Model Atmospheres and Spectra of Peculiar Stars

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Abstract. The method and results of the computation of the model atmospheres and spectral energy distributions of chemically peculiar stars are discussed. The models and spectra are computed with special consideration of the particular problems encountered for peculiar and hydrogen deficient stars in the later stages of evolution. We present some computed model atmospheres and fits to observed spectra of Sakurai’s object, V838 Mon, and RS Oph.

1. Introduction

Recently extended grids of model atmospheres and spectra were computed using the most complete sets of opacities (see Kurucz 1993, 1999; Hauschildt et al. 1999). However, in most of the computations solar abundances (Anders & Grevesse 1989) or solar abundances scaled by the metallicity factor [Fe/H] are used. On the other hand, abundances of at least light elements, i.e. H, He, Li, C, and N, in the atmospheres of evolved stars can significantly differ from the solar abundance ratios. The reason for this is because convection and other mixing processes dredge up the products of the nucleosynthesis from the stellar interior. Naturally, the temperature structure of their model atmospheres and computed spectra respond to any change of abundances (see Pavlenko & Yakovina 1994, Pavlenko 2003).

2. Procedure

The plane-parallel model atmospheres of evolved stars in LTE, with no energy divergence were computed using the SAM12 program (Pavlenko 2003). The program is a modification of ATLAS12 (Kurucz 1999).

Chemical equilibrium is computed for the molecular species by assuming LTE. The nomenclatures of molecules accounted for are different in atmospheres of hydrogen rich and hydrogen poor, carbon-rich and carbon poor stars. We ac-
count mainly for the molecules which are the most abundant or most important sources of opacities.

SAM12 uses the standard set of continuum opacities from ATLAS12. The adopted opacity sources account for changes in the opacity as a function of temperature and elemental abundance. We add some opacity sources which are of importance in the atmospheres of carbon-rich, hydrogen-deficient stars (see Pavlenko 2003 for more details). The opacity sampling approach (Sneden et al. 1976) is used to account for atomic and molecular line absorption.

Synthetic spectra are calculated with the WITA6 program (Pavlenko 1997), using the same approximations and opacities as SAM12. To determine the best fit parameters, we compare the observed fluxes $F_\nu$ with the computed fluxes $F_\nu^c$ following the scheme of Pavlenko & Jones (2003).

3. Fits to Stellar Spectra

V838 Mon

The peculiar variable star V838 Mon was discovered during an outburst at the beginning of 2002 January (Brown 2002). Two further outbursts were then observed in 2002 February (Munari et al. 2002a; Kimeswenger et al. 2002; Crause et al. 2003) and in general the optical brightness in the V-band of the star increased by 9 mag. Since 2002 March, a gradual fall in V-magnitude began which, by 2003 January, was reduced by 8 mag.

Kaminsky & Pavlenko (2005) carried out a determination of the physical parameters of line formation in the framework of a self-consistent approach, using fits of synthetic spectra to observed spectra in the wavelength range 5500-6700 Å.

We obtained $T_{\text{eff}} = 5330 \pm 300$ K, $5540 \pm 270$ K and $4960 \pm 190$ K, for February 25, March 2, and March 26, respectively. The iron abundance $\log N(\text{Fe}) = -4.7$ does not appear to change in the atmosphere of V838 Mon from February 25 to March 26, 2002. Our results agree well with Kipper et al. (2004).

Up until November 2002 both the effective temperature and luminosity of V838 Mon dropped significantly with time; Evans et al. (2002) classified it as an L-supergiant (see also Tylenda 2005). In the optical spectra there are strong TiO bands as well as bands of a few diatomic molecules which can be fitted by a theoretical spectrum computed with $T_{\text{eff}} = 2000$ K (Pavlenko et al. 2005). Then, at $\lambda < 0.5 \mu m$, Desidera & Munari (2002) discovered spectroscopically a hot companion, later confirmed by Wagner & Starrfield (2002), and classified as a B3V star by Munari et al. (2005). Modelling of a combined B2 V + M9 III spectrum allows us to determine the radius of V838 Mon in November 2002 as $R \sim 6000 R_\odot$, if the two stars form a binary system (Pavlenko et al. 2007).

Sakurai’s object

V4334 Sgr (Sakurai’s Object), the “novalike object in Sagittarius” discovered by Y. Sakurai on February 20, 1996 (Nakano et al. 1996), is a very rare example of the extremely fast evolution of a star during a very late final helium-burning event (Duerbeck & Benetti 1996).
Theoretical spectral energy distributions computed for a grid of hydrogen-deficient and carbon-rich model atmospheres have been compared with the observed optical (0.35–0.97 \( \mu m \)) and infrared (1–2.5 \( \mu m \)) spectra of V4334 Sgr (Sakurai’s Object) in 1997–1998 (Pavlenko et al. 2000, Pavlenko & Duerbeck 2001, Pavlenko & Geballe 2002). We showed that the main features in the observed spectra are strong bands of CN, and C\(_2\) in the optical spectra and C\(_2\) and CO bands in the IR. Observed spectra are well fitted by Asplund et al. (1999) abundances. Hot dust produces significant excess continuum at the long wavelength ends of the 1997 spectra.

Fits to the IR spectra yield an effective temperature of \( T_{\text{eff}} = 5500 \pm 200 \) K for the April date and \( T_{\text{eff}} = 5250 \pm 200 \) K for July. In the spectrum of Sakurai’s object observed in 1997 the \(^{12}\)CO and \(^{13}\)CO bands are well-resolved at 2.3 \( \mu m \). We determined \( ^{12}\)C/\( ^{13}\)C \( \approx 4 \pm 1 \), consistent with the interpretation of V4334 Sgr as an object that has undergone a very late thermal pulse (Pavlenko et al. 2005).

**RS Oph**

The recurrent nova RS Ophiuchi undergoes nova eruptions every \( \sim 10–20 \) years as a result of thermonuclear runaway on the surface of a white dwarf close to the Chandrasekhar limit. RS Oph is known to have undergone at least five eruptions, in 1898, 1933, 1958, 1967 and 1985; eruptions in 1907 and 1945 may have been missed (see contributions by Anupama and Wallerstein in these proceedings). Both the progress of the eruption, and its aftermath, depend on the, as yet, poorly known composition of the red giant in the RS Oph system. Therefore, Pavlenko et al. (2008) carried out a detailed study of the IR spectra of RS Oph to understand better the effect of the giant secondary on the recurrent nova eruption. We modelled the infrared spectrum in the range 1.4–2.5 \( \mu m \) to determine the metallicity and effective temperature of the red giant.

Synthetic spectra were computed for a grid of M-giant model atmospheres having a range of effective temperatures \( 4000 < T_{\text{eff}} < 3000 \) K, gravities \( 0 < \log g < 1 \), and abundances \(-1 < [\text{Fe/H}] < +0.5 \), and fitted to the infrared spectra of RS Oph as it returned to quiescence after its 2006 eruption.
After dereddening by $E(B - V) = 0.73$, we found that the slopes of the spectral energy distribution (SED) and the intensity of molecular bands in the modelled spectra depend on both $T_{\text{eff}}$ and $[\text{Fe/H}]$ (Fig. 1). We determined $T_{\text{eff}} = 4100 \pm 100$ K, $\log g = 0.0 \pm 0.5$, $[\text{Fe/H}] = 0.0 \pm 0.5$, $[\text{C/H}] = -0.8 \pm 0.2$, $[\text{N/H}] = +0.6 \pm 0.3$ in the atmosphere of the secondary.

These results agree at least qualitatively with Wallerstein et al. (1997)

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**References**


Kurucz., 1993, CD ROM 9, 18. Harvard-Smithsonian Observatory


Nakano, S., Sakurai, Y., et al. 1996, IAU Circ. 6322


Pavlenko, Y. V., 1997, Astron. Reps, 41, 537


Pavlenko, Ya., Kaminsky, B., Lyubchik, Y., Yakovina, L. 2007, ASPC, 363, 225


Sneden, C., Ivans, I. I., Kraft, R. P. 2000, MmSAI, 71, 657


Wagner, R.M., Starrfield, S.G. 2002, IAUC, 7992, 2

Wallerstein, G., Harrison, T., Munari, U., 2006, BAAS, 38, 1160
Discussion

Schönrich: Could you determine the oxygen abundance, too, and could the problems with TiO bands be solved by an overabundance of nitrogen with respect to oxygen?

Pavlenko: We know that in the RS Oph atmosphere log $N(O) > log N(C)$. We do not consider the TiO modelling in our work. We plan to determine log $N(O)$ from the water spectrum in the IR region. It is very difficult to see how to expect that log $N(O)$ can be changed during the evolution of RS Oph.