Models and ISO spectra of AGB carbon stars

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1. Introduction

A characteristic feature of stars on the asymptotic giant branch (AGB) is that they show large amplitude pulsations with periods of about 100 to 1000 days. The pulsation creates strong shock waves in the stellar atmosphere, causing a levitation of the outer layers. This cool and relatively dense environment provides favourable conditions for the formation of molecules and dust grains. Radiative acceleration of the dust and momentum transfer to the gas can lead to a slow wind with a high mass loss rate which influences the further evolution of the star (e.g. Fleischer et al. 1992, Höfner & Dorfi 1997). The dust-free inner parts of the stellar atmosphere are modulated by the running shock waves in a complicated time-dependent way which affects observable properties and cannot be simulated with hydrostatic model atmospheres (Aringer et al. 1997, Alvarez & Plez 1997, Höfner et al. 1997).

2. Modelling Method

To interpret various observations we have developed improved time-dependent dynamic models of the atmosphere and circumstellar envelope (Höfner et al. 1997). In contrast to most earlier dynamic models in the literature which simply use a constant gas absorption coefficient (independent of the thermodynamical conditions) our new calculations are based on opacities derived from detailed molecular data (Jørgensen 1997). As discussed by Höfner et al. (1997) this has a dramatic influence on the atmospheric structure and the resulting synthetic spectra.

By solving the equations of grey radiation hydrodynamics together with a time-dependent description of the dust formation we obtain the spatial structure of the object (density, temperature, degree of condensation, etc.) as a function of time (cf. Höfner & Dorfi 1997 for details of the modelling method). Detailed radiative transfer calculations based on these models yield synthetic spectra and other observable quantities (Loidl et al. 1997a,b).

3. Observations

The Short Wavelength Spectrometer (SWS) on board of the Infrared Space Observatory (ISO) satellite provides a unique opportunity to simultaneously study molecular and dust features originating in the atmospheres of AGB stars. To investigate the spectral variability of several carbon- and oxygen-rich AGB variables during a pulsation cycle we have started an ISO observing program. We obtained full grating scans with a typical resolution of about 600 in the wavelength region between 2 and 43 μm. A description of the data reduction can be found in Hron et al. (1997). The spectra of R Scl shown in Fig.1 are rebinned to a resolution of 100 to make them comparable with our synthetic opacity sampling spectra.

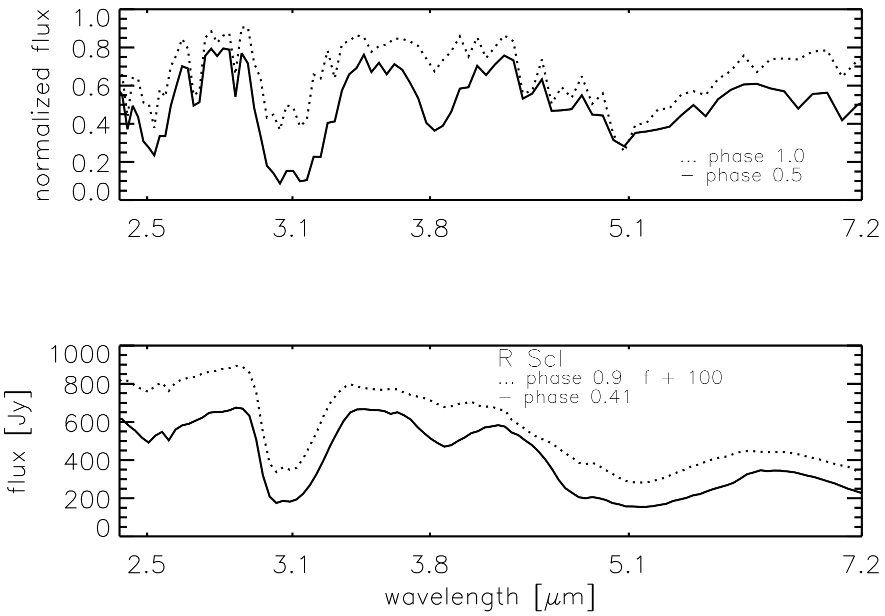

Figure 1. Synthetic spectra of a dynamic model (upper panel) for approximately the same phases as the ISO-SWS spectra of R Scl (lower panel). Dotted lines correspond to a phase near maximum luminosity (phase $\approx$ 1.0), while full drawn lines corresponds to near minimum (phase $\approx$ 0.5). Note that the synthetic spectra are normalised to the local continuum, while the observed spectra are on an absolute scale, which among other things results in a different slope of the spectra in the two panels. For clarity, the spectrum of R Scl near maximum light has been shifted by 100 Jy.

4. Results

We compare our observed spectra of R Scl with results of a model atmosphere computation. The dynamic model has the following parameters:

$T_* = 2880$ K, $L = 7000\ L_\odot$, $M = 1\ M_\odot$, C/O = 1.40,

$\Delta u = 4$ km s^{-1} and P = 390 days

We have computed opacity sampling spectra which include the molecules CO, CH, C_2, CN, HCN, C_2H_2 and C_3. Prominent absorption features in the models and the observations are the ones around 2.5, 3.1, 3.8 and 5.1 μm (see Fig.1).

The 3.8 μm feature shows large variations both in our models and in the observations of R Scl. This feature is almost only due to C_2H_2 (see Fig.2) which is a very temperature sensitive molecule. The models are hottest around maximum light (i.e., phase ≈ 1.0) and at those temperatures less C_2H_2 is available. Therefore the feature almost disappears around maximum light (see Fig.1). As demonstrated by Fig.2, the 3.1 μm feature is a blend of C_2H_2, HCN and C_3, while the 5.1 μm feature is due to C_3 and CO. Due to the larger degree of saturation in the spectral lines of these two very strong bands, their variation with phase is smaller than for the 3.8 μm band.

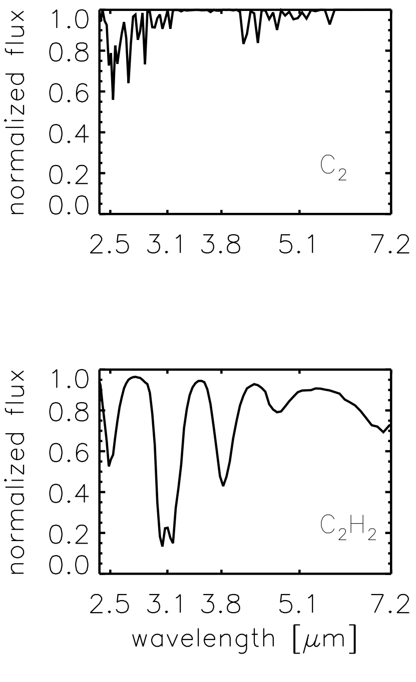

Figure 2. Synthetic opacity sampling spectra at phase 0.50 for the molecules C_2, HCN, C_2H_2 and C_3.

As one can also see from Figure 2, the 2.5 μm feature is a blend of the molecules C_2H_2, HCN and C_2 (plus a contribution of CO). The partial pressure of C_2 has its maximum value relative to the gas pressure at higher temperatures (i.e., usually deeper in the atmosphere) than the partial pressures of C_2H_2 and

HCN have. Therefore one will not expect the C_2 and the C_2H_2/HCN band intensities to vary identically with phase during the pulsation. In our models, the variation of C_2 shows a phase shift compared to C_2H_2 and HCN. The computed difference in intensity at phase 1.0 and 0.5 is much smaller for the C_2 bands (and bands of other diatomic molecules) than for bands of the polyatomic molecules. This is due to the smaller response to pulsational variations by the lower photosphere than by the upper one and to the different sensitivity of the molecules to a given change in the thermodynamical conditions. The relative stability of the diatomic band intensities (which contribute significantly to the feature) results in the relatively weak phase variation of the 2.5μm feature compared to that seen e.g. for the 3.8μm feature which is almost exclusively due to the highly variable C_2H_2.

At wavelengths longer than about 4μm the intensity variation of the diatomic bands is opposite to that of the polyatomics, in the sense that the diatomic bands are slightly stronger at phase 1.0 than at phase 0.5 whereas the polyatomic bands are stronger at phase 0.5 than at phase 1.0 throughout the whole wavelength range discussed here.

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