

# INFREDED SPECTRA OF COOL STARS – NATURE AND MODELS (Review)

Ya.V. Pavlenko

Main Astronomical Observatory of National Academy of Sciences  
Kyiv-127, 03680 Ukraine *E-mail:* yp@mao.kiev.ua

**ABSTRACT.** Problems of modeling of IR spectra of the cool stars are discussed. Some results for M-giants, C-giants, peculiar stars and brown dwarfs are shown.

**Key words:** Infrared spectra, M-dwarfs, L-dwarfs, synthetic spectra, Sakurai's spectra

## 1. Water spectra of M-dwarfs

More than 70% of stars in the vicinity of the Sun are M dwarfs. These numerous low-mass stars ( $0.08 M_{\odot} \leq M < 0.6 M_{\odot}$ ), together with substellar objects - brown dwarfs ( $M \leq 0.08 M_{\odot}$ ) can contain an appreciable amount of the baryonic matter in the Galaxy. Research of M dwarf spectra are of interest for many branches of modern astrophysics. Verification of the theory of stellar evolution and structure of stars, the detection among M dwarfs of a subset of young brown dwarfs, the physical state of plasma of their atmospheres at low temperatures, as well as the chemical and physical processes of dust formation are only a few of them.

The dominant opacity sources in the optical and IR spectra of M dwarfs are electronic band systems of diatomic molecules, such as TiO and VO, as well as rotational-vibrational bands of  $H_2O$ .  $H_2O$  provide special interest for modern astrophysics. Long history of  $H_2O$  band modelling in stellar spectra is described elsewhere (see Pavlenko 2002 and references therein).

Recently Jones et al. (2002) carried out a number of different tests on the fits of observed spectra of M-dwarf in order to find preferred model fits. For every spectrum they carry out the minimisation of a 3D function  $S = f(x_s, x_f, x_w) = 1/N \times \sum (1 - F_{obs}/F_{syn})^2$ , where  $F_{obs}$ ,  $F_{syn}$  are observed and computed fluxes,  $N$  is the number of points in observed spectrum to be fitted,  $x_s$ ,  $x_f$ ,  $x_w$  are relative shift in wavelength scale, a normalisation factor which was used to coincide observed and computed spectra and parameter of instrumental broadening, respectively. As input data Jones et al. (2002) used AMES line lists of  $H_2O$  (Partridge & Schwenke 1998), CO (Goorvich 1984) and NEXTGEN model atmospheres of Hauschildt et al. (1999).

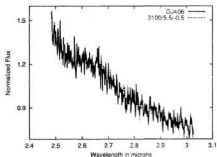


Figure 1: The observed spectrum of GJ 406 compared to a 3100 K,  $\log g = 5.5$ , solar metallicity synthetic spectrum. See Jones et al. (2002) for more details.

Fits to observed spectrum of late spectral type dwarf GJ 406 with strong water bands in the IR are shown in Fig. 1.

## 2. M-dwarfs. CO spectra

M dwarf infrared spectra additionally contain absorption bands of CO. One of most promising observational regions is located in the K band from 2.2 to 2.4  $\mu m$ . Second overtone bands  $^{12}C^{16}O$  and  $^{13}C^{16}O$  are located here. As well as parameters such as effective temperature and gravity, they can be used for determination of carbon and oxygen abundances and the  $^{12}C/^{13}C$  ratio in atmospheres of late-type stars. The determination of the  $^{12}C/^{13}C$  ratio in M dwarf atmospheres is especially interesting. The ratio is a good age indicator for more massive ( $M > 1 M_{\odot}$ ) late-type stars. Following the conventional theory of stellar evolution (see Aller & McLaughlin 1965), M dwarfs save their initial  $^{12}C/^{13}C$  from their time of formation. Since the

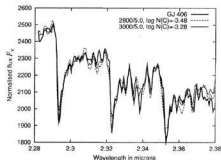


Figure 2: Fit to observed spectrum of GJ406. Synthetic spectra are shown for  $T_{\text{eff}} = 2800$  and  $3000$  K for NEXTGEN model atmosphere (Haushildt et al 1999), line lists of  $\text{H}_2\text{O}$  (Partridge & Schwenke 1998), CO (Goorvich 1994) and VALD (Kupka et al. 1999).

galactic  $^{12}\text{C}/^{13}\text{C}$  ratio is expected to change by around a factor of four over the lifetime of the galaxy, the determination of the  $^{12}\text{C}/^{13}\text{C}$  ratio for M dwarfs potentially gives a strong constraint on their age. Then, atmospheric models need to include additional physical processes in their prescription for mixing between nucleosynthetic cores and observable atmospheres (Palla et al. 2000). On the other hand, M-dwarfs are not expected to modify their  $^{12}\text{C}/^{13}\text{C}$  and are fully convective. Thus the  $^{12}\text{C}/^{13}\text{C}$  ratios for a diverse sample of M dwarfs is expected to be a relatively straight-forward function of time and galactic location. However, determining the  $^{12}\text{C}/^{13}\text{C}$  ratio is only a strong constraint on age if that ratio is a single-valued function of time and Galactic location. If that underlying assumption is not valid, any dispersion of  $^{12}\text{C}/^{13}\text{C}$  in M-dwarf atmospheres might give for us some evidences about mixing processes inside our Galaxy. Unfortunately, due to the technical reasons we can carry out the analysis only for dwarfs of the solar vicinity.

Recently Pavlenko & Jones (2002) performed an extended study of formation of CO bands in atmospheres of late M-dwarfs. Namely, the best fit for M-dwarf GJ 406 was found for  $2800$  K for the solar abundance case, and  $3000$  K for  $\log N(\text{C}) = -3.28$ , Fig. 2. The new estimation of effective temperature corresponds better with empirical values for the effective temperature of the spectral class M6V than the Jones et al. (2002) analysis found using a similar technique but using a region dominated by water vapour. Best fits for GJ406 are found for solar metallicity rather than the metal poor result found by Jones et al. (2002).

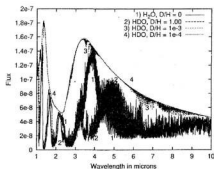


Figure 3: HDO and  $\text{H}_2\text{O}$  molecular bands computed for different D/H for  $1200/5.0$  model atmospheres.

### 3. Brown dwarfs. Deuterium test

Lithium depletion takes place pre-main sequence stars and massive brown dwarfs when the temperature in the core is high enough ( $T \sim 2.5 \cdot 10^6$  K) to produce the following reaction  $\text{Li}(p,\alpha)^4\text{He}$ . Less massive brown dwarfs ( $M < 0.060 M_{\odot}$ ) are unable to reach these temperatures in their interior and this fact has been used to define a substellar criterion by the presence of Li in the atmosphere of these objects, the so called "Lithium test" (Rebolo et al. 1992). This test has been widely proved to determine the true substellar nature of several brown dwarfs (Rebolo et al. 1996, Ruiz et al. 1997, Martin et al. 1998). Additionally the frontier of objects which burn lithium and those less massive which have not yet depleted it (Lithium Depletion Boundary, LDB) provide an alternative method to date clusters younger than  $150$  Myr (Martin et al. 1998; Stauffer et al. 1998, 1999; Basri & Martin, 1999).

Deuterium is an element which can be depleted at lower temperatures than Lithium ( $T \sim 8 \cdot 10^5$  K) in the fusion reaction  $\text{D}(p,^3\text{He})$ . That means that objects below a mass around  $0.011-0.013 M_{\odot}$  (Saumon et al. 1996, Burrows et al. 1997, Chabrier et al. 2000) should preserve their deuterium from the time of formation. Those objects will never burn any element and several authors established at this frontier the separation between brown dwarfs and planets (Saumon et al. 1996). Following the same arguments than in the case of lithium, the "deuterium test" have been recently proposed (Béjar et al. 1999, Chabrier et al. 2000) to discriminate between substellar objects and stars which have burned their deuterium in less than  $1-3$  Myr (D'Antona & Mazitelly 1998, Chabrier et al. 2000). This deuterium test, if applicable in practice,

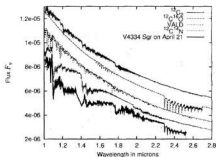


Figure 4: Strongest absorption features identifications in the 1.0-2.5  $\mu\text{m}$  spectrum of Sakurai's Object spectra during 1997, computed for  $T_{\text{eff}}/\log g = 5500/0.0$  model atmosphere of Asplund et al. (1999) abundances. Spectra are artificially shifted on the y-axis. See Pavlenko & Geballe for more details.

will provide a tool to date cluster younger than 50 Myr, including those younger than 7 Myr, in which the lithium dating is no longer valid, because all the stars preserve their initial content (D'Antona & Mazitella 1998, Chabrier et al. 2000).

In Fig.3 we show some spectral energy distributions of ultracool dwarf of  $T_{\text{eff}} = 1200$  K,  $\log g = 5.0$  from a grid of "dusty" C-models of Tsuji (1999) and Shchwenke and Partridge (1998) list of  $\text{H}_2\text{O}$  and HDO lines. Chemical equilibrium of HDO and  $\text{H}_2\text{O}$  were computed using information of molecular levels of  $\text{H}_2\text{O}$  in AMES database (Shchwenke and Partridge 1998). Synthetic spectra were computed by program WITA6 with step 0.05 nm and then convolved with gaussian of 1 nm. SEDs were computed for different D/O ratios (see Pavlenko 2002c for more details).

It's worth to note:

- Bands of HDO are shifted in the IR region in respect to  $\text{H}_2\text{O}$  bands.
- The best regions for D/H ratio determinations are 3.5-4, 6-7 microns as well as a region around 8 micron.

#### 4. 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 extremely fast evolution of a star during a very late final helium-burning event (Duerbeck & Benetti 1996). During the first few months after discovery,

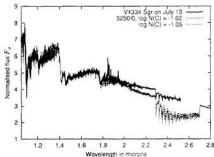


Figure 5: Fits to IR SEDs of V4334 Sgr in 1997.

Sakurai's Object increased in visual brightness to  $V \sim 12^{\text{m}}$ . In 1997 it increased further to  $V \sim 11^{\text{m}}$ . In March 1997 the first evidence of dust formation was seen (Kimeswenger et al. 1997, Kamath & Ashok 1999, Kerber et al. 2000). In early 1998 the optical brightness of Sakurai's Object decreased (dimming first reported by Liller et al. 1998), but then recovered. However, during the second half of 1998 an avalanche-like growth of the dusty envelope occurred, causing a rapid decrease in optical brightness and the complete visual disappearance of the star in 1999. At present essentially only thermal emission by dust can be observed (Geballe et al. 2002). Our view of the born again star has been completely obscured by the dust it has produced.

IR spectra of Sakurai's object is governed by absorption of a few molecules (4). Fits of theoretical SEDs to observed in 1997 - 1998 ones allow us to determine  $T_{\text{eff}}$  and  $E_{\text{B-V}}$  of Sakurai's object at the latest stages of its evolution (Fig. 5 in the frame of self-consistent approach (Pavlenko et al. 2000, Pavlenko & Duerbeck 2001, Pavlenko & Geballe 2002). Fits to IR spectra allows to clearly determine an infrared excess due to emission of hot ( $T > 1000$  K) dust (Fig.5. see Pavlenko & Geballe 2002 for more details).

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