Uncovering the pulsating photospheres of Miras: comparing the CODEX models with PTI time series

M. Hillen, T. Verhoelst, B. Acke, P. Degroote, H. Van Winckel

Instituut voor Sterrenkunde, KU Leuven Belgium

Introduction

Le Bouquin et al. (2009) **proved** the **existence** of **molecular layer(s)** around **M-type Mira variables**, consisting of water, CO and a continuum opacity at 2 stellar radii. Theoretically it was **not yet understood how such a molecular layer forms**, **evolves and contributes to the mass-loss and stellar wind**. The CODEX dynamical opacity-sampling model atmospheres are the latest attempt to model the extended pulsating atmosphere and provide a physically self-consistent basis for the molecular shell scenario. A quantitative comparison of these models with observed broadband light curves and interferometric snapshots shows a decent agreement, although a slight discrepancy between the visual phase of the observations and of the best-fitting model arises: **models around visual minimum, displaying the molecular layer most prominently, appear to fit all observed phases better!** The extensive spectro-photometric and interferometric time series obtained with the PTI allows to do a more detailed comparison to (dis)prove this conclusion.

CONCLUSIONS: 1) The PTI dataset confirms that the treatment/behavior of **water in the outer layers** of the CODEX models near **visual maximum** phases **needs to be revised**!

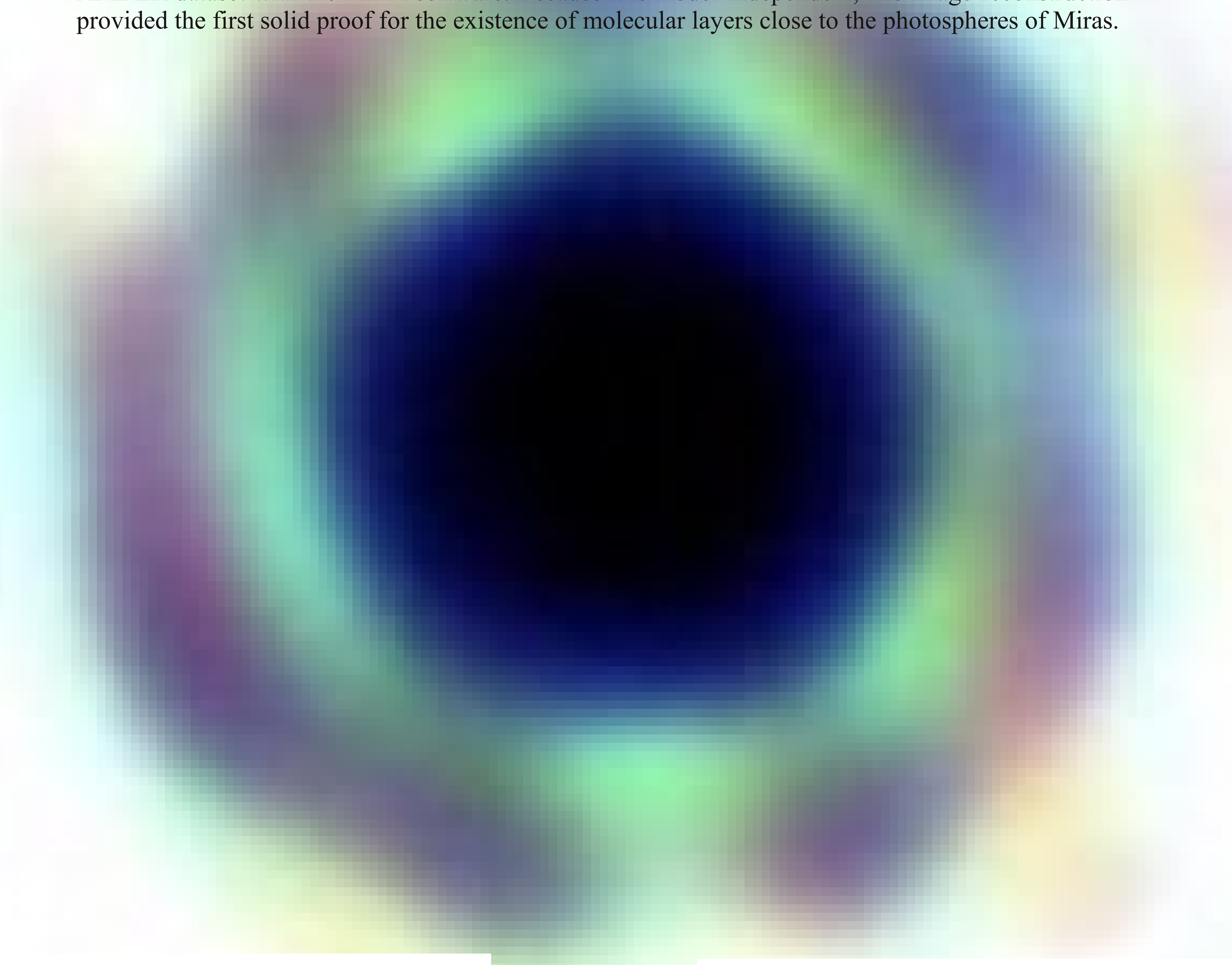
2) **Image reconstruction** campaigns at **medium spectral resolution** are needed, with a focus on phases around **maximum light** to independently constrain the outer atmospheric structure at the wavelengths where molecules (i.e. water in particular) are dominant.

Palomar Testbed Interferometer data

TU And, a Mira of spectral type M5 and **P~317d**, was observed with the PTI during **65 nights** between 1999 and 2005, sampling the **full pulsation, spread over several cycles**. In a night, typically a handful of squared visibilities are obtained on one of the **3 fixed baselines** in **5 channels within** the **K-band**. As a byproduct also the photon counts per spectral channel are released. Although the error on the absolute calibration of these **spectro-photometric** data is rather large, the relative shape with respect to wavelength is very precise (see Fig. 1). Figure 2 shows the visibilities per visual phase bin.

The background figure

The background picture is taken from Le Bouquin et al. (2009), but inverted in color. It is the combined result of their **wavelength-dependent image reconstruction** of a large interferometric AMBER dataset with the MiRA software. Because it is model-independent, this image-reconstruction provided the first solid proof for the existence of molecular layers close to the photospheres of Miras.



The CODEX models

A detailed description of the CODEX models can be found in **Ireland et al. (2008,2011)**. The 4 model series have been constructed to match the periods of o Cet, R Leo and R Cas. The publicly available spectra and CLV's are computed with an **opacity-sampling** method for **10 phases in a few cycles** of each non-linear self-excited pulsation model series. With the spectra and CLV's, any observable of up to medium spectral resolution can be computed, given a filter profile. Figure 1 plots the model integrated fluxes of the R52 series (P~307d) in the PTI and V bandpasses on top of the observations as a function of visual phase.

Figure 1: The PTI spectro-photometric time series: the upper 2 panels show the relative variation in time with respect to the 2.2μm channel of the channels at 2.0, 2.1, 2.3 and 2.4μm, panel 3 shows the absolute variation in the 2.2μm channel and panel 4 shows the visible light curve. The solid lines represent the R52 models scaled with an angular diameter of 2.1mas to match the absolute flux. The red arrow highlights the visual phase where model and observations disagree the most.

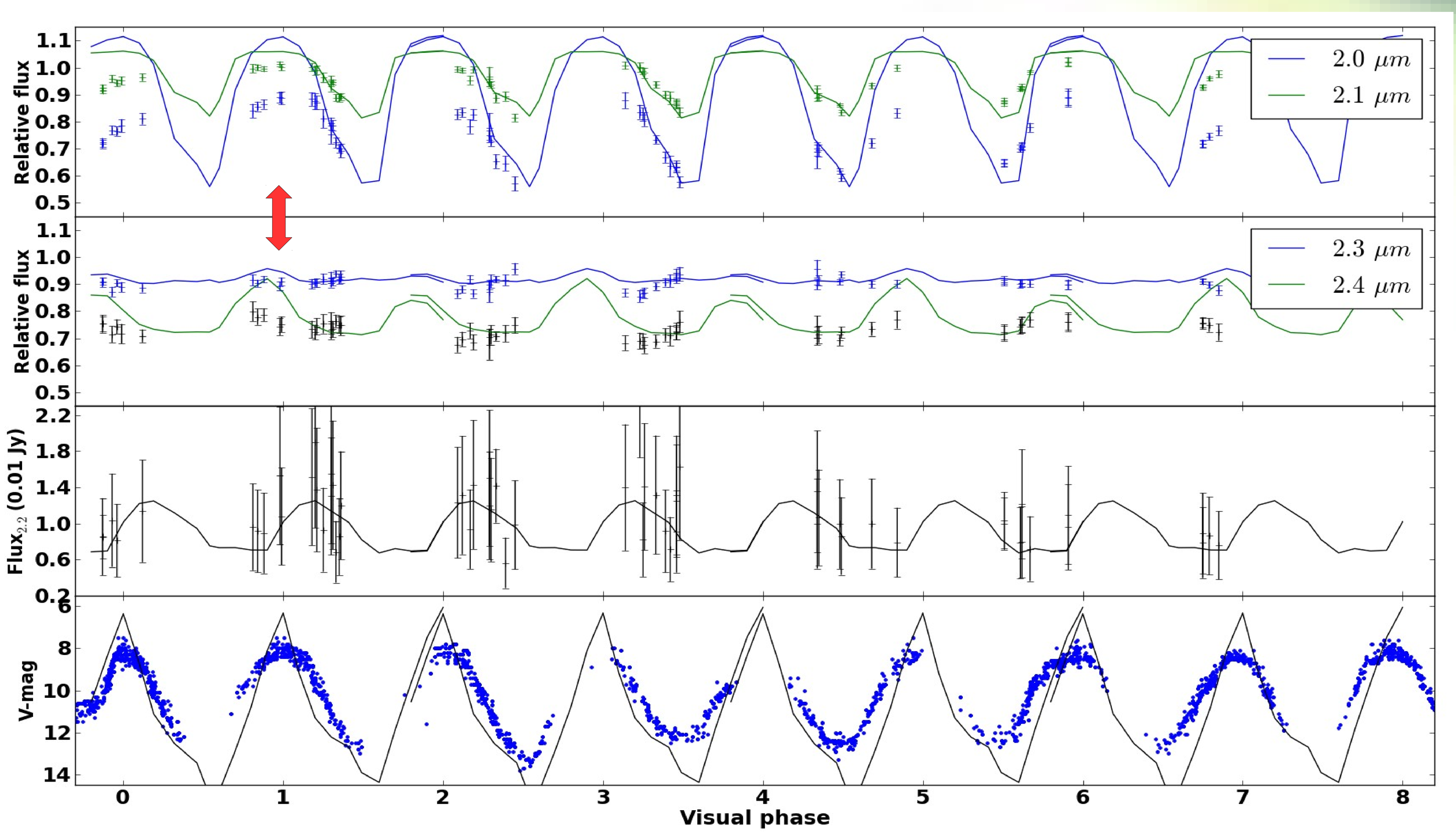
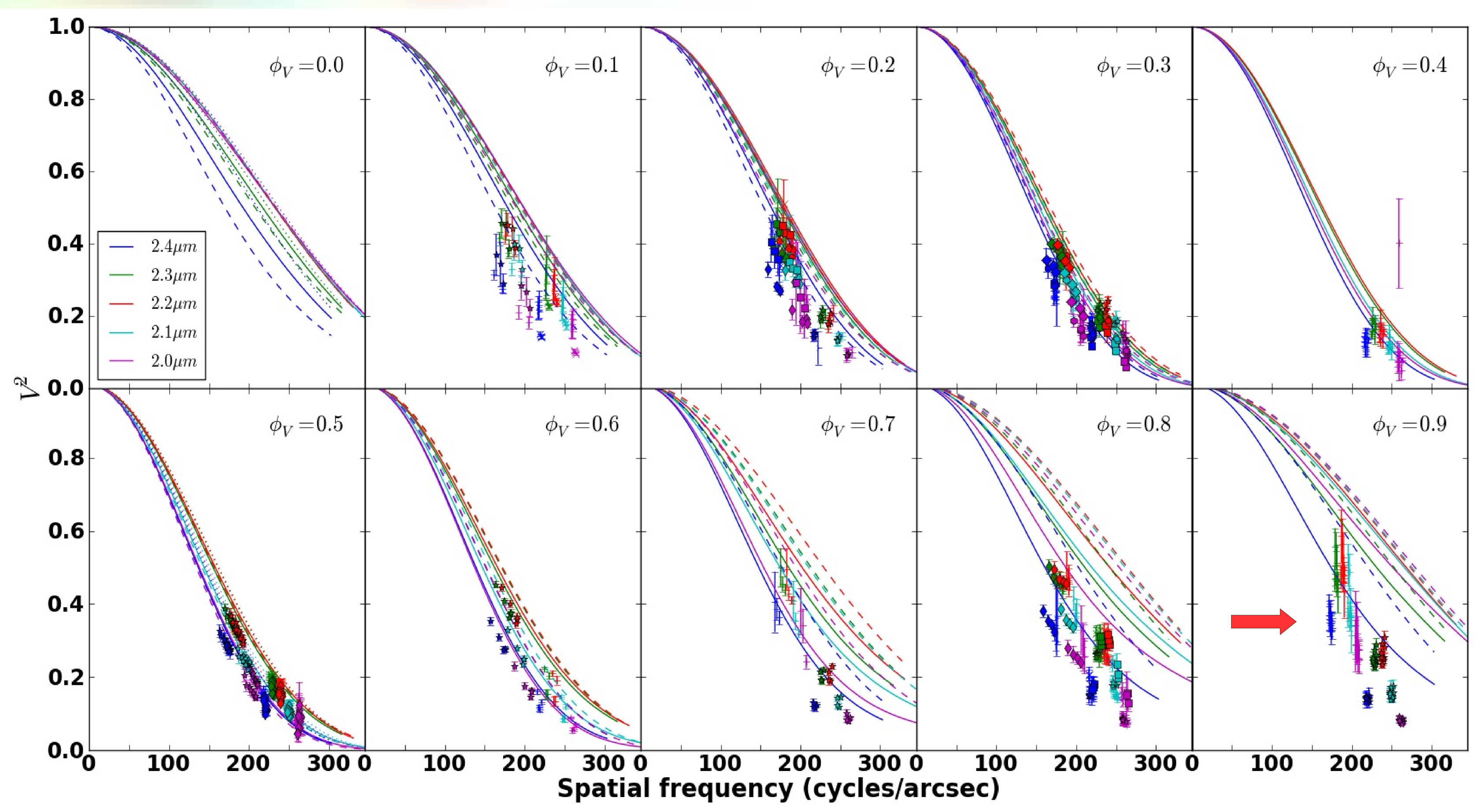


Figure 2: PTI squared visibilities binned per visual phase. Data from different cycles are plotted with a different symbol. The different line styles correspond to consecutive cycles in the R52 model series. The color is a proxy for wavelength as depicted in the legend. The red arrow highlights the visual phase where the agreement between model and observations is worst.



Discussion

Of the 4 model series available, R52 matches TU And closest in period (ΔP=10d). The **2.2μm flux** is **well matched** together with the average level in the visual light curve, although its amplitude is slightly too high. In the **other near-IR channels**, we see a clear **discrepancy** between the observations and the model predictions **around phases of visual maximum**! The amplitude of the discrepancy **correlates with** the **water opacity**: at 2.0 and 2.4μm the effect is largest. With the **visibilities**, a similar picture emerges: in phases 0.3 – 0.6 the model concurs the observations, while at visual maximum the **model predicts a too small object**! Moreover, the observed cycle-to-cycle variations (every phase contains observations from several cycles) are smaller than those predicted by the model. A closer look at the λ-dependence, suggests water is lacking in the outer parts of the extended atmosphere.

Contact:

Michel.Hillen@ster.kuleuven.be

Instituut voor Sterrenkunde

Celestijnenlaan 200D BUS 2401

3001 Leuven

Tel +32-16-32.70.27

KATHOLIEKE UNIVERSITEIT LEUVEN