T-4
Atomic & Optical Theory

Spectroscopy and Dynamical Modeling of Circumstellar Dust Shells Around Carbon-Rich Long-Period Variable Stars

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Almost all Miras and most long-period variables (LPVs) are highly evolved low- and intermediate-mass stars located on the Asymptotic Giant Branch (AGB) in the Hertzsprung-Russell diagram. These objects are large amplitude pulsators with typical periods of the order of $P \approx 1$ yr, high luminosities $L_* \approx 10^4\ L_\odot$, low effective temperatures $T_* < 3000$K, and high-mass loss rates up to $dM/dt \approx 10^{-4}\ M_\odot\ yr^{-1}$. The outflows from these cool stars are sites of copious grain formation, which is sometimes so effective, that the circumstellar dust shell (CDS) totally obscures the central object. In fact, these circumstellar shells are considered to be the major sources for the replenishment of the interstellar medium with processed material, in particular in the form of complex molecules and of solid dust particles.

These high-mass loss winds cannot be a long-lasting phenomenon, since the stars themselves, when reaching the AGB, typically have masses of the order of one solar mass. Therefore, this high-mass loss has a profound impact on the final evolutionary phase of the mass losing star, thereby producing the remaining Planetary Nebula, or even single thin detached shells.

To obtain a reliable understanding of the processes connected to such dusty winds, it is necessary to check the reliability of corresponding hydrodynamic dust shell models by a detailed comparison of the model prediction with specific astronomical observations.

The approach to model circumstellar dust shells around LPVs comprises

• the explicit solution of the time dependent hydro-equations in Lagrangian coordinates for a spherical symmetric geometry, with the simulation of the interior pulsation by a sinusoidally varying inner boundary (piston),

• a detailed treatment of the formation, growth and evaporation of carbon grains by means of the moment method, which includes an equilibrium chemistry for the important hydrocarbons,

• treatment of radiative transfer through the dust in terms of frequency integrated moments by a generalized Eddington approximation for a spherical grey atmosphere,

• the description of post-shock cooling of the gas by an LTE cooling function,

• non-LTE molecular spectral line synthesis by solving the observer's frame radiation transport equation for the gas.

To study the structure and dynamics of such CDS, the carbon monoxide (CO) molecule is an especially well suited diagnostic probe. It is very abundant, in both carbon and oxygen rich objects, stable, and relatively chemically inert. Its infrared and microwave spectrum is fairly simple, and line positions and oscillator strengths are well determined.

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Probably the best studied representative of its class is the bright, carbon-rich, infrared Mira IRC+10216, which has been observed at many wavelengths with significant spectral and spatial resolution since its discovery by Neugebauer & Leighton in 1969.

In the two figures we present a model for IRC+10216. Figure 1 shows the radial structure of the dust shell model at t = 72.25 P and t = 73.25 P (the period P is 650 days.). We have in detail; (a) velocity v and radiative acceleration on dust α, (b) density ρ and degree of condensation f_{cond}, i.e., fraction of C-atoms not bound in CO, which are condensed into grains, (c) grain formation rate $J_*/n_{<H>}$, i.e., number of grains formed per second and H-atom, and number of grains per H-atom $n_d/n_{<H>}$, (d) gas temperature T_{gas} and radiative equilibrium temperature T_{eq}. Dashed lines refer to the r.h.s. ordinate.

During this time increment a new dust layer is formed around 5 R_0, as indicated by the degree of condensation. The radiation pressure acting on this dust leads to the acceleration of a dust amplified shock starting at a material velocity < 5 km s^{-1}, and to an enhanced density of the matter overrun by the shock in the region around 5 R_0. Subsequently the velocity of the accelerated material increases further, while its temperature and density at the corresponding positions decrease due to the expansion.

In Figure 2, the temporal evolution of the synthetic line profiles (right panel) is compared with observed 2 - 0 P(7) overtone lines from IRC+10216. The dates of the observations are separated by ≈ 2.5 P and ≈ 3.5 P. The observations were obtained using a dual-beam Fourier Transform spectrometer at the coudé focus the Kitt Peak National Observatory 4-meter telescope. It is worth noting that for CO gas at these temperatures, the thermal Doppler broadening is less than 1 km s^{-1}, so that the broad widths of the observed and calculated lines result entirely from hydrodynamical expansion. The observed (left panel) spectra nicely show the development of a low-velocity absorption around -5 km s^{-1}, and it is worth noting that this feature evolves on approximately equal time scales in the observations and the calculations.

Once having fixed the thermal and hydrodynamical structure in the circumstellar envelope from studying unreactive molecular species such as CO, the long term goal is to investigate the chemistry. This involves observed species such as NH_3, SiH_4, C_2H_2, and HCN, thought to be involved in catalytic dust grain surface chemistry, and other observed species such as C_3 and C_5, thought to be involved in ion-molecule chemistry.

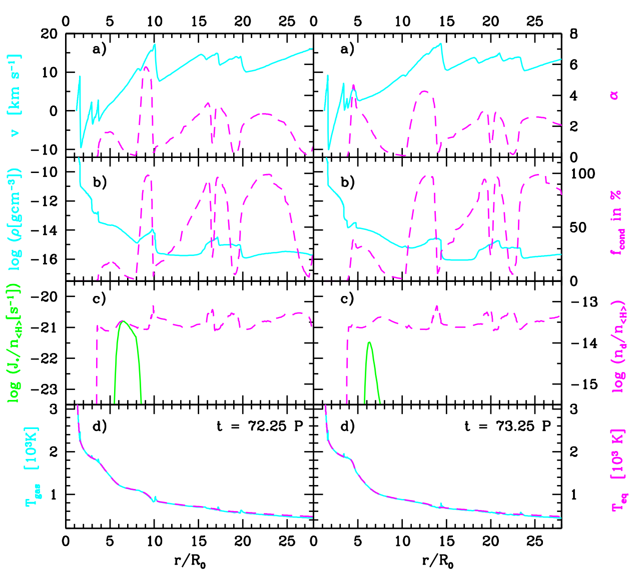

Figure 1.

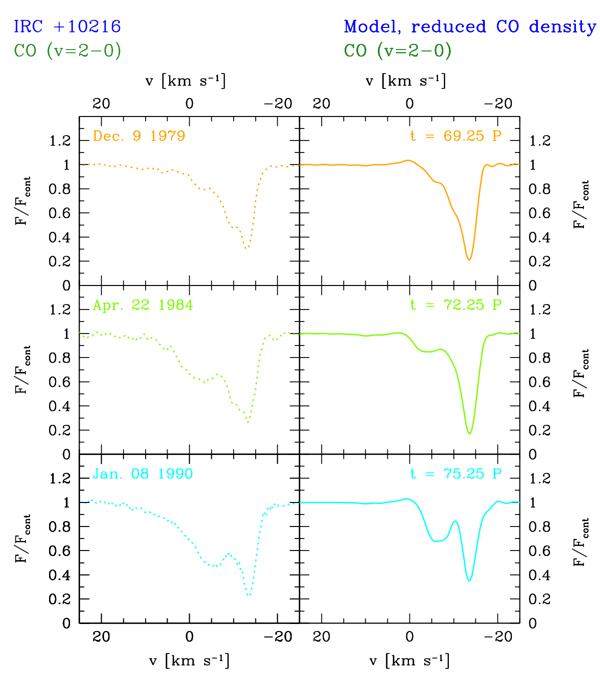

Figure 2.

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