Theoretical Models for Substellar Objects

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Abstract. We present theoretical models for substellar objects (SSOs) covering a mass range from $1 \, M_{\text{Jup}} = 10^{-3} \, M_{\odot}$ to $\sim 0.1 \, M_{\odot}$, characteristic of giant planets and brown dwarfs. Evolutionary models are based on the most recent theoretical developments in the field: equation of state (EOS), non-gray atmosphere models, and synthetic spectra including grain formation. The influence of irradiation by a close stellar companion is explored.

1. Input Physics for the Models

1.1. Interior

SSOs are dense objects, with typical central conditions $T_c \lesssim 10^5$ K and $\rho_c \sim 10^2$-$10^3$ g cm$^{-3}$. One therefore needs to apply corrections to the ideal gas, in order to take into account particle interactions (ion–ion, ion–electron, electron–electron) and pressure ionization. Recent laser-driven shock-wave experiments at Livermore (Collins et al. 1998) explored conditions typical of SSO interiors, reaching pressures of 5 Mbar on liquid D$_2$ at high temperature, and showed a very good agreement with the Saumon–Chabrier EOS (described in Saumon, Chabrier, & VanHorn 1995, and references therein). Our models for SSOs use this EOS for a hydrogen and helium mixture. The contribution of metals does not exceed 1%, and they are therefore neglected (Chabrier & Baraffe 1997).

1.2. Atmosphere and Spectrum Synthesis

The atmospheres of low-mass stars (LMSs) and SSOs ($T_{\text{eff}} \lesssim 5000$ K), contain numerous molecules, such as TiO and VO, main absorbers in the optical, or H$_2$ and H$_2$O which contribute mostly in the near-infrared (a review is given in Allard et al. 1997). They are well reproduced by the NextGen grid of non-gray model atmospheres (Hauschildt, Allard, & Baron 1999), which includes hundreds of millions of molecular transitions. As one goes down the effective temperature scale towards Jovian conditions ($T_{\text{eff}} \sim 170$ K), the chemistry becomes more and more complicated as many species condense into grains, in
particular Al$_2$O$_3$, CaTiO$_3$, or MgSiO$_3$, below $T_{\text{eff}} \sim 2600$ K. At temperatures cooler than $\sim 1400$ K, for the pressures considered, carbon is mostly found in CH$_4$. Our latest model atmospheres, the so-called DUSTY models (Allard et al. 2000) include grain formation, taking into account their effect on the EOS, as well as on the radiative transfer. We also considered the case, in the so-called COND models, where the grains have settled below the photosphere: they still modify the atmosphere EOS but no longer affect the opacity. The latter models are similar to what was done by the Tucson group (Burrows et al. 1997).

2. Evolution

Consistent evolutionary calculations have been performed with our model interiors and three different grids of atmospheres. For objects hot enough to prevent the formation of grains ($T_{\text{eff}} \gtrsim 2600$ K), we have used the NextGen models (Baraffe et al. 1997, 1998), for cooler objects, we have used both the DUSTY and the COND models (Chabrier et al. 2000, see Chabrier & Baraffe 2000 for a review).

We find that the inclusion of grains in the atmosphere affects the evolution only moderately. Their opacity produces a blanketing effect that lowers the effective temperature by 10% at most at a given age. The hydrogen-burning minimum mass changes very little as well, it amounts to 0.072 $M_\odot$ ($T_{\text{eff}} = 1700$ K, $L = 5 \times 10^{-5} L_\odot$) for grainless models, whereas DUSTY models give a slightly lower value of 0.07 $M_\odot$ ($T_{\text{eff}} = 1550$ K, $L = 4 \times 10^{-5} L_\odot$).

Evolutionary tracks for LMSs and SSOs from 1 to 0.001 $M_\odot$ are displayed in Figure 1 on a $T_{\text{eff}}$–$\log g$ diagram, together with isochrones from 1 Myr to 5 Gyr. They are produced with DUSTY models, but differ only slightly from NextGen tracks since the treatment of grains in the atmosphere scarcely affects the star's evolution. This diagram is of particular interest in deriving the approximate intrinsic parameters of a star, its mass and age, directly from two of its observed properties, its effective temperature and gravity.

3. Color–Magnitude Diagram

The most recent models of LMSs and SSOs are compared to the photometric observations of field stars and brown dwarfs of known distance in the $M_K$ vs. $J$–$K$ color–magnitude diagram (CMD) shown in Figure 2. The NextGen models follow the observations closely down to the bottom of the main sequence but fail in the brown-dwarf regime, where the DUSTY models show the onset of grain formation and bring an improved agreement with the observed sequence. However, the DUSTY models predict redder colors as mass decreases, due to the presence of dust in the atmosphere. On the other hand, the COND models, where all the dust has gravitationally settled, predict bluer colors, mainly because of the strong CH$_4$ absorption in the $K$ band, and give a good fit to the position of Gl 229B at the lower end of the mass scale. Actually, the dust is expected to settle as mass decreases, and the DUSTY tracks should turn back (in near-IR colors) towards the blue and meet the COND tracks. The redder brown dwarfs observed give a hint of this deviation from the DUSTY tracks. A full dynamical model
Figure 1. Evolutionary tracks in a $\log g$ (cm s$^{-2}$) vs. $T_{\text{eff}}$ (K) diagram for LMSs (solid curves) and SSOs (dashes) from 1 to 0.001 $M_\odot$ (masses in $M_\odot$ are indicated on the curves). Isochrones for 1 Myr, 10 Myr, 100 Myr, and 5 Gyr (bottom to top) are shown in dotted lines.

for the grains would be required to tell whether there is a complete sequence between the L dwarfs and the methane dwarfs or if the transition is sharp and a gap is to be expected.

4. Spectral Sequence

Figure 3 shows a spectral sequence of model atmospheres of brown dwarfs to giant planets at 20 pc. They are calibrated to absolute flux using radii from consistent evolutionary models (Chabrier et al. 2000) and matched to a 5 Gyr isochrone. The dust grains in the atmosphere are allowed to settle when they exceed the local gas mass density. The spectra shown here change rather continuously from the warmer objects to the cooler ones as some molecular bands appear and others vanish. No clear boundary can therefore be defined between brown dwarfs and giant planets from their atmospheric properties.

The effect of dust opacity can be seen by comparison with a model where the dust is not allowed to settle and stays in the atmosphere: the larger opacity lowers the flux at the blue end of this wavelength range whereas the flux at the redder end is larger due to a more important backwarming effect. The opposite can be seen with a model with no dust opacity at all.

The detection limits of ground- and space-based instruments displayed in Figure 3 show that it is possible to detect isolated SSOs down to fairly low effective temperatures.
Figure 2. Theoretical isochrones in a $M_K$ vs. $J-K$ CMD for NextGen models at 1 Gyr (dashed–dotted line), and for DUSTY (○, labels give masses in $M_\odot$ and $T_{\text{eff}}$) and COND (×) models at 100 Myr (dashed line) and 1 Gyr (solid line). Observational data are plotted with ● (Leggett 1992), □ (Dahn et al. 2000), △ (Reid et al. 2000) and ○ (identified brown dwarfs).

5. Irradiation by a Parent Star

It is a different story altogether for brown dwarfs or giant planets orbiting a star: they can easily be hidden in the flux of the much brighter star. However, dust clouds in the SSO’s atmosphere may increase its albedo sufficiently to make it detectable in the optical, where the clouds are brightest.

We have computed models of a $T_{\text{eff}} = 1000$ K planet irradiated by a solar-type (G2 V) star at orbital distances of 0.05, 0.1, and 0.2 AU. The resulting spectra are shown in Figure 4 together with the spectrum of the free-floating planet. In this simple test case, the irradiation is assumed to be isotropic. The planet model includes dust formation and opacities and is iterated to conserve a constant intrinsic flux in the radiative layers.

As can be seen, the parent star can substantially heat the planet’s atmosphere, causing the dust clouds to vanish and the molecular bands even to disappear from its spectrum. However, the expected effect is small, and the planet
stays significantly fainter than its parent star with its flux still peaking in the near infrared.

6. Conclusion and Perspectives

![Figure 3](image)

Figure 3. Spectral sequence of dusty SSO atmospheres at 20 pc. From top to bottom: $T_{\text{eff}} = 2500, 1900, 1800, 1300, 700, 400,$ and $200$ K (solid curves). Models at 1800 K with no dust settling (dashed curve), and at 400 K without dust opacity (dotted curve) are also shown. Detection limits of a few instruments are indicated.

The CMD of Figure 2 and others not shown here (see Chabrier et al. 2000) demonstrate the good agreement between the present theoretical models of SSOs including dust formation and opacity and the observations. They can be used to calibrate the intrinsic properties of late M to L dwarfs.

However, the models do not reproduce a full sequence down to the methane dwarfs and the gap between the DUSTY and COND tracks needs to be investigated. The next step of our theoretical work will be to include the dynamical processes of grain formation, diffusion, and settling.

We also intend to improve the reflected-light calculations with a consistent treatment of the evolution of irradiated planets for different values of the orbital distance and of the masses of the planet and parent star.
Figure 4. Spectrum of a young extrasolar giant planet ($T_{\text{eff}} = 1000$ K) irradiated by a G2 V primary at 15 pc (topmost spectrum) at orbital distances of 0.05, 0.1, 0.2 AU and $\infty$ (from top to bottom). The long-dashed curve is the spectrum of a 1000 K blackbody.

References


Discussion

Tristan Guillot: A comment: your 0.05 AU models assume $T_{\text{eff, intrinsic}} = 1000$ K. In the case of a 1 $M_{\text{Jup}}$ planet, we get typically after a few Myr $T_{\text{eff, intrinsic}} \sim 100$ K.

Jean-François Gonzalez: Yes, but this model doesn’t necessarily correspond to a real exoplanet. It is a test case, done with models that we know to be reliable, as supported by brown-dwarf observations. Computations with colder models are being currently being done and will be available soon.