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Expect the unexpected: non-equilibrium processes in brown dwarf atmospheres

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Abstract. Brown Dwarf atmosphere are a chemically extremely rich, one example being the formation of clouds driven by the phase-non-equilibrium of the atmospheric gas. Cloud formation modelling is an integral part of any atmosphere simulation used to interpret spectral observations of ultra-cool objects and to determine fundamental parameters like log(g) and $T_{\rm eff}$. This proceeding to the workshop *GAIA and the Unseen: The Brown Dwarf Question* first summarizes what a model atmosphere simulation is, and then advocates two ideas: A) The use of a multitude of model families to determine fundamental parameters with realistic confidence interval. B) To keep an eye on the unexpected, like for example, ionisation signatures resulting plasma processes.

Key words. Stars: abundances – Stars: atmospheres

1. Introduction

Brown dwarfs atmospheres are chemically very active as cloud particles form inside their atmosphere if the atmospheric gas is in phase-non-equilibrium. This formation process transforms the atmosphere into an inhomogeneously depleted gas with an additional strong opacity component in form of cloud particles. Other processes that drive the atmosphere out of equilibrium are, for example, the impact of galactic cosmic rays and rotationally driven winds. Neither of the latter two is included in any consistent atmosphere model yet

The discovery of the new and unexpected requires to understand the underlying model assumptions, in this case, the extant to which model atmosphere simulations are applicable and how to make the most of the diversity at hand.

Physical modelling and numerical simulations are the backbone of understanding observational data. Ideally, a consistent description of physical and chemical processes is aimed for which is determined by a minimum set of global parameters. Stellar atmosphere modelling has greatly inspired the brown dwarf modelling community, and hence, the global parameter normally referred to are the effective temperature, $T_{\rm eff}$, which represents the total observable flux emitted, the surface gravity, log(g), the radius or mass, and the element abundances. These global parameters are linked to the formation (mass, element abundances) and evolution ($T_{\rm eff}$, element abundances) of the object. The physical principles at the base of every model atmosphere are energy, momentum and mass conservation. The solution of the radiative and convective energy transport provides the local gas temperature,

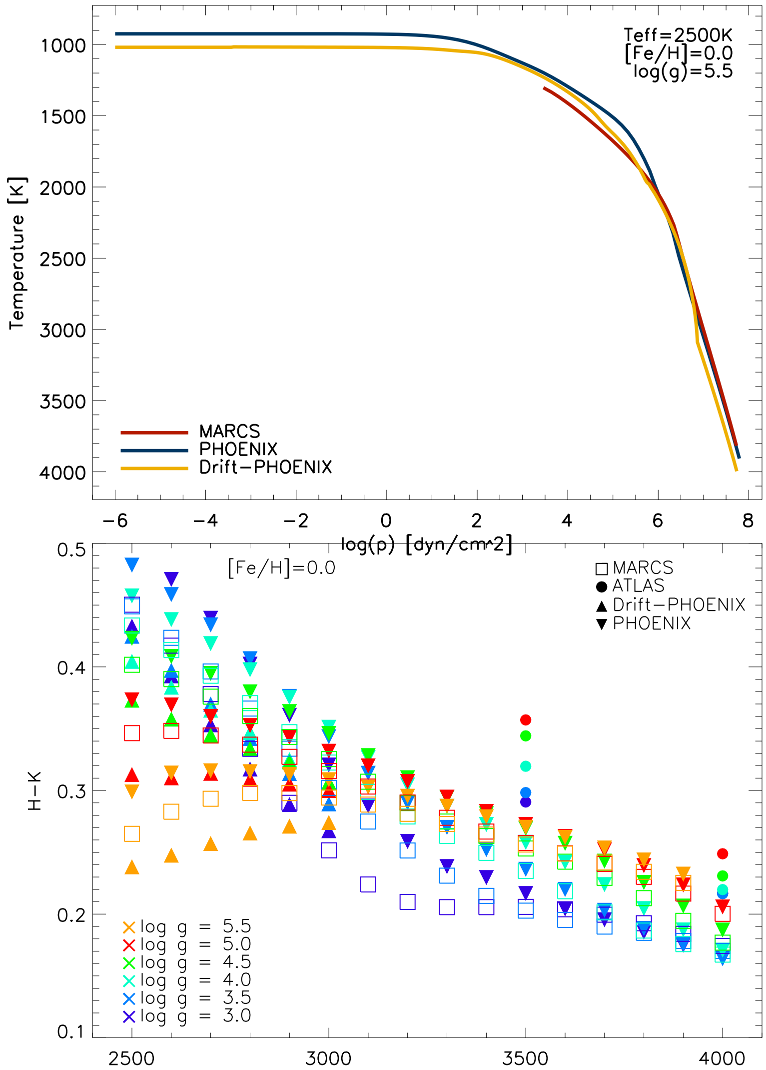

Fig. 1. **Top:** Differences in the resulting (T_{gas}, p_{gas}) structure of MARCS, PHOENIX, and DRIFT-PHOENIX model atmosphere simulations for a brown dwarf atmosphere of T_{eff}=2500K and log(g)=5.5. **Bottom:** Differences in the H-K colour (UKIDSS filters) depending on the effective temperature, T_{eff}, and surface gravity, log(g), for ATLAS, MARCS, PHOENIX, and DRIFT-PHOENIX model atmosphere simulations.
The assumed element abundances are solar but will differ in detail for the individual elements. (Please refer to Bozhinova et al. (2014) for detailed references to the model atmosphere grids.)

T_{gas} (e.g. top panel in Fig. 1), the convective velocity, v_{conv}, for each atmosphere layer and the wavelength dependent energy distribution F_λ (the synthetic spectrum). 1D (brown dwarf) model atmospheres assume hydrostatic equilibrium which provides the local gas pressure, p_{gas}. A calculation of the chemical composition of the atmosphere for ($T_{gas}(z)$, $p_{gas}(z)$) (e.g. top panel in Fig. 1) based on the pre-scribed element abundances allows the calculation of the gas-phase opacities that are needed for the radiative transfer calculation through the atmosphere. The chemical composition, ($T_{gas}(z)$, $p_{gas}(z)$, v_{conv}), and the initial element abundances determine the formation of clouds in brown dwarf and in planetary atmospheres. Clouds have a strong feedback onto the atmospheric structure as they deplete element abundances and provide a strong source for radiative heating and cooling by their opacity.

Several groups do perform such model atmosphere simulations that span across several spectral types (see references in Plez 2011; Rojas-Ayala et al. 2013; Bozhinova et al. 2014) but comparison studies or the use of different model atmosphere grid to determine confidence intervals are still sparse. The use of different model atmosphere grids for data interpretation should be made good scientific practice in the times of GAIA and PLATO. The *Virtual Observatory* will soon be providing the opportunity to apply more than one model atmosphere families to observations. This would also allow an open mind regarding processes that are not yet included in model atmosphere simulations (e.g. non-thermal ionisation) and that could help with *weather* detections on brown dwarfs (Morales-Calderón et al. 2006; Biller et al. 2013; Buenzli, E. et al. 2014).

2. The need of model diversity

Sarro et al. (2013) present a module that will be used to detect and characterize ultra-cool dwarfs in the *Gaia* database. The module was trained with Phoenix-based AMES and BT-settle models for solar metallicity, and errors suggested range from 10K to 300K. The energy transfer core module including the gas-phase chemistry is the same for both model families used. Therefore, the biggest difference between these Phoenix derivatives is the cloud modelling which is important for T_{eff} < 2700K. Differences in line list data will only play a role at high effective temperatures where no clouds form in the atmosphere.

The need for model atmosphere diversity has been demonstrated, for example, with respect to disk detection. Sinclair et al. (2010) re-analyzed far-IR Spitzer data, and they show that the number of disk detections varies if different model atmospheres were used to determine the far-IR excess.

Southworth (2012) presents parameters of 38 exoplanets based on an analysis of homogeneous set of observations. As the author states, the physical properties of any transiting planet can as yet not be determined by observing the planet alone but additional constrains are needed. These constrains are provided through parameters from the host stars that are determined by applying multiple stellar evolutionary models (Sect 3.1. in Southworth 2012), which then allows to discuss systematic errors as presented in e.g. Table 4 in Southworth (2012) (see also the paper's Appendix).

The work by Bozhinova et al. (2014) suggest that the difference in model atmosphere results can be used to provide a better estimate of the confidence interval for planetary equilibrium temperatures and for the location of the habitable zone around M dwarfs. Both measures are related to the sustainability of life-important chemical species. A change of only 20K can already hinder the existence of liquid water on a planetary surface. We note, that it is very unrealistic to claim that any of the model atmospheres can achieve such a accuracy in predicting global parameters with such a precision from observed spectra. Comparative spectrum fitting as in Dupuy et al. (2010); Patience et al. (2012); Bonnefoy et al. (2014) demonstrate this clearly. Kane (2014) demonstrates the uncertainty of the habitable zones location resulting from stellar parameter uncertainties for confirmed exoplanetary host stars and *Kepler* candidate hosts.

Figure 1 (top) shows as an example the comparison of the local gas temperature - gas pressure profile (T_{gas}, p_{gas}) for a brown dwarf atmosphere simulation from three different model families. Each of these three models represents one symbol in Fig. 1 (bottom) which shows the differences between the model families in H-K colour plotted for the available effective temperatures, T_{eff}, and surface gravities, log(g). Differences are largest for low T_{eff}, but this reflects more the differences between cloud-free (ATLAS, MARCS, Phoenix) and cloudy models (Drift-Phoenix). The differences at the high-temperature end of the T_{eff}-axis are suggested to result from differences in gas-opacity data, element and chemical abundances, convective treatment.

Plavchan et al. (2014) note that such model differences may be responsible for uncertainties of planetary radii as derived for planets in the *Kepler* sample. They suggest that improving stellar parameters is essential for resolving this radius issue, which hence requires a sensible use of model atmospheres results.

3. The unexpected

Brown dwarfs seemed the perfect example for a static atmosphere, until it was understood that cloud formation plays a major role for their atmospheres (Tsuji et al. 1996). Then, older brown dwarfs were though to be the perfect example for a neutral atmosphere, until it was suggested that detections of radio emission (Berger et al. 2001) should be related to ionisation processes inside the atmosphere (Helling et al. 2011b). Meanwhile, different processes were shown to contribute to the increase of the local ionisation, including wind-driven gas ionisation (Stark et al. 2013) and gas and cloud particle ionisation by cosmic rays (Rimmer & Helling 2013). The atmospheric clouds can easily ionise in a turbulent atmosphere (Helling et al. 2011a) leading to electron or dust dominated discharge regimes (Fig. 10 in Helling et al. 2013). If a small-scale discharge successfully sets of, an ionisation front develops that travels through the atmospheric gas and eventually emerges as a large-scale lightning or sprite. Bailey et al. (2014) present a table of typical lightning signatures and refer to detectors for possible observations on Earth. This suggest that similar observations might be possible for brown dwarfs in the future, or that such signatures may be present but hidden in existing data.

4. Conclusions

As a result of the Gaia workshop, Drift-Phoenix will be included into the model atmosphere database of the Virtual Observatory to allow a multi-model approach to observations.

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