here, calculations are presented using a new dynamic atmospheric model, for which the parameters[1] were somewhat tuned to fit this aspect. Line profiles for the CO 5–2 P30 line were computed for various phases during a pulsation period. The spectral synthesis was carried out exactly as described in detail in Nowotny et al. (2005b,c). As also found there, the RV curves look more complicated for the highest resolution calculated (300.000), but become similar to observed ones if the spectra are rebinned to a resolution of 70.000 (comparable to FTS spectra). Lacking visual phases for the models, the synthetic RVs in Fig. 1 (right) are shifted by an arbitrary value of 0.3. It can be recognised, that the results of the computations resemble the observations reasonably well (line-doubling, S-shape, amplitude ΔRV, etc.). This fundamental characteristic of Miras can now be reproduced even quantitatively in a self-consistent way by the new model.

Acknowledgements. This work was supported by the “Fonds zur Förderung der Wissenschaftlichen Forschung” under project number P14365–PHY and the Swedish Research Council.

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[1] $L_*=7\cdot10^3 L_\odot$, $M_*=1.5 M_\odot$, $T_*=2600$ K, C/O=1.4, P=490 d, $\Delta u_p=6$ km$\cdot$s^{-1}