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Dynamical models of circumstellar dust shells around Long-period Variables: Spectrum, lightcurves, intensity profiles, and visibilities of IRC +10216

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Based on dynamical models for circumstellar dust shells (CDS) around long–period variables, including time–dependent hydrodynamics and a detailed treatment of carbon grain formation, continuum radiative transfer calculations have been carried out for a model which is capable of explaining several different observations of the prominent carbon star IRC +10216. It is shown that the resulting theoretical lightcurves exhibit the superposition of different oscillations: The oscillation with the period of the interior pulsation of the star is superposed by an oscillation with a longer period which is produced by the dynamical structure of the CDS. This dust shell model also causes a pronounced non–monotonic course of the spatial intensity distribution across the CDS, leading to the occurrence of wavelength–dependent internal structures of the calculated visibility functions. A quantitative comparison with specific observations obtained for IRC +10216 shows, that the layered distribution of dust across the CDS might be a natural physical explanation of the multiperiodic photometric lightcurves, the step–like behaviour of the brightness profile, and the internal structures present in the measured visibilities.

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INTRODUCTION

Observations of Long–period variables (LPVs) show several rather complex characteristics, which are by now not very well understood. These comprise for example non–sinusodial *lightcurves*, showing a drift in time either of the average magnitude or of the amplitude (e.g. Le Bertre 1992),

pronounced internal structures in the *spatial spectra* (visibilities) of the circumstellar shells (e.g. Ridgway & Keady 1988, Danchi et al. 1994) ,

step–like structures in the *brightness profile* on a spatial scale of a few stellar radii at least in the case of IRC +10216 (Richichi 1993).

The observations also indicate that a considerable amount of dust is present in the circumstellar shells of most LPVs.
To arrive at a reliable physical description of circumstellar dust shells (CDS) around LPVs one has to consider the complex interplay among hydrodynamics, thermodynamics, and formation, growth, and evaporation of dust grains.
The consistent treatment of these interactions leads to a number of dynamical effects, e.g.

a discrete, shell–like radial distribution of dust (Fleischer et al. 1992),

dust accelerated shocks (Fleischer et al. 1992) , and

a multiperiodic temporal behavior of the CDS (Fleischer et al. 1995a,b)

which strongly influence the optical appearance of these models (Winters et al. 1994b, 1995).

In this poster, we present these effects for one hydrodynamical model which is capable of explaining several different observations of the prominent carbon star IRC +10216.

HYDRODYNAMICS (DETAILS SEE FLEISCHER ET AL. 1992)

We use a 1–D Lagrangian code in spherical symmetry, which includes the *simultaneous* solution of hydrodynamics, (equilibrium) chemistry, dust formation, –growth, and –evaporation (Gauger et al. 1990), and a grey, semianalytical treatment of the radiative transfer problem (Lucy, 1971, 1976) for calculating the equilibrium temperature. As a result we get the complete atmospheric structure of the shell at any desired instant of time t.

RADIATIVE TRANSFER (DETAILS SEE WINTERS ET AL. 1994a)

Based on this atmospheric model, we solve the radiative transfer equation in spherical geometry by means of a Feautrier–type iteration between moment equations and formal solution of the transfer equation in (p, z) coordinates. The radiative transfer processes considered are grey absorption and thermal emission by the gas and frequency dependent absorption and thermal emission by the dust component. The dust opacity is calculated in the small particle limit of Mie theory for spherical grains, whose optical properties are described by the complex refractive index of amorphous carbon as given in Preibisch et al. 1993 .

The result of this calculatuion is the angle– and frequency dependent radiation field at the given instant of time t.

MODEL PARAMETERS AND RESULTING QUANTITIES

Due to the consistent treatment of the dynamical dust shell problem, our models are completely determined by specifying *6* parameters. The model for IRC +10216 presented here is determined by:

stellar mass	M_*	$=$	$1 M_\odot$
stellar temperature	T_*	$=$	2500 K
stellar luminosity	$L_*(t=0)$	$=$	$2.4\,10^4 L_\odot$
carbon–to–oxygen ratio	$\epsilon_{\rm C}/\epsilon_{\rm O}$	$=$	1.20
pulsation period	P	$=$	650 d
piston amplitude	$\Delta u_{\rm P}$	$=$	6 km/s

This model yields values for the final outflow velocity, the mass loss rate, and the dust–to–gas ratio by mass of

average outflow velocity	$< v_\infty >$	$=$	14.3 km/s
observation	13.7 . . . 14.8 (Olofsson et al. 1993)		
average mass loss rate	$< \dot{M} >$	$=$	$1.2\,10^{-4} M_\odot$/yr
observation	$\approx 5\,10^{-5}$ (Knapp & Morris 1985)		
average dust–to–gas mass ratio	$< \rho_{\rm d}/\rho_{\rm g} >$	$=$	$8.1\,10^{-4}$
observation	$\approx 1.3\,10^{-3}$ (Knapp 1985)		

RESULTS

- Resulting values of the outflow velocity, the mass loss rate, and the dust–to–gas mass ratio are in reasonable agreement with the respective values derived from observations of IRC +10216 (cf. 3.2)

- Observed spectrum at minimum and maximum phase of the lightcurve is well reproduced by the synthetic energy distribution obtained at the respective phases from the model calculation. *We derive a distance to IRC +10216 of* $d = 170$ *pc* (cf. Fig. 1)

- Spatial structure of the dust shell model is not recovered each pulstion cycle, but only after approximately 4 pulsation periods. => *The dust shell possesses its own intrinsic timescale* (cf. Figs. 2 and 4). Synthetic brightness profiles at longer wavelengths show a step–like structure on a spatial scale of a few stellar radii. Synthetic visibilities show a rippled internal structure at longer wavelengths (cf. Fig. 2)

- Spatial spectra observed at different wavelengths near maximum phase of the lightcurve are satisfactorily reproduced by the synthetic visibilities obtained at a respective phase of the model calculation (open triangles at $t \approx 10.7\,$P in Fig. 4), assuming the distance of 170 pc derived from the energy distribution (cf. Fig. 3)

- Synthetic *lightcurves show a multiperiodic behavior* in agreement with the trend observed at different wavelengths over 3 periods (cf. Fig. 4). In particular, *the* *temporal evolution of the minima, which is different at short and long wavelengths is correctly reproduced by the model calculation*

- *Observed brightness profile of IRC +10216 at* $1.65\mu m$ *is well reproduced by the synthetic profile, assuming a distance of 170 pc* (cf. Fig. 5)

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