EXTREMELY PECULIAR STARS

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ABSTRACT. The procedure and results of modelling atmospheres, spectral energy distributions and spectra of peculiar stars are discussed. A special attention is drawn to the consideration of the particular problems encountered for peculiar and hydrogen deficient stars on the later stages of evolution. We present some results obtained by fits to observed optical and IR spectra of Sakurai's object, V838 Mon, and RS Oph.

Key words: Stars: evolution: cataclysmic; stars: individual: V838 Mon, V4334 Sgr, RS Oph

1. Introduction

Life of a star is long. Still sometimes one becomes very bright and evolves in the very short time scales. Stellar spectra demonstrate the drastic changes due to the variation of physical conditions in atmospheres and envelopes. The majority of the observed events occur on the latest stages of evolution. The peculiar stars provide the real challenge for observers and theoreticians.

Abundances of at least light elements, i.e. H, He, Li, C, and N, in the atmospheres of evolved stars of the intermediate mases 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 response on any change of abundances (see Pavlenko & Yakovina 1994). Strictly speaking we cannot use for analysis of stellar spectra of the evolved stars the model atmospheres from the extended grids computed recently for fixed abundances (see Kurucz (1993, 1999), Hauschildt et al. (1999). Moreover, in most of the computations the solar abundances (Anders & Grevesse 1989) or solar abundances scaled by the metallicity factor [Fe/H] are used which is grude enough approximation of the abundances distribution in the atmospheres of the evolved stars.

Mdelling spectra of the most evolved stars require much more complicate approach. Their atmospheres are hydrogen deficient but helium and carbon rich. The opacity due to H^- absorption is not as important for them. The menagery of opacity sources in their atmospheres differ from the solar case (Asplund et al. 1999).

2. Procedure

The plane-parallel model atmospheres of the evolved stars in LTE, with no energy divergence were computed by SAM12 program (Pavlenko 2003). The program is a modification of ATLAS12 (Kurucz 1999). 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 element abundance. We add some opacities sources which are of importance in the atmospheres of carbon-rich, hydrogen-deficient stars (see Pavlenko 2003 for more details).

Chemical equilibrium is computed for the different sets of molecular species, by assuming LTE. The nomenclatures of molecules accounted for are different in stellar atmospheres atmospheres of C/O > 1 and C/O < 1.

The opacity sampling approach (Sneden et al. 1976) is used to account for atomic and molecular line absorption. We account mainly for the molecules which are the most abundant or most important sources of opacities. In the case of atmospheres with C/O < 1 we account absorption of VO, TiO, H_2O and molecules from the Kurucz (1993) CDs.

In atmospheres with C/O > 1 rich models of $T_{\rm eff}<$ 5000 K diatomic molecules contained carbon atoms are main contributors of the opacity. In the atmospheres of $T_{\rm eff}<$ 3000 K HCN, NHC, C_3 and other polyatomic carbon molecules contribute to the opacity in the IR part of the spectra (see Harrison at al. 2006 and refs therein).

Synthetic spectra are calculated with the WITA6 program (Pavlenko 1997), using the same approximations and opacities as SAM12.

2.1. Fits to observed spectra

To determine the best fit parameters, we compare

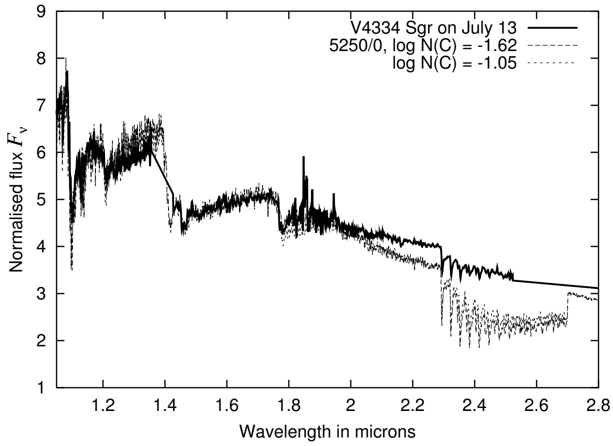

Figure 1: fits to observed spectrum of of Sakurai's Object on 1997 July 13, see Pavlenko et al. (2002) for more details.

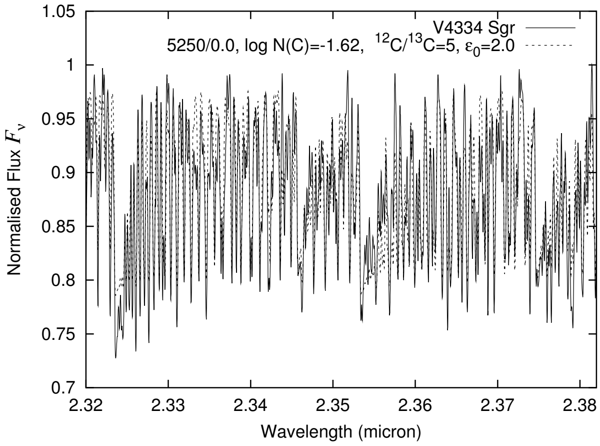

Figure 2: Best fit to 1998 July spectrum found by the minimisation procedure outlined in the text, for $\log N(\mathrm{C}) = -1.05$, see Pavlenko et al. (2005) for more details.

the observed fluxes F_ν with the computed fluxes following the scheme of Jones et al (2002) and Pavlenko & Jones (2003). We let

$$F_\nu^x = \int F_\nu^y \times G(x-y) * dy,$$

where r_ν^y and $G(x-y)$ are respectively the fluxes computed by WITA6 and the broadening profile. We adopt a gaussian + rotation profile for the latter. We then find the minima of the 3D function

$$S(f_\mathrm{s}, f_\mathrm{h}, f_\mathrm{g}) = \sum (F_{obs} - F^x)^2,$$

where f_s, f_g, f_g are the wavelength shift, the normalisation factor, and the profile broadening parameter, respectively. The parameters $f_\mathrm{s}, f_\mathrm{h}$ and f_g are determined by the minimisation procedure for every computed spectrum. Then, From the grid of the better solutions for the given abundances and/or other parameters (microrurbulent velocity, effective temperature, isotopic ratios, etc), we choose the best-fitting solution.

3. Results

3.1. Sakurai's object

V4334 Sgr (Sakurai's Object) discovered by Y. Sakurai on February 20, 1996 (Nakano et al. 1996) is a very rare example of 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 μm) and infrared (1–2.5 μm) spectra of V4334 Sgr (Sakurai's Object) on 1997 - 1998 (Pablenko 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. 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 $T_{\rm eff}$= 5500 $\pm$ 200 K for the April date and $T_{\rm eff}$= 5250 $\pm$ 200 K for July.

Fits of our theoretical spectra to the ^{12}CO and ^{13}CO bands in Sakurai's spectrum at 2.3 μm observed in 1997 allows us to determine the $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratio $^{12}\mathrm{C}/^{13}\mathrm{C} \simeq 4 \pm 1$ (Pavlenko et al. 2005). It is worth noting that we account here a contribution of some additional flux provided by the hot dust on the wavelengths of the first overtone CO bands. The low ratio of $^{12}\mathrm{C}/^{13}\mathrm{C}$ is consistent with the interpretation of V4334 Sgr as an object that has undergone a very late thermal pulse.

3.2. V838 Mon

The peculiar variable star V838 Mon was discovered during an outburst in 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 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) obtained $T_{\rm eff}$= 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 $\log N(\mathrm{Fe}){=}{-4.7}$ does not appear to change

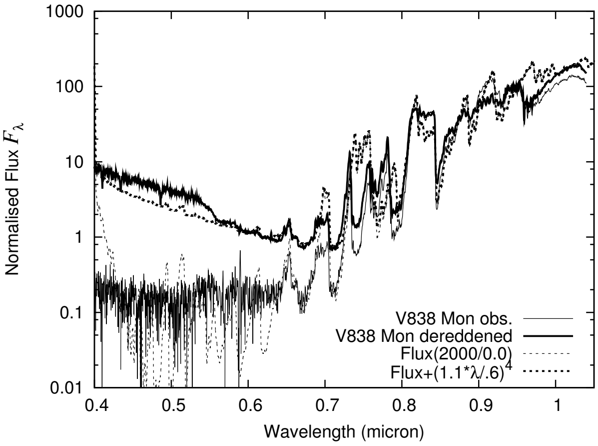

Figure 3: The fit to the observed V838 Mon spectrum on November 6, 2002 , see Pavlenko et al. (2006) for more details.

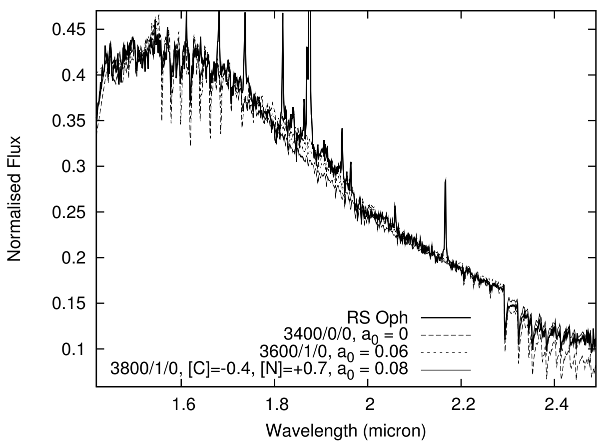

Figure 4: The best fit to the observed spectrum for the cases veiling-free and 'veiled' models, see Pavlenko et al. (2007) for more details.

in the atmosphere of V838 Mon from February 25 to March 26, 2002. Our results agree well with Kipper et al (2005).

Up until November 2002 both effective temperature and luminosity of V838 Mon drop significantly with time (see also Tylenda 2005). Evans et al. (2002) classified one as an L-supergiant (see also Tylenda 2005). The infrared spectrum of V838 Mon shows deep absorption bands of H_2O . In the optical spectra there are strong TiO bands as well as bands of a few diatomic molecules witch can be fitted by theoretical spectrum computed with $T_{\rm eff}$= 2000 K (Pavlenko et al. 2005). Then, at $\lambda < 0.5$ μm Desidera & Munari (2002) discovered spectroscopically a hot companion later confirmrd by Wagner & Starrfield (2002) and classified as B3V star by Munari et al. (2005). Modelling combined B2 V + M9 III spectrum allows us to determine radius of V838 Mon in November 2002 R $\sim$ 6000 R$\odot$, if both stars form the binary system (Pavlenko et al. 2007).

3.3. RS Oph

Recurrent nova (RNe) provide another class of the extremely evolutionary changes. The best studied recurrent RNe RS Oph forms the binary system (WD +red giant M2 III). RS Oph is known to have undergone at least five eruptions, in 1898, 1933, 1958, 1967 and 1985; eruptions in 1907 and 1945, perhaps, were missed.

Recently Pavlenko et al. (2007) carried out detailed study of the IR spectra of RS Oph to better understand the effect of the giant secondary on the recurrent nova eruption. Both the progress of the eruption, and its aftermath, depend on the poorly known yet composition of the red giant in the RS Oph system.

Synthetic spectra were computed for a grid of M-giant model atmospheres having a range of effective temperatures 4000 < $T_{\rm eff}$< 3000 K, gravities 0 < log g < 1, and abundances -1 < [Fe/H] < + 0.5, and fitted to infrared spectra of RS Oph as it returned to quiescence after its 2006 eruption. Pavlenko et al (2007) modelled the infrared spectrum in the range $1.4 - 2.5\mu$m to determine metallicity and effective temperature of the red giant. This allows us to refine both parameters from analysis of the best fits of the synthetic spectra to the observed spectrum of RS Oph .

We found, that the slopes of the spectral energy distribution (SED) and the intensity of molecular bands in the modelled spectra depend on both $T_{\rm eff}$ and [Fe/H]. This allows us to determine $T_{\rm eff}$ = 3800 $\pm$ 100 K, $\log g$ = 1.0 $\pm$ 0.5, [Fe/H] = 0.0 $\pm$ 0.5, [C] = -0.4, [N] = $+0.9$ in the atmosphere of the secondary, together with a degree of 'veiling' in the observed spectra; it is not clear at this stage whether the 'veiling' is due to dust in the environment of RS Oph or to inadequate atmospheric cancellation (see Pavlenko et al 2007 for more details).

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