

## Atmospheres of Brown Dwarfs

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**Abstract** Brown Dwarfs are the coolest class of stellar objects known to date. Our present perception is that Brown Dwarfs follow the principles of star formation, and that Brown Dwarfs share many characteristics with planets. Being the darkest and lowest mass stars known makes Brown Dwarfs also the coolest stars known. This has profound implication for their spectral fingerprints. Brown Dwarfs cover a range of effective temperatures which cause brown dwarfs atmospheres to be a sequence that gradually changes from a M-dwarf-like spectrum into a planet-like spectrum. This further implies that below an effective temperature of  $\lesssim 2800\text{K}$ , clouds form already in atmospheres of objects marking the boundary between M-Dwarfs and brown dwarfs. Recent developments have sparked the interest in plasma processes in such very cool atmospheres: sporadic and quiescent radio emission has been observed in combination with decaying X-ray-activity indicators across the fully convective boundary.

**Keywords** (Stars:) brown dwarfs · Stars: low-mass · Stars: atmospheres · infrared: stars · Radio lines: stars · X-rays: stars

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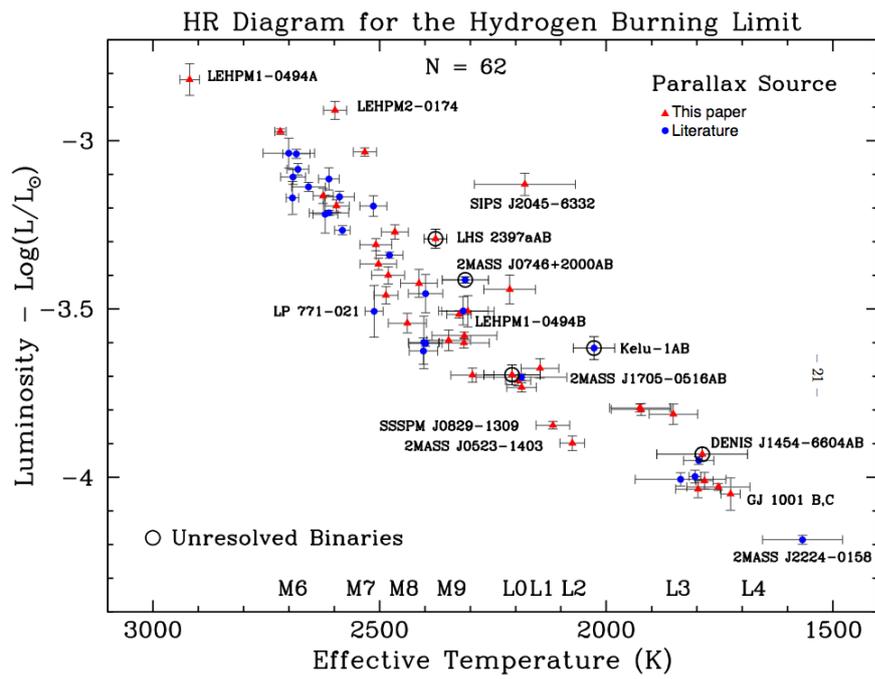
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## 1 Introduction

Brown dwarfs are free-floating stellar objects with masses below the hydrogen-burning limit of  $\sim 0.075M_{\odot}$  and with radii of  $\approx 1R_{\text{Jup}}$  for mature objects, although this can vary with cloud cover and metallicity. They are the low-mass extension of the sub-solar main-sequence in the Hertzsprung-Russel diagram (HRD, Fig. 1). Their total emitted flux, and hence their effective temperature  $T_{\text{eff}}$ , is lower than that of M-dwarfs. Brown dwarfs become increasingly dimmer as they age because their mass is too small to sustain continuous hydrogen burning. Only in their youth, the heaviest brown dwarfs fuse some helium and maybe lithium. Hence, the class of brown dwarfs comprises members that are just a little cooler than M-dwarfs (L dwarfs) and members that can be as cold as planets (T and Y dwarfs). Several formation mechanisms are suggested, including the classical star-forming scenario of a local gravitational collapse of an interstellar molecular cloud. The formation efficiency may have changed depending on time and location. The oldest brown dwarfs could be as old as the first generation of stars that formed in the universe. Their metallicity would be extremely low leaving the spectrum almost feature-less (Fig. 9 in Witte et al 2009). Luhman (2012) reviews the formation and evolution of brown dwarfs, including the initial mass function and circumstellar disks. Observational evidence builds up for that brown dwarfs and giant gas planets overlap in masses and in global temperatures (see review Chabrier et al 2014). Joergens (2014) reviews the emergence of brown dwarfs as a research area started by a theoretical prediction of their existence, and emphasizes the research progress in formation and evolution of brown dwarfs. Allard et al (1997) reviewed model atmospheres of very low mass stars and brown dwarfs discussing model aspects like updating gas-phase opacities, convection modelled by mixing length theory, and the  $T_{\text{eff}}$ -scale for M-dwarfs. The present review summarizes the progress in brown dwarf observations extending now from the UV into the radio, revealing new atmospheric processes and indicating overlapping parameter ranges between brown dwarfs and planets (Sect. 2). Special emphasis is given to cloud modelling as part of the brown dwarf atmospheres, a field with increasing importance since the first review on brown dwarf atmospheres by Allard et al (1997) (Sect. 3). Since Allard et al (1997), a considerably larger number of brown dwarfs is known which allows first statistical evaluations, one example being the search for correlation between X-ray emission and rotational activity in brown dwarfs. Wavelength-dependent variability studies have gained momentum, and the idea of weather on brown dwarfs is commonly accepted since the first variability search by Tinney and Tolley (1999a). In the following, we summarize the observational achievements for field brown dwarfs. We ignore the specifics of young brown dwarfs as this is reviewed in e.g. Luhman (2012) and concentrate on evolved brown dwarfs, not on individual star forming regions or brown dwarfs with disks. Section 4 discusses the idea of model benchmarking as it emerged in the brown dwarf community. Section 5 gives an outlook regarding new challenges like multi-dimensional atmosphere modelling and kinetic gas-phase chemistry.



**Fig. 1** The low-mass end of the main sequence in the HRD diagram showing the transition from the stellar M-dwarf to the substellar brown dwarf regime (Dieterich et al 2013).

## 2 Brown dwarf observations in different spectral energy ranges

In this section of the review we aim to bring the reader up to date with the observations of brown dwarfs. We describe the recent results focusing on cloud effects in low gravity objects, and their comparison with young extrasolar planets, as well as observations of low metallicity objects. We also discuss the recent reports of photometric and spectroscopic variability of brown dwarfs, which is linked to patchy clouds, temperature fluctuations within the atmosphere and weather effects, as well as high energy phenomena that are linked to emissions seen in the radio, X-ray and UV wavelength regimes.

### 2.1 Optical and IR spectral types

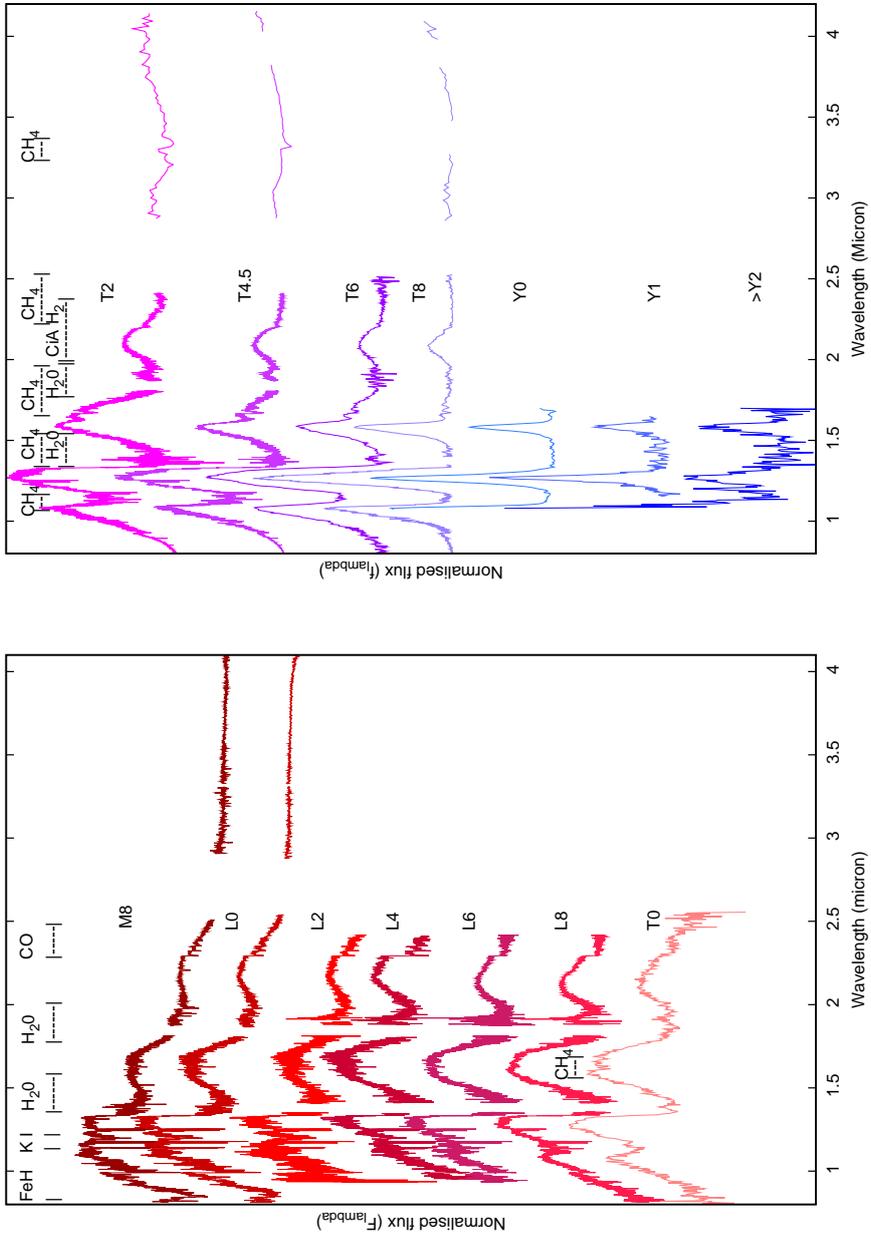
Although the first brown dwarf to be discovered was the L4 dwarf GD165B (Becklin and Zuckerman, 1988), it was not identified as such until the discovery of Gl229B (Nakajima et al, 1995) and Teide 1 (Rebolo et al, 1995) in 1995. Since then, astronomers have searched for a way of classifying brown dwarfs. These objects are very different from the M dwarfs known at the time, and the contrast between the dusty L dwarfs and the methane rich T dwarfs is stark. Both these spectral types are discussed extensively in the literature and are not described here in great detail (Burrows et al 2001; Lodders and Fegley 2006 for an overview).

The L dwarfs are similar to M dwarfs in photospheric chemical composition, containing alkali lines of (K, Na) and metal hydrides (FeH) and oxides (TiO, VO) and water. As we progress through the spectral types from L0 to L9, the TiO and VO bands weaken, the alkali lines become weaker and more pressure broadened, and the water bands and FeH strengthen in the optical. In the near-IR, CO strengthens towards the mid-L dwarfs, and then weakens again as methane begins to form. The change between the L and T dwarfs, often called the L-T transition region is characterized by the near-infrared colours of the brown dwarfs changing, while the effective temperature of the objects remains the same (Figure 2; see Kirkpatrick et al 1999 for a review). T dwarfs, sometimes called methane dwarfs are characterized by the methane absorption seen in the near-IR that gets progressively stronger as one progresses through the subclasses, making the  $J - H$  and  $H - K$  colours bluer. In the optical, the spectrum is affected by collisionally induced molecular hydrogen absorption and FeH.

2011, marked the discovery of an additional, and later spectral type, the Y dwarf. There are  $\sim 20$  Y dwarfs known to date (Cushing et al, 2011; Luhman et al, 2011; Kirkpatrick et al, 2012, 2013; Cushing et al, 2014). The majority of these have spectral types ranging between Y0 and Y2 and were discovered using the *Wide-field Infrared Survey Explorer* (WISE). WISE was designed to discover Y dwarfs: its shortest wavelength band at  $3.4\mu\text{m}$  was selected to fall in the centre of the fundamental methane absorption band at  $3.3\mu\text{m}$  and the W2 filter at  $4.6\mu\text{m}$  detects radiation from the deeper, hotter layers in the atmosphere. When combined, the W1-W2 colour is very large, allowing the detection of Y dwarfs (Kirkpatrick et al, 2011).

All the Y dwarfs show deep H<sub>2</sub>O and CH<sub>4</sub> absorption bands in their near-infrared spectra, similar to late-T dwarfs (Figure 2). These water clouds were measured in detail by Morley et al (2014b). The *J* band peaks of the Y dwarfs are narrower than those of the latest type T dwarfs, and the ratio of the *J* and *H* band flux is close to 1, meaning that the *J* – *H* trend towards the blue for T dwarfs turns back towards the red for Y0. This trend also occurs for the *Y* – *J* colour. This colour reversal is thought to be caused by alkali atoms, that normally dominate the absorption in the shorter wavelengths, being bound in molecules, thus reducing the alkali atom opacity (Liu et al, 2010). While the *H* band spectra of T dwarfs are shaped by CH<sub>4</sub> and H<sub>2</sub>O, for Y dwarfs as the effective temperature decreases, NH<sub>3</sub> absorption becomes important (Lodders and Fegley, 2002; Burrows et al, 2003).

Cushing et al (2011) estimate  $T_{\text{eff}} = 350 \dots 500\text{K}$  for the Y0 dwarfs, with their masses between  $\sim 5$  and  $20 M_{\text{Jup}}$ . However, using a luminosity measurement derived from a *Spitzer* based parallax, Dupuy and Kraus (2013) estimate their effective temperatures to be typically 60-90 K hotter. This difference in temperature is possibly caused by using near-IR spectra, a regime where only 5% of the Y dwarf flux is emitted and so models do not always accurately reproduce the observations (Dupuy and Kraus, 2013). Using models containing sulphide and chloride clouds from Morley et al (2012), Beichman et al (2014) obtain the lower effective temperatures, suggesting that previous results apply on a model dependent bolometric correction. There is one other Y dwarf, not discovered by WISE: WD0806-661B, which was until recently, the most likely candidate for the lowest mass and temperature Y dwarf at 6-10  $M_{\text{Jup}}$  and 330-375 K, although there are as yet no spectra of this object. This has since been superseded by the discovery of WISEJ085510.83-071442.5, a high proper motion Y dwarf at 2 pc. This object is our fourth nearest neighbour and has an estimated effective temperature of 225-260 K and a mass of 3-10  $M_{\text{Jup}}$  (Luhman, 2014).



**Fig. 2** The near-infrared spectral sequence from early-M dwarfs to early-Y brown dwarfs. All spectra are normalised to 1 at their peak and then a flux offset is applied (Kirkpatrick, 2013).

### 2.1.1 Brown dwarf classification

Brown dwarf spectral types do not fit into the standard Morgan-Keenan stellar spectral types system because their age-mass-temperature degeneracy causes the classical stellar mass-temperature relationship to break down for such ultra-cool objects. An object of a specific spectral type (or effective temperature) may be higher mass and old, or lower mass and young. For instance, an L5 dwarf ( $T_{\text{eff}} \sim 1500$  K) in the Pleiades cluster (125 Myr) has a mass of  $25 M_{\text{Jup}}$ , but a field dwarf of the same spectral type is much more massive at  $70 M_{\text{Jup}}$  (Chabrier et al, 2000).

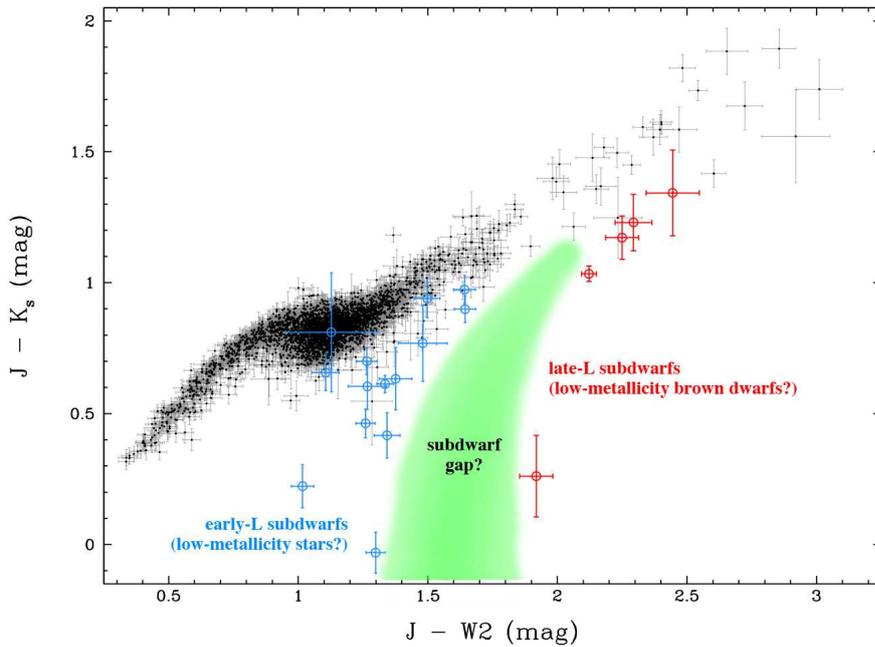
There are in general three methods of identifying a brown dwarf's spectral type: the first, by comparison with spectral templates as is usual for stars that fit the Morgan-Keenan classification scheme, the second is by using indices derived from spectral parameters and the third is by comparing broadband photometry to spectral standards. The first two methods are described for the L dwarf classification in the optical wavelength range by Kirkpatrick et al (1999) and Martín et al (1999), respectively. The most commonly used method is to compare spectra of objects to "standard" or "template" spectra and to use spectral indices as a secondary calibration tool, for instance to judge metallicity or gravity (see Sect. 2.1.3 for the gravity classification scheme). The template scheme was extended into the near-IR by Reid et al (2001), and the indices by Geballe et al (2002). This index scheme is now more widely used than that of Martín et al (1999) and extends down to T9. Burgasser et al (2006) combined the index scheme of Geballe et al (2002) with their template (Burgasser et al, 2002) to create a unified way of spectral typing T dwarfs. When using these methods to classify L and T dwarfs it should be noted that the assigned spectral types are limited to only the parts of the spectrum that are measured. For objects on the L-T transition, it is not unusual to have optical and near-IR derived spectral types that differ by  $>1$  spectral type.

### 2.1.2 Low metallicity brown dwarfs

Low metallicity brown dwarfs (subdwarfs) provide an insight into the coolest, oldest brown dwarfs. The existence of low-metallicity brown dwarfs indicates that such low-mass stars also formed in a younger universe when the metallicity was lower than today. It is further of interest to comparing their atmospheres to those of low metallicity extrasolar planets which formed as by-product of star formation.

Only a handful of ultracool subdwarfs are known to date (Burgasser et al, 2003; Burgasser, 2004; Cushing et al, 2009; Sivarani et al, 2009; Lodieu et al, 2010; Kirkpatrick et al, 2010; Lodieu et al, 2012; Mace et al, 2013; Kirkpatrick et al, 2014; Burningham et al, 2014). Of the  $\sim 30$  objects known to date, only 11 have spectral types later than L2 (Kirkpatrick et al, 2014; Burningham et al, 2014; Mace et al, 2013). The naming scheme for subdwarfs follows that for M dwarfs developed by Gizis (1997) and upgraded by (Lépine et al, 2007), moving from dM for metal rich M dwarfs to subdwarfs (sdM), extreme subdwarfs (esdM) and ultra subdwarfs (usdM) in order of decreasing metallicity.

Burgasser et al (2008) noted that L subdwarfs are overluminous in  $M_J$ , but slightly underluminous in  $M_K$ . This change is suggested to be caused by a reduced cloud opac-



**Fig. 3** The effective temperature gap between brown dwarfs and M-dwarfs increases with lower metallicity (lower  $J-K_s$ ). Known late-M (SpecT < sdL5 – blue circles) and L subdwarfs (SpecT > sdL5 – red circles) and AllWISE proper motion stars (solid black dots) are shown (Kirkpatrick et al 2014). Kirkpatrick et al (2014) suggest that the wedge (green zone) covers an area in the diagram where L subdwarfs may rarely be found.

ity causing strong TiO, FeH, Ca I and Ti I features, and enhanced collisional-induced  $H_2$  opacity in the  $K$  band as predicted by Ackerman and Marley (2001); Tsuji et al (1996b). These sources of opacity will be discussed in more detail in Section 3. Kirkpatrick et al (2014) suggests that an L subdwarf "gap" exists between the early L and late L subdwarfs. This could be explained if lower metallicity brown dwarfs would generally be the older objects. For older brown dwarfs, an effective temperature gap is observed to occur between the hotter, deuterium-burning subdwarfs (blue symbols in Fig. 3), and the coolest, lowest mass members of similarly aged hydrogen burning stars (M-dwarfs, red symbols in Fig. 3). This temperature gap is predicted to increase for older populations Kirkpatrick et al (2014).

Recently, a population of T subdwarfs has emerged (Burningham et al, 2014; Mace et al, 2013). T dwarf colours are very sensitive to small changes in metallicity - a shift of 0.3 dex can change the  $H-[4.5]$  colours of T8 dwarfs as much as a 100 K change in effective temperature (Burningham et al, 2013). The T dwarfs exhibit enhanced  $Y$  and depressed  $K$  band flux, indicative of a high gravity, and hence older age, and low metallicity atmosphere (Burgasser et al, 2002). The increased  $Y$  band flux is caused as the lower metallicity reduces the opacity in the wings of the alkali lines, resulting in a brighter and broader peak flux (Burgasser and Kirkpatrick, 2006). The

*K* band flux depression is created as pressure-enhanced collision induced absorption by molecular hydrogen becomes more important, as molecular features are removed from the spectra (Saumon et al, 1994).

### 2.1.3 The surface gravity of brown dwarfs

Young, low gravity brown dwarfs have very similar properties to directly-imaged exoplanets (Faherty et al, 2013b) and it has been suggested that younger brown dwarfs ( $\log(g) \approx 3$ ) may have thicker clouds in their atmospheres than those present in older objects ( $\log(g) \approx 5$ ) of the same effective temperature (Barman et al, 2011; Currie et al, 2011; Madhusudhan et al, 2011). Helling et al (2011b) demonstrate that the geometric cloud extension<sup>1</sup> increases with decreasing surface gravity  $\log(g)$  in cloud-forming atmospheres, an effect likened to an increasing pressure scale height  $H_p \sim 1/g$ , and Marley et al (2012) suggest that these clouds persist for longer, at higher temperatures, than in older objects.

Many brown dwarfs have been identified in young open star clusters (e.g. Sigma Ori: (Bihain et al, 2009; Peña Ramírez et al, 2012), Serpens: (Spezzi et al, 2012); Pleiades: (Casewell et al, 2011, 2007); see Luhman et al 2012 for a review). However, there also exists a field population of low gravity, young brown dwarfs (e.g. Reid et al 2008; Cruz et al 2009; Kirkpatrick et al 2010). A comprehensive scheme for defining the gravity of these objects was devised by Kirkpatrick et al (2008) and Cruz et al (2009) in the optical, and Allers and Liu (2013a,b) in the near-infrared. The classification introduces a suffix of  $\alpha$ ,  $\beta$ , or  $\gamma$  to the spectral type, indicating the gravity.  $\alpha$  implies a normal gravity field dwarf, whereas  $\beta$  is an intermediate-gravity object and  $\gamma$  represents a low-gravity object. These suffixes can also be used as a proxy for age.

In the optical, the suffixes are assigned based on measurements of the Na I doublet and the K I doublet which are weaker and sharper in a low gravity object, the VO absorption bands which are stronger, and the FeH absorption features which are weaker. We note that decreasing hydride molecules are typical for low metallicity stars of higher mass, hence higher temperature. The abundance of such hydrogen-binding molecules decreases in brown dwarfs because cloud formation decreases the metal components available.

In the near-infrared, the VO and FeH bands are considered simultaneously with the alkali lines to derive  $\log(g)$ . The changing shape of the *H*-band is also taken into consideration. It becomes more triangular-shaped caused by increasing water absorption as a sign of low gravity (Lucas et al, 2001; Rice et al, 2011). All of these features are altered as there is less pressure broadening due to the object having a low surface gravity causing the pressure scale height to increase (Rice et al, 2011; Allers and Liu, 2013a). In general, alkali absorption features are weaker, and the overall colours of lower gravity objects are redder than those of their higher gravity counterparts (Faherty et al, 2013c). The redder colour is due, in part, to the changes in

<sup>1</sup> The geometrical cloud extension, or cloud height, can be defined in various ways. Woitke and Helling (2004) used the degree of condensation for Ti (their Eq. 16) for defining the cloud height. The distance between the gas pressure at the nucleation maximum and the gas pressure where all cloud particles have evaporated determine the cloud height in Helling et al (2011b).

the near-infrared broadband features, but also due to more photospheric dust (Helling et al, 2011b). An additional feature is that while young M dwarfs ( $\log(g) \approx 3$ ) are brighter than their older ( $\log(g) \approx 4.5$ ) counterparts, young L dwarfs ( $\log(g) \approx 3$ ) are underluminous in the near-infrared for their spectral type. This may be due to the additional dust in their photosphere (Faherty et al, 2013a) or due to a cooler spectral type/temperature relation being required.

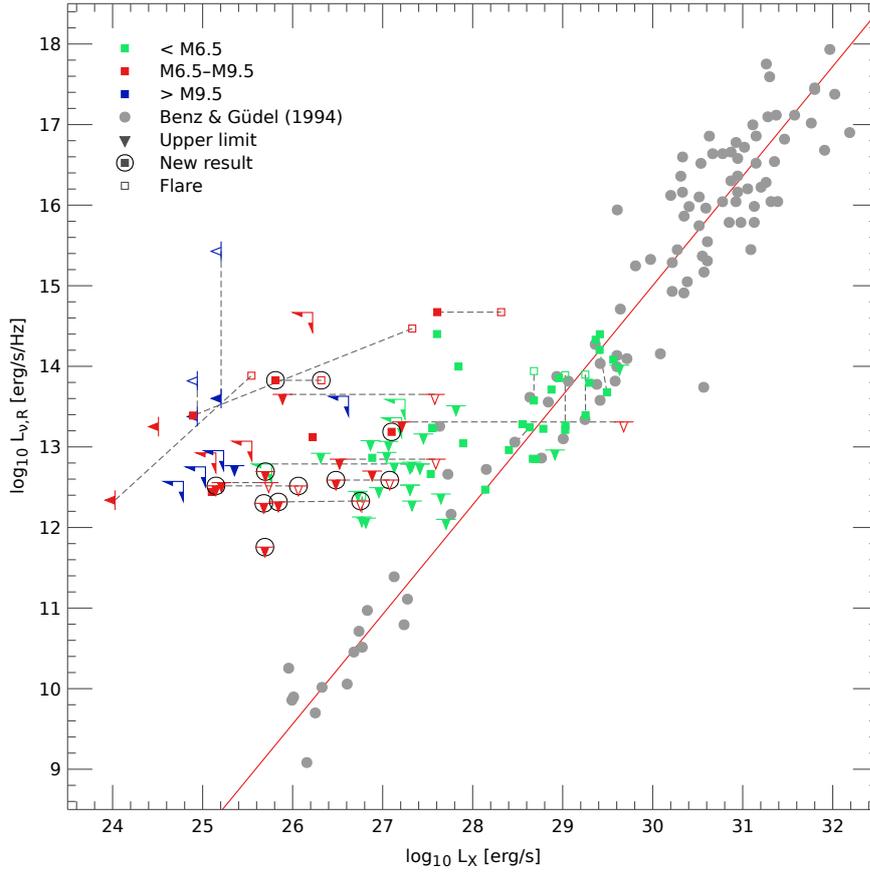
There are a handful of directly-imaged planetary mass companions that have estimated effective temperatures in the brown dwarf regime (e.g. Bonnefoy et al 2013), for example 2M1207b ( $\sim 10$  Myr,  $\sim 1600$  K, SpecT $\sim$ mid L) and HR8799b ( $\sim 30$  Myr,  $\sim 1600$  K, SpecT $\sim$  early T). These planets are underluminous and have unusually red near-infrared colours, when compared to field brown dwarfs, as well as displaying the characteristic peaked  $H$ -band spectra. There are  $\sim 30$  brown dwarfs that have been kinematically linked to moving groups and association aged between 10 and 150 Myr, that share these features, thus indicating that low gravity brown dwarfs may provide a clue to the atmospheric processes occurring on young exoplanets.

## 2.2 High energy processes in non-accreting brown dwarfs

Despite brown dwarfs being objects that are brightest in the near-IR, this has not prevented searches for other types of emission, particularly those associated with higher energy processes such as those seen in early M dwarfs. However, the magnetic dynamo mechanism is used to explain magnetic field generation in solar-type stars, and there is a direct correlation between rotation and magnetic activity indicated by  $H\alpha$ , X-rays and radio emission (Noyes et al, 1984; Stewart et al, 1988; James et al, 2000; Delfosse et al, 1998; Pizzolato et al, 2003; Browning et al, 2010; Reiners et al, 2009; Morin et al, 2010). This relationship between the radio ( $L_{v,R}$ ) and X-ray ( $L_X$ ) luminosities holds for active F-M stars, and  $L_X \propto L_{v,R}^\alpha$  ( $\alpha \sim 0.73$ ) is known as the Güdel-Benz relation (Figure 4: Güdel and Benz 1993; Benz and Güdel 1994). As the dynamo operates at the transition layer between the radiative and convective zones (the tachocline), this mechanism cannot explain radio activity in fully convective dwarfs ( $>M3$ ), and although  $H\alpha$  and X-ray activity continues into the late M dwarf regime, the tight correlation between X-ray and radio luminosity breaks down which suggests that a separate mechanism is likely to be responsible for radio emission.

### 2.2.1 X-ray and UV observations

Many searches for X-ray emission in L dwarfs were conducted (Stelzer and Neuhäuser, 2003; Berger et al, 2005; Stelzer et al, 2006), but only one detection is known to date. The L dwarf binary Kelu-1, composed of two old brown dwarfs, was detected with *Chandra* in the energy range of 0.63, 0.86, 1.19 and 1.38 keV, resulting in an estimation of the 0.1-10 keV X-ray luminosity to be  $L_X = 2.9 \times 10^{25}$  erg s $^{-1}$  (Audard et al, 2007). It has been suggested that this emission does not originate from flares as there was no concurrent radio detection at a frequency  $\sim 8$  GHz (Audard et al, 2007). Audard et al (2007) suggested that the ratio between luminosity (radio,  $H\alpha$ , or X-rays) and bolometric luminosity ( $L/L_{\text{bol}}$ ) increases with decreasing effective temper-



**Fig. 4** The Güdel-Benz relationship between  $L_X$  (0.2-2 keV) and  $L_{\nu,R}$  (Williams et al 2013b). Limits are shown as downward pointing triangles. Objects with spectral types of M6 or earlier (green), M6.5-M9.5 dwarfs (red) and spectral types of L0 or later (blue) are shown. Grey circles show the original Güdel-Benz relation from Benz and Güdel (1994). Dashed lines connect multiple measurements of the same source.

ature. They concluded that the chromospheric magnetic activity ( $H\alpha$  emission) and the activity in the hot coronal loops (X-ray emission) decreases with effective temperature, indicating a different mechanism responsible for the radio emission in ultra cool dwarfs.

Williams et al (2013b) suggest that ultracool dwarfs with strong axisymmetric magnetic fields tend to have  $L_{\nu,Radio}/L_X$  consistent with the Güdel-Benz relation (Fig. 4), while dwarfs with weak non-axisymmetric fields are radio luminous. Slower rotating dwarfs have strong convective field dynamos and so also stay near the Güdel-Benz relation, whereas some rapid rotators may violate the Güdel-Benz relation. Williams et al (2013b) also note that dwarfs with a weaker magnetic field tend to have later spectral types, and lower X-ray luminosity, which may be related

to their cooler temperatures. They also note that in general, radio-bright sources, tend to be X-ray under luminous compared to radio dim brown dwarf sources.

There are as yet no UV detections of brown dwarfs where the emission is attributed to atmospheric processes. Only brown dwarfs with disks such as the young TW Hydra member 2MASS1207334-39 have been observed to show UV emission. H<sub>2</sub> fluorescence is detected and attributed to accretion (Gizis et al, 2005).

### 2.2.2 Optical H $\alpha$ emission

The H $\alpha$  luminosity (indicative of chromospheric activity) in late M and L dwarfs also decreases with lower mass and later spectral type. Schmidt et al (2007) estimate that of their 152 strong sample, 95% of M7 dwarfs show H $\alpha$  emission (consistent with Gizis et al 2000). This fraction decreases with spectral type to 8% of L2-L8 dwarfs showing H $\alpha$ . For the L dwarfs in particular, 50% of L0 dwarfs being active declines to 20-40% of L1 dwarfs and only 10% of L2 dwarfs and later spectral types. This decline is similar to the breakdown in the rotation-activity relationship seen for the X-ray activity (Section 2.2.1) and has been attributed to the high electrical resistivities in the cool, neutral atmospheres of these dwarfs (Mohanty et al, 2002).

Sorahana et al (2014) have recently suggested that molecules may be affected by chromospheric activity. The active chromosphere heats the upper atmosphere, causing the chemistry in that region to change, resulting in the weakening of the 2.7  $\mu\text{m}$  water, 3.3  $\mu\text{m}$  methane and 4.6  $\mu\text{m}$  CO absorption bands as seen in *AKARI* spectra of mid-L dwarfs.

Despite the predicted decrease in H $\alpha$  emission, some objects of late spectral type show H $\alpha$  emission. For example, the L5 dwarfs 2MASSJ01443536-07 and 2MASS1315-26. In quiescence, these objects show H $\alpha$  fluxes similar to those of other dwarfs of the same spectral type. However in outburst, 2MASS0144-07 has an H $\alpha$  flux measurement more than 10 times higher than the mean (Liebert et al, 2003), and for 2MASS1315-26 the H $\alpha$  emission is  $\sim 100$  times stronger than for L dwarfs of a similar spectral type (Hall, 2002).

### 2.2.3 Radio emission

A number of brown dwarfs have been detected to be radio loud. This non-thermal emission may be low level quiescent (Berger, 2002), exhibiting variability (Antonova et al, 2007), showing variability that is periodic and linked to rotation (Berger et al, 2005; McLean et al, 2011), highly polarised and bursting (Burgasser and Putman, 2005), pulsing synchronised with the rotation period, and highly polarised (Hallinan et al, 2007; Berger et al, 2009) or a combination of some of these (Williams et al, 2013a). Some of these objects (TVLM513-46546, 2MASSJ0036+18, LSRJ1835+3259, 2MASSJ1047539+21 Route and Wolszczan 2012; Hallinan et al 2008) emit periodic, 100% polarised radiation, normally detected at 4-8 GHz with spectral luminosities of  $\approx 10^{13.5} \text{ erg s}^{-1} \text{ Hz}^{-1}$  (Hallinan et al, 2006; Route and Wolszczan, 2012). These pulses are caused by the cyclotron maser instability (CMI), the emission mechanism that occurs on Jupiter (Treumann, 2006; Nichols et al, 2012; Morioka et al, 2012). CMI emission requires a relatively tenuous population of energetic particles

confined to a relatively strong magnetic field; in particular, the cyclotron frequency,  $f_{ce} = eB/m_e c$ , must be much greater than the plasma frequency  $f_{pe} = \sqrt{4\pi e^2 n_e / m_e}$ . Whenever detailed observations are available, the free energy in the plasma is seen to be provided by electrons moving along the magnetic field lines, which can originate in magnetospheric-ionospheric (M-I) shearing and possibly plasma instabilities. These observations suggest that BDs can self-generate stable,  $\sim$ kG-strength magnetic fields (Berger, 2006). The underlying assumption is, however, that enough free charges are present to form a plasma in these extremely cold atmospheres ( $<2000$  K).

Although this mechanism for emission is quite well characterised, and can account for the polarised flaring behaviour, two of these dwarfs also produce quiescent, moderately polarised emission. This indicates that a second mechanism such as synchrotron or gyrosynchrotron emission (Berger, 2002; Osten et al, 2006; Ravi et al, 2011) may be occurring, or that the CMI emission is becoming depolarised in some way as it crosses the dwarf's magnetosphere (Hallinan et al, 2008). It has been suggested that some of the variability seen in these sources may be due to variation in the local plasma conditions (Stark et al, 2013), perhaps linked to magnetic reconnection events (Schmidt et al, 2007) or due to other sporadic charged events in the plasma (Helling et al 2011b,a, 2013; Bailey et al 2013).

It is still unknown what features distinguish radio "active" from radio "inactive" dwarfs. The relationship may depend on mass, effective temperature, activity, magnetic field strength and rotation rate. All the known radio "active" dwarfs have a high  $v \sin i$ -value, indicating short rotation periods ( $\sim 3$ hrs) (Antonova et al, 2013; Williams, 2013). This may indicate a link between rotation rate and emission, but could also indicate a dependence on the inclination angle,  $i$ , instead of the velocity, thus making detection of radio emission dependent on the line of sight and the beamed radiation emitted (Hallinan et al, 2008).

### 2.3 Observed variability in Brown Dwarfs

The number of campaigns that search for spectro-photometric variability has increased since it was first suggested by Tinney and Tolley (1999b). Such variability would indicate non-uniform cloud cover (e.g. Ackerman and Marley 2001) and weather-like features, such as those seen on Jupiter. The majority of the early searches concentrated on L dwarfs, suggesting that variability could be due to holes in the clouds (Gelino et al, 2002; Ackerman and Marley, 2001). Surveys suggest that between 40–70% of L dwarfs are variable (Bailer-Jones and Mundt, 2001; Gelino et al, 2002; Clarke et al, 2002), although most of these surveys involve small numbers of objects and the authors vary on what is considered a detection. The majority of these studies were performed in the  $I$  band where the amplitude of variability is at the 1–2% level (Clarke et al, 2002, 2008) on timescales of tens of minutes to weeks, and is in general not periodic. There has now been a shift towards using the near-IR for variability studies (Enoch et al, 2003; Clarke et al, 2008; Khandrika et al, 2013; Girardin et al, 2013; Buenzli et al, 2014; Radigan et al, 2014; Wilson et al, 2014) where the frequency of variability is estimated to be  $\sim 10$ –40%. So far, however, high amplitude

periodic variability ( $> 3\%$ ) has been limited to the L-T transition objects, while lower amplitude variability is detected in both early L and late T dwarfs.

Heinze et al (2013) reported sinusoidal variability of the L3 dwarf DENIS-P J1058.7-1548 in the  $J$  and [3.6] micron bands, but no variability in the [4.5] micron band. They suggested that the variability may again be due to inhomogeneous cloud cover, where the thickest clouds have the lowest effective temperature, but there may also be an effect related to magnetic activity (starspots, chromospheric or aurorae) suggested by a weak  $H\alpha$  detection. This result is similar to the findings on the radio loud M8.5 dwarf TVLM513-46546 (Littlefair et al, 2008). TVLM513 shows  $i'$  and  $g'$  band variability in antiphase, initially suggesting the variability is due to patchy dust clouds coupled with the object's fast rotation. However, more recent results show that the  $g'$  and  $i'$  bands are no longer correlated. The  $g'$  band variability has remained stable, but the  $i'$  band lightcurve has evolved. However, the optical continuum variability is in phase with the  $H\alpha$  flux, again suggesting some magnetic processes are also occurring (Metchev et al, 2013).

The first T dwarf to be confirmed as variable was the T2.5 dwarf SIMP J013656.5+093347 (Artigau et al, 2009) which was determined to be variable at the 50 mmag level in the  $J$  band. A rotation period of 2.4 days was determined from the lightcurves. More interestingly, the lightcurve evolves from night to night (Fig. 2 in Artigau et al (2009)), perhaps due to evolving features such as storms. Radigan et al (2012) studied a similar object, the T1.5 dwarf 2MASS2139, and again found evidence of an evolving light curve in the  $J$ , and  $K_s$  wavebands, which after extensive analysis they attributed to heterogeneous clouds with regions of higher opacity. In general, these objects exhibit variable lightcurves, modulated as the object rotates, which evolve on a period of hours (Apai et al, 2013a), days (e.g. Artigau et al 2009; Radigan et al 2012) or even years (Metchev et al, 2013).

While the majority of studied T dwarfs lie at the L-T dwarf transition region, some late T dwarfs ( $>T5$ ) have also been determined to be variable (Clarke et al, 2008). Initially, these atmospheres were thought to be relatively cloud-free, however recent work by Morley et al (2012) suggests that sulphide clouds may exist there (see Sect. 3.4). Buenzli et al (2012) studied one such object and determined a phase offset between different wavelengths while sinusoidal variability was present on the rotation prior of the object. This phase shift is directly linked to the pressure (and hence cloud constituents) probed at each of the observed wavelengths (Marley et al, 2010; Morley et al, 2014a). The lower pressure regions (high altitude) cause the highest phase lag with respect to the highest pressure layers (lowest altitude) and may be as large as half a rotation period. The authors attribute this lag to a change in the opacities (gas or cloud) without a change in the temperature profile, a change in the temperature-pressure profile without a change in the opacity or a combination of the two resulting in a "stacked-cell" atmosphere as seen in Saturn (e.g. Fletcher et al 2011). Robinson and Marley (2014) interpret the phase lag in the frame of their 1D model as being due to thermal fluctuations. However, their model is unable to reproduce the variability on a timescale of  $\sim$ hours, as seen in the observations, claiming that a 3D model will be required to explore the dynamics fully.

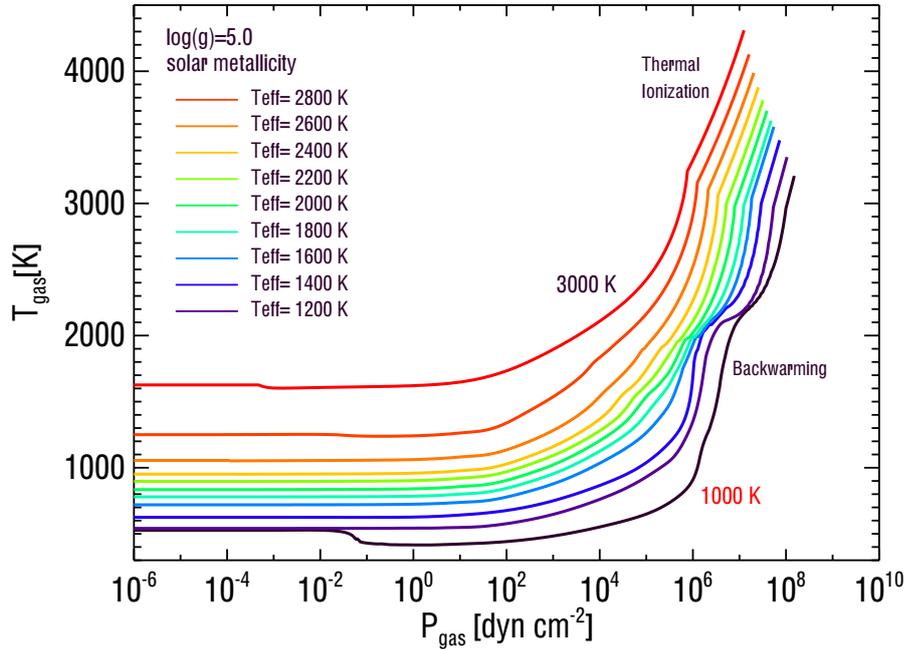
An alternative to ground based observations is to move into space, minimising differential refraction and atmospheric effects. One of the largest space based vari-

ability surveys to date was performed by Buenzli et al (2014) who studied 22 brown dwarfs ranging from L5 to T6 with *HST*. Six of these objects are determined to be variable with another 5 marked as potentially variable. This survey was not sensitive to objects with long periods, but it still suggests that the majority of brown dwarfs have patchy atmospheres, and that there is no spectral type dependence on the fraction of dwarfs that are variable.

Perhaps one of the best studied variable objects is Luhman 16B. Luhman 16AB is the third closest system to the sun at only 2pc (Luhman, 2013) being a L7.5 and T0.5 dwarf binary. Gillon et al (2013) reported variability on a 4.87 hour period with strong night to night evolution which was attributed to a fast evolving atmosphere on the cooler T0.5 dwarf. The L7.5 dwarf is not found to be variable. Burgasser et al (2014) performed spectral monitoring of the system, modelling the T dwarf using a two-spot model and inferring a cold covering fraction of  $\sim 30\text{-}55\%$  varying by 15-30% over a rotation period. This resulted in a difference of  $\sim 200\text{-}400$  K between the hot and cold regions. Burgasser et al (2014) interpreted the variations in temperature as changes in the covering fraction of a high cloud deck resulting in cloud holes which expose the deeper, hotter cloud layers. They also suggested the rapidly evolving atmosphere may produce winds as high as  $1\text{-}3 \text{ km s}^{-1}$  which is consistent with an advection timescale of 1-3 rotation periods. A new analysis of this system, was produced by Crossfield et al (2014) who used Doppler imaging techniques to produce a global surface map, sensitive to a combination of CO equivalent width and surface brightness, of the T dwarf Luhman 16B. The map shows a large, dark mid-latitude region, a brighter area on the opposite hemisphere located near the pole and mottling at equatorial latitudes (Fig. 2 in Crossfield et al 2014). The authors interpreted the map in one of two ways. Either the darker areas represent thicker clouds, obscuring the hotter, inner regions of the atmosphere, and the bright regions correspond to cloud holes providing a view of this warmer interior, or the map shows a combination of surface brightness and chemical abundance variations. They predict that the high latitude bright spot could be similar to polar vortices seen in solar system giant planets, in which case it should be seen in future mapping of this object.

Another class of brown dwarfs that shows photometric variability are those in close ( $< 10$  hrs) detached binary systems with white dwarfs (WD0137-349, WD+L6-L8,  $P=116$  min: Maxted et al 2006; Burleigh et al 2006; GD1400, WD+L6,  $P=9.98$ hrs Farihi and Christopher 2004; Dobbie et al 2005; Burleigh et al 2011; WD0837+185, WD+T8,  $P=4.2$ hrs: Casewell et al 2012; NLTT5306, WD+L4-L7,  $P=101.88$  min: Steele et al 2013; CSS21055, WD+L,  $P=121.73$  min: Beuermann et al 2013). These systems are likely tidally locked and as a result one side of the brown dwarf is continually heated by its much hotter white dwarf companion. Three of the five known systems show variability in optical wavelengths at the 1% level. One of these objects, WD0137-349 has been studied extensively in the near-infrared (Casewell et al, 2013). The white dwarf in this system is 10 times hotter than the brown dwarf, resulting in a difference in brightness temperature of  $\sim 500\text{K}$  between the day and night sides, likely causing vigorous motion and circulation in the atmosphere (e.g. Showman and Kaspi 2013a). While the substellar objects in these systems are brown dwarfs, and not extrasolar planets, their atmospheres behave in a similar way, both absorbing the (mainly) ultraviolet emissions from their host, and also reflecting the incident light.

There are brown dwarfs known in close orbits with main sequence stars that are also irradiated (e.g. WASP-30b: Anderson et al 2011, Kelt-1b: Siverd et al 2012), but as their host stars are much more luminous, and the brown dwarf atmosphere scale height is too small to allow transmission spectroscopy, these are much more challenging to observe.



**Fig. 5** The local temperature-pressure ( $T_{\text{gas}}-P_{\text{gas}}$ )-structure of brown dwarfs ( $\log(g)=5.0$ ) for effective temperature  $T_{\text{eff}} = 1000 \dots 3000\text{K}$ . Shown are results from DRIFT-PHOENIX model atmosphere simulations for solar element abundances (Witte et al 2009, 2011) [courtesy: Isabel Rodriguez-Barrera]

### 3 Theory of brown dwarf atmospheres

Most, if not all, observational findings reported in the previous sections result from or are influenced by atmospheric processes. The following section will therefore summarize the physics as we expect it to occur in ultra-cool atmospheres of brown dwarfs, including planets and M-dwarfs (Sect. 3.1). Special emphasis will be given to cloud formation processes and their modelling. Section 3.4 contains a summary of different approaches to treat cloud formation as part of model atmospheres.

#### 3.1 The brown dwarf atmosphere problem

The atmosphere of a brown dwarf is composed of a cold gas with temperatures  $\approx 3000\text{K} \dots < 500\text{K}$ , generally decreasing outwards due to the upper atmosphere being an open boundary by extending into space (Fig. 5). Local temperature inversions could occur due to locally heating processes: A locally increased opacity could lead to radiative heating (e.g. backwarming, see Fig. 5) or cooling, Alfvén wave propaga-

tion could cause the occurrence of chromospheric structures, and irradiation would provide an additional, external flux source.

The description of the atmosphere of a brown dwarf requires to model the local thermodynamic ( $T_{\text{gas}}$  [K],  $p_{\text{gas}}$  [dyn/cm<sup>2</sup>]), hydrodynamic ( $v_{\text{gas}}$  [cm/s],  $\rho_{\text{gas}}$  [g/cm<sup>3</sup>]) and chemical properties ( $n_x$  [cm<sup>-3</sup>],  $x$  - chemical species (ions, atoms, molecules, cloud particles)) in order to predict observable quantities based on the radiative flux  $F_\lambda$  [erg/s/cm<sup>2</sup>/Å]. The goal is to perform this task by using a minimum of global quantities that are observationally accessible like the resulting total radiative flux  $F_{\text{tot}} = \int F_\lambda d\lambda$  through the atmosphere. The classical 1D model atmosphere problem (e.g. Mihalas 1982) is determined by the effective temperature  $T_{\text{eff}}$  ( $F_{\text{tot}} = \sigma T_{\text{eff}}^4$ ,  $\sigma$  [erg cm<sup>-2</sup>s<sup>-1</sup>K<sup>-4</sup>] - Stefan-Boltzmann constant with the luminosity  $L = 4\pi R^2 \sigma T_{\text{eff}}^4$  and the radius ( $R$  [cm])), the surface gravity  $\log(g)$  ( $\log(g) = \log(GM/R^2)$ ,  $G$  [cm<sup>3</sup>g<sup>-1</sup>s<sup>-2</sup>] - gravitational constant,  $M$  - object mass) and the element abundances of the object. Material quantities like the equation of state, and further chemistry and opacity data close this system of equations. Brown dwarf atmosphere models (Lunine et al 1986; Burrows et al 1989; Tsuji et al 1996a; Tsuji 2002; Ackerman and Marley 2001, 2013; Allard et al 2001; Burrows et al 2002; Gustafsson et al 2008; Witte et al 2009, 2011; for earlier references on M-dwarfs see Allard et al 1997) that are widely applied to optical and IR observations (Sects. 2.1, 2.3)

- calculate the local gas temperature by solving the radiative and convective energy transport through a stratified medium in local thermal equilibrium (LTE) with an open upper boundary,
- assume flux conservation according to a total energy given by  $T_{\text{eff}}$  ( $F_{\text{tot}} = F_{\text{rad}} + F_{\text{conv}} = \sigma T_{\text{eff}}^4$ ),
- calculate local gas-phase composition for a set of element abundances to determine the opacity of the local gas (Mostly, chemical equilibrium is assumed, in some simulations, CO/CH<sub>4</sub>/CO<sub>2</sub> and N<sub>2</sub>/NH<sub>3</sub> are treated kinetically to better fit observed spectra.),
- calculate the local gas pressure assuming hydrostatic equilibrium.

Brown dwarfs deviate from the classical model atmosphere (e.g. textbook Mihalas 1982) in that clouds form inside their atmospheres. During the formation process, elements are consumed resulting in depleted gas-phase opacity sources like TiO, SiO and others. The cloud particles are a considerable opacity source which introduces a backwarming effect (see Fig. 5). Convection plays an important role in transporting material into regions that are cool enough for the condensation processes to start or progress (see also Fig. 8). Convection is a mixing mechanisms that can also drive the local gas-phase out of chemical equilibrium if the transport is faster than the chemical reaction towards the local equilibrium state (Noll et al 1997).

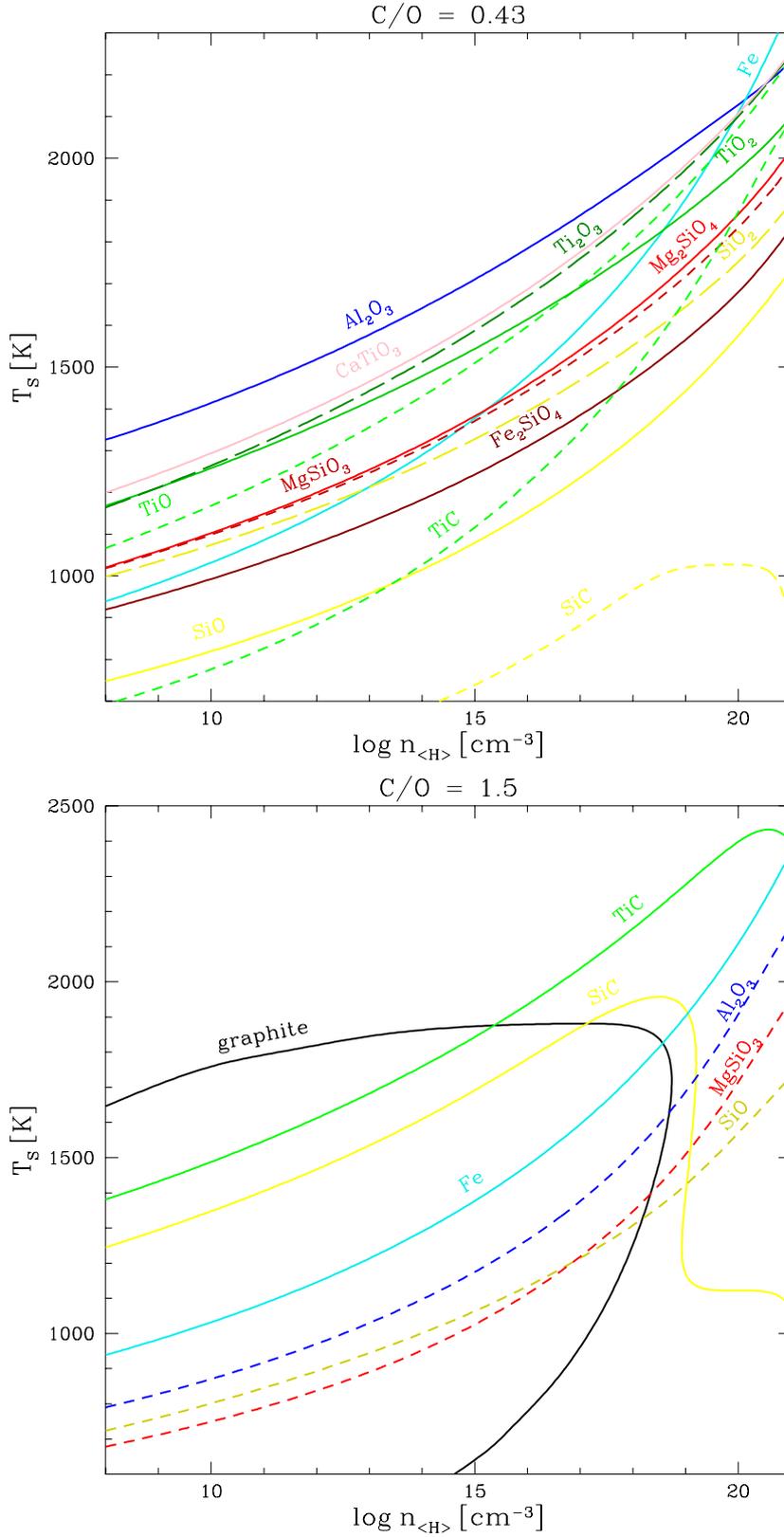
So far, the focus of brown dwarf model atmospheres was on one dimensional simulations in the vertical ( $z$ ) direction. This assumption implies that the brown dwarf atmosphere is homogeneous in the other two dimensions ( $x, y$ ). Observation of irradiated brown dwarfs (Casewell et al 2012) suggest what is known for irradiated planets since Knutson et al (2009), namely, that global circulation may also occur on brown dwarfs. We note, however, that the driving mechanisms for global circulation are likely being dominated by rotation in brown dwarfs compared to irradiation alone in

close-in planets (Zhang and Showman 2014). Variability observations of time-scales different than the rotational period (Sect. 2.3) have long been interpreted as a sign for an inhomogeneous cloud coverage of brown dwarfs. *To summarize, the aim of building a model for an atmosphere is to understand the interaction between different processes and to calculate quantities that can be compared to experiments or observation. The input quantities are the global properties  $T_{\text{eff}}$ ,  $L_*$ ,  $\log(g)$ , mass or radius, element abundances, plus material constants for gas chemistry, cloud formation and opacity calculations. The output quantities are details of the atmosphere like the local gas temperature,  $T_{\text{gas}}$  [K], the local gas pressure,  $p_{\text{gas}}$  [bar], the local convective velocity,  $v_{\text{conv}}$  [cm/s], the local number densities of ions, atoms, molecules,  $n_x$  [ $\text{cm}^{-3}$ ], local grain size,  $a$  [cm], local number of cloud particles,  $n_d$  [ $\text{cm}^{-3}$ ], local material composition of grains, the cloud extension, and many more details. Directly comparable to observations is the the resulting spectral surface flux  $F_\lambda$ .*

### 3.2 The chemical repository of the atmosphere

The chemical repository of an atmosphere, including atoms, molecules and cloud particles, is determined by the element abundances available throughout the atmosphere. Different wavelengths with different optical depths probe different atmospheric layers with their specific chemical composition. *Primordial element abundances*, that should be characteristic for a young, hot brown dwarf, are determined by where and when a brown dwarf formed as the interstellar element abundances increase in heavy elements over time (Yuan et al 2011) and may depend on the star formation history of the brown dwarf's birthplace (Henry and Worthey 1999; Cheng et al 2012). The primordial abundances should be preserved in the brown dwarf's interior and below any atmospheric region that could be affected by cloud formation and down-mixing of processed element abundances. Given the long life times of brown dwarfs, we expect element sedimentation inside the brown dwarf core similar to what we know from white dwarfs. The element abundances that determine the spectral appearance of a brown dwarf are *processed element abundances* and they differ from the primordial values due to the effect of element depletion by cloud formation, element enrichment by cloud evaporation and the convective mixing of such chemically altered element abundances.

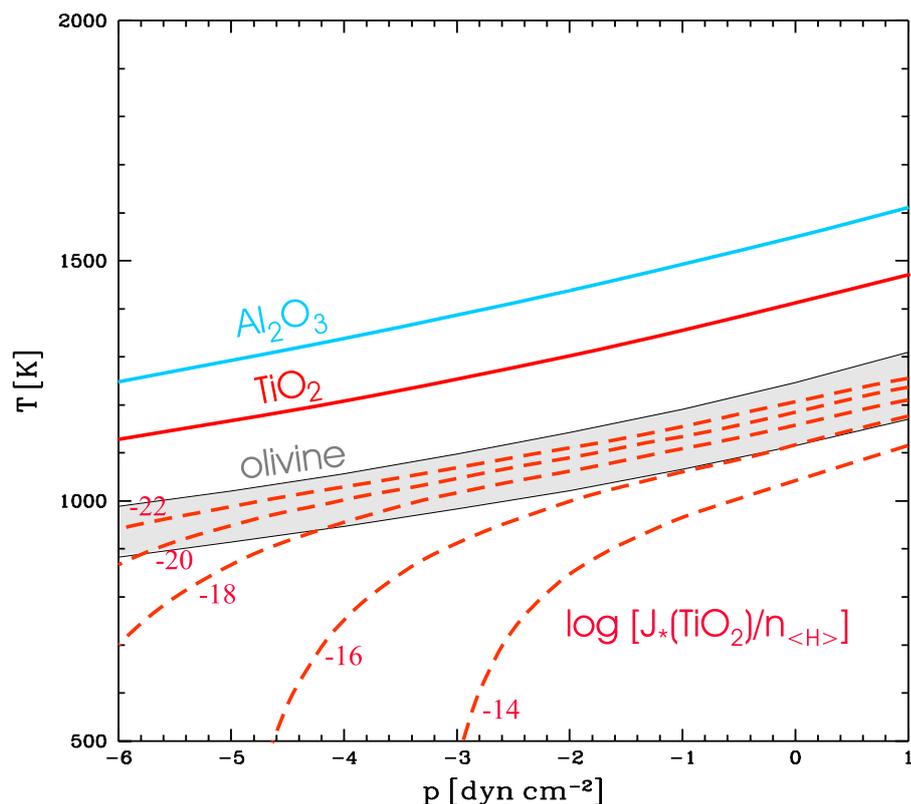
The primordial element abundances are almost always assumed to be the solar element abundances or a scaling thereof. These values are inspired by seismological measurements and 3D simulations to fit high-resolution line profiles. The element abundance values determined for the Sun depend a little on the method and/or simulation applied (Pereira et al 2013, see also discussion in Helling et al 2008a). In principle, there is no reason why any star's element abundances should precisely scale with the solar element abundances (Bergemann et al 2014). Allard et al (1997) summarized the chemical composition in brown dwarf atmospheres as the basis of every model atmosphere simulation.



**Fig. 6** Thermal stability of various materials in an oxygen-rich ( $C/O < 1$ ; top) and a carbon-rich ( $C/O > 1$ , middle) solar abundance gas. All curves show  $(T_{\text{gas}}, n_{\langle H \rangle})$  where the supersaturation ratio  $S_s = 1$  ( $s = \text{TiO}[s], \text{Fe}[s], \text{graphite}, \dots$ ; Eq. 1). The materials will evaporate in the parameter space above each curve. In the case of graphite, the evaporation parameter space is above and to the right of the curve [courtesy P. Woitke].

### 3.3 Fundamental ideas on cloud formation

The following section provides a summary of basic ideas of how clouds form. The formation processes and underlying concepts are based on a microscopic approach which, in the very end, will depend on our quantum-mechanical understanding of chemical reactions leading to more and more complex structures that describe the transition from the gas-phase into the solid or liquid phase. Section 3.4 will summarize different approaches to cloud formation modelling that are applied by different research groups to solve the brown dwarf atmosphere problem.



**Fig. 7** A considerable supersaturation is required for the seed formation processes to occur. The seed formation rate of  $\text{TiO}_2$  (nucleation rate  $J_*$ , dashed red line) is highest far below the thermal stability curve for the solid material  $\text{TiO}_2[\text{s}]$  (solid red line). Thermal stability for  $\text{Al}_2\text{O}_3[\text{s}]$  and the olivines in a solar abundance gas are shown for comparison. [courtesy P. Woitke]

#### 3.3.1 Thermal stability

The concept of thermal stability is used in all but one cloud model to determine if a cloud exists in an atmosphere. Figure 6 shows thermal stability curves usually used

for this procedure, and which are often called 'condensation curves' in the literature. Such a material is in *phase equilibrium* which is described by the supersaturation ratio  $S_s = 1$  of a material  $s$  ( $s = \text{SiO}[s], \text{TiO}_2[s], \text{MgO}[s], \text{Fe}[s], \text{Mg}_2\text{SiO}_3[s], \dots; [s]$  referring to 'solid') with the supersaturation ratio being defined as

$$S_s = \frac{p_x(T_{\text{gas}}, p_{\text{gas}})}{p_{\text{sat},s}(T_s)}. \quad (1)$$

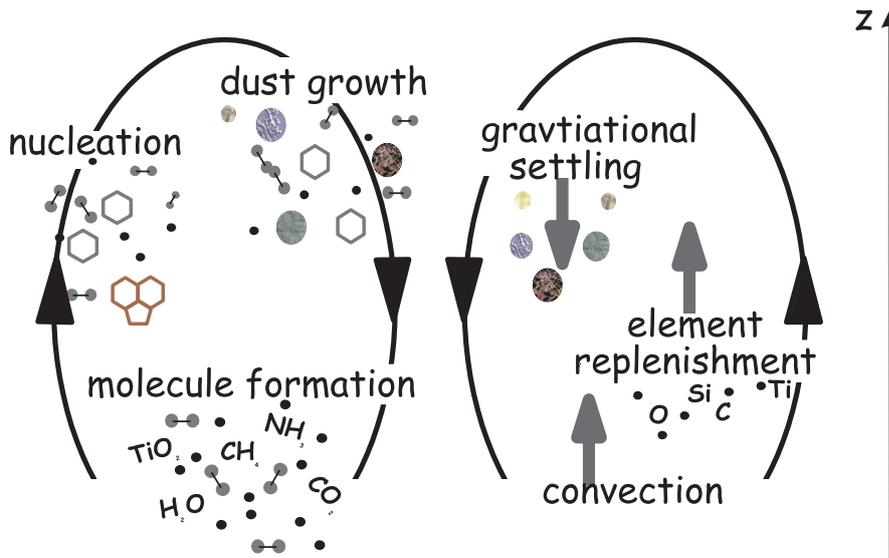
$p_x(T_{\text{gas}}, p_{\text{gas}})$  is the partial pressure of the growing gas species  $x$ , and  $p_{\text{sat},s}(T_s)$  is the saturation vapour pressure of the solid  $s$ . The application of the law of mass action to  $p_x$  shows that  $S_s$  is well-defined no matter whether the monomer of solid  $s$  exists in the gas-phase or not (Helling and Woitke 2006). Hence, the concept of thermal stability does not allow to investigate if and how a particular condensate does form. Figures 6 demonstrate below (i.e.,  $\leq$ ) which temperatures a material would be thermally stable in an oxygen-rich (top) and a carbon-rich (bottom) environment.

### 3.3.2 Cloud formation processes

Cloud formation (Fig. 8) starts with the formation of condensation seeds in brown dwarfs and giant gas planets where no tectonic processes can provide an influx of dust particles into the atmosphere.<sup>2</sup> This process is a sequence of chemical reactions through which larger molecules form which then grow to clusters and eventually, a small, solid particle emerges from the gas phase. Such reaction chains have been extensively studied in soot chemistry pointing to the key role of PAH (polycyclic aromatic hydrocarbons) in carbon-rich environments (Göres 1993). The modelling aspect of such chemical paths is greatly hampered by cluster data being not always available for a sensible number of reactions steps, and computational chemistry plays an important role for our progress in astrophysics' cloud formation (e.g. Catlow et al 2010). Figure 7 demonstrates that the seed formation process requires a considerable supersaturation of the respective seed forming species: The seed formation rate,  $J_*$ , peaks at a far lower temperature than the thermal stability of the same material suggests. This is very similar to Earth where water vapour condensation on ions requires a supersaturation of 400%. Iraci et al (2010), for example, demonstrate that equilibrium water ice formation is impossible on Mars.

Once condensation seeds have formed, other materials are already thermally stable (Fig. 6) and highly supersaturated (Fig. 1 in Helling et al 2008c). This causes the growth of a substantial mantle via dust-gas surface reactions. The cloud particles forming in an oxygen-rich gas will therefore be made of a mix of all available materials as many materials become thermally stable in a rather narrow temperature interval (top panel, Fig. 6). Once the cloud particles have formed, other intra-particle collision processes may alter the particle size distribution. Such collisions depend on the momentum transfer between particles and may result in a further growth of the

<sup>2</sup> The formation of weather clouds on Earth involve water condensation of pre-existing seeds particles (*condensation nuclei*) which origin from volcano outbreaks, wood fires, ocean salt spray, sand storms, and also cosmic-ray-induced ion-ion cluster reactions (see CERN CLOUD experiment). Noctilucent clouds in the upper Earth atmosphere, however, require the recondensation of meteoritic material to understand their existence (Saunders et al 2007).



**Fig. 8** The circuit of dust that determines cloud formation: cloud particle formation (nucleation, growth) → gravitational settling (drift) → element depletion & element replenishment by convective mixing (Woitke and Helling 2004).

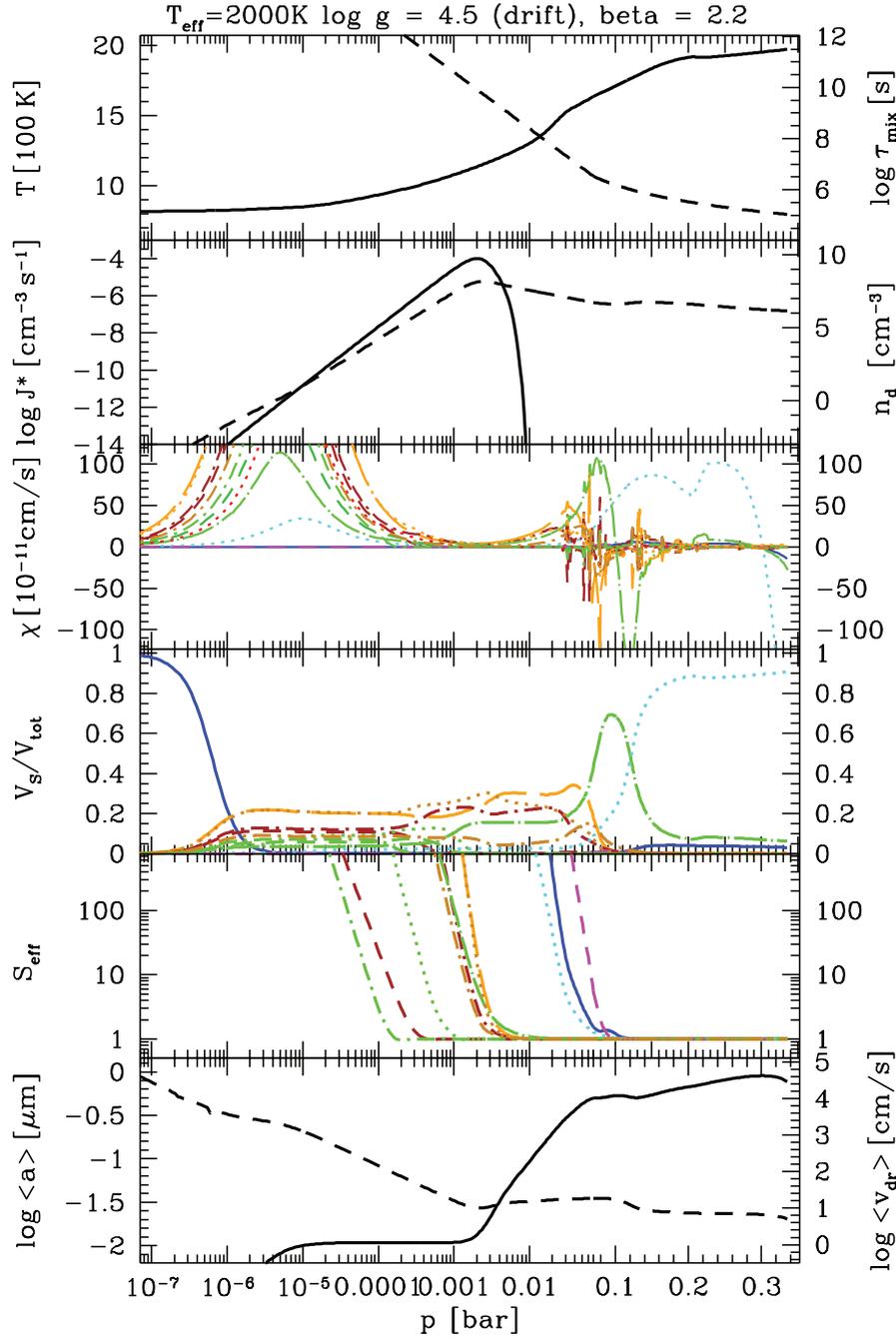
particle or in destruction (Güttler et al 2010; Wada et al 2013). Collisions between charged grains may lead to an acceleration of the coagulation process in brown dwarf atmospheres (e.g. Konopka et al 2005).

### 3.3.3 Some results on cloud formation

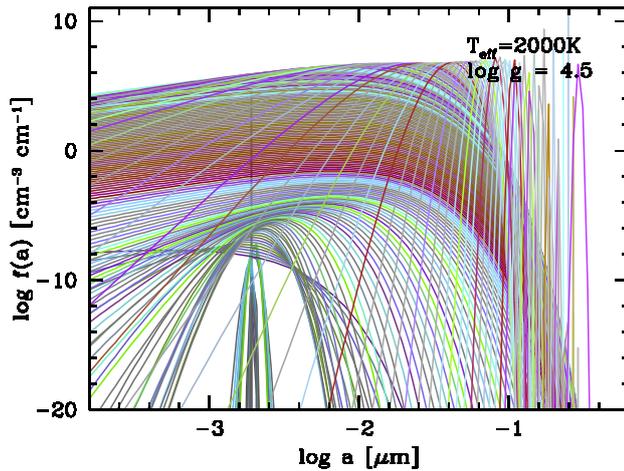
We use modelling results from Helling & Woitke to demonstrate the origin of basic cloud properties and feedback mechanisms that determine the formation of clouds. Refined results of a DRIFT-PHOENIX atmosphere simulation (Witte et al 2011) are used for this purpose.

The upper boundary of the cloud is determined by the formation of condensation seeds. Figure 9 demonstrates that a substantial grain growth can only set in when condensation seeds have formed despite of extremely high supersaturation of potentially condensing materials (5th panel). The seed formation rate,  $J_*$  [ $\text{cm}^{-3}\text{s}^{-1}$ ] (2nd panel, solid), is calculated for  $\text{TiO}_2$ -nucleation for which cluster data exists (see Helling and Fomins 2013). It determines furthermore the number density of cloud particles,  $n_d$  [ $\text{cm}^{-3}$ ] (2nd panel, dashed) in the entire cloud. Below a shallow  $\text{TiO}_2$ [s] layer, all thermally stable materials grow almost simultaneously (3rd and 4th panel) producing core-mantle cloud particles with a mixed mantle composition.

A closer inspection of the material volume fractions ( $V_s/V_{\text{tot}}$ ) and the grain growth velocity ( $\chi_s$ ) reveals a changing material composition in the cloud with height. The reasons are element consumption and thermal instability: The condensates can not grow further if element depletion causes a sub-saturation, or evaporation sets in if the local temperature is too high. The result is that also the individual supersaturation



**Fig. 9** Cloud model results as part of a DRIFT-PHOENIX atmosphere model ( $T_{\text{eff}} = 2000\text{K}$ ,  $\log(g)=4.5$ , solar metallicity). **1st panel:** local gas temperature  $T_{\text{gas}}$  [K] (solid), convective mixing time scale  $\tau_{\text{mix}}$  [s] (dashed); **2nd panel:** seed formation rate  $J_*$  [ $\text{cm}^{-3}\text{s}^{-1}$ ] (solid), cloud particle number density  $n_d$  [ $\text{cm}^{-3}$ ] (dashed); **3rd panel:** grain growth velocity  $\chi_s$  [ $\text{cm s}^{-1}$ ]; **4th panel:** material volume fraction  $V_s/V_{\text{tot}}$  [%]; **5th panel:** effective supersaturation ratio  $S_{\text{eff}}$  for each material  $s$ ; **6th panel:** mean grain size  $\langle a \rangle$  [ $\mu\text{m}$ ] (solid), drift velocity  $v_{\text{dr}}$  [ $\text{cm s}^{-1}$ ] (dashed). The different colours refer to the same different solid in each of the panels. The subscript  $s$  refers to the different condensate materials:  $s=\text{TiO}_2$ [s] (blue),  $\text{Mg}_2\text{SiO}_4$ [s] (orange, long-dash),  $\text{SiO}$ [s] (brown, short-dash),  $\text{SiO}_2$ [s] (brown, dot - short-dash),  $\text{Fe}$ [s] (green, dot - long-dash),  $\text{Al}_2\text{O}_3$ [s] (cyan, dot),  $\text{CaTiO}_3$ [s] (magenta, dash),  $\text{FeO}$ [s] (green, dash),  $\text{FeS}$ [s] (green, dot),  $\text{Fe}_2\text{O}_3$ [s] (green, dot - short-dash),  $\text{MgO}$ [s] (dark orange, dot - short-dash),  $\text{MgSiO}_3$ [s] (dark orange, dot).



**Fig. 10** Grain size distributions,  $f(a)$  [ $\text{cm}^{-3} \text{m}^{-1}$ ], differ for different atmospheric layers due to different cloud formation processes contributing and/or dominating. The plot shows the evolution of the grain size distribution from the start of the cloud formation by seed formation (narrow gray-ish peaks), the continues production of seed particles which simultaneously grow (peaks growing in height and moving to the right towards larger grain sizes; blue colours), and the growth dominated distributions (peaks have constant heights and keep moving to the right; purple colours).  $f(a)$  is shown for the same atmosphere model like in Fig. 9.

ratios approach one, but each at a different temperature (i.e. atmospheric height in 1D models).

Element depletion affects also the seed formation (mainly due to Ti). No more new seed particles can form below a certain height as the increasing temperature hampers the clusters' thermal stability. All cloud particles that exist below this height have rained in from above. These particles fall into a gas of increasing density and temperature. The increasing gas density causes an increasing mean grain size ( $\langle a \rangle$ ) until the grains fall faster than they can grow. A part of the lower cloud has therefore an almost constant mean grain size. Below that, the temperature is too high and even high-temperature condensates like Fe[s] and  $\text{Al}_2\text{O}_3$ [s] evaporate. The thermal stability of the most stable materials determines the cloud's lower boundary. The lower edge of the cloud is made of large particles that consist of very heat-resistant materials like  $\text{Al}_2\text{O}_3$ [s] with inclusions of Fe[s] and  $\text{TiO}_2$ [s].

### 3.3.4 Why do we need a cloud model?

Important input quantities for model atmosphere simulations, and for retrieval methods, are opacity data for the gas-phase and for the cloud particles. Molecular line lists have been a big issue for a long time (Allard et al 1997; Hill et al 2013). But the calculation of the gas phase absorption coefficient requires also the knowledge of the number density of the absorbing species which is determined by the element abundances of the constituting elements. The element abundances are strongly influenced by how many cloud particles form of which composition and where in the

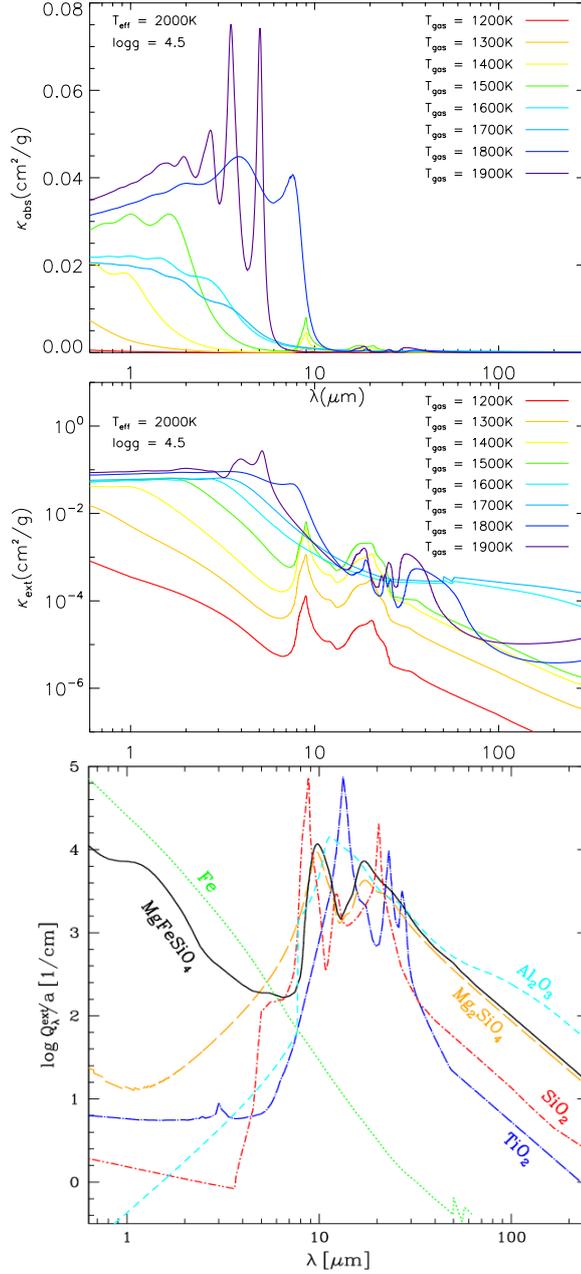
atmosphere. A detailed cloud model is therefore needed to calculate how many cloud particles deplete the gas where and of which elements. Helling et al (2008c) detail in their Fig. 7 the changing  $[\text{Ti}/\text{H}]$ ,  $[\text{Si}/\text{H}]$ ,  $[\text{Fe}/\text{H}]$ , etc abundances with atmospheric height and global parameters when cloud formation is considered.

The cloud opacity is determined by the size distributions of the cloud particles and their material composition as well as the optical constants (refractory index). The cloud opacity changes with height because of the height dependent grain size distribution, but also the material composition of the cloud particles changes with height (Figs. 9, 10). Figure 10 depicts the number of cloud particles for each atmospheric layer considered in the underlying atmosphere model: each atmospheric layer is characterized by one curve. The distribution of the number of particles (denoted by  $f(a)$ ) also changes with atmospheric height. The evolution of the cloud particle size distributions is determined by the cloud formation processes summarized in Sect. 3.3.3. The delta-like distributions (dark green curves) are characteristic for the top of the cloud where the nucleation process dominates and surface growth is not yet efficient (compare also panel 2 & 3 in Fig. 9). The distributions,  $f(a)$ , broaden when grain growth becomes efficient and  $f(a)$  increases in height when nucleation takes place simultaneously (wide purple curves). This is the case just below the cloud top. Once the size distributions 'move' in grain-size space towards the right (towards larger grain sizes) with a constant peak value, the nucleation has stopped. This is indicative for those cloud regions where the cloud particles rain into deeper atmospheric layers. The deeper cloud layers are characterized by narrow size distributions of large grains as all cloud particles in that layer had time to grow. Eventually, the distribution functions move back into the small-grain region of Fig. 10 because the cloud particles evaporate.

Figure 11 shows wavelength-dependent cloud opacities for individual cloud layers. The silicate absorption features appears clearly in the low-temperature part of the cloud (compare lowest panel Fig. 11). Scattering dominates the cloud extinction shortward of  $4 \dots 9 \mu\text{m}$  depending on the cloud particle sizes. Hence, for both, the gas opacity and the cloud opacity, a rather detailed cloud model needs to be applied to determine the cloud particle sizes, their size distribution and their material composition depending on the local thermodynamic properties inside the atmosphere.

### 3.4 Different approaches to describe cloud formation in atmosphere simulations

Cloud models are an integral part of each brown dwarf (and planetary) model atmosphere simulation as they determine the remaining element abundances that define the local gas-phase composition of the spectrum forming atmosphere layers. In the following, we summarize the different cloud models that are to date applied and published in model atmosphere simulations of brown dwarfs (and planets and M dwarfs). This section is an update of Helling et al (2008a) and it includes all brown dwarf cloud models that are part of an atmosphere simulation. Ackerman and Marley (2001) discuss some of the older cloud models (Lunine et al 1986; Rossow 1978). A more planet-focused review is provided in (Marley et al, 2013). Lunine et al (1986) and in their next paper Burrows et al (1989) were the first to introduce a cloud opac-



**Fig. 11 Top two:** Cloud opacity,  $\kappa_{\text{abs}}^{\text{dust}}(\lambda)$  and  $\kappa_{\text{ext}}^{\text{dust}}(\lambda) = \kappa_{\text{abs+scat}}^{\text{dust}}(\lambda)$  [ $\text{cm}^2 \text{g}^{-1}$ ], as function of wavelength,  $\lambda$  [ $\mu\text{m}$ ], for different layers for a warm brown dwarf ( $T_{\text{eff}} = 2000\text{K}$ ,  $\log(g) = 4.5$ ). Different colours indicate different layers in the DRIFT-PHOENIX model atmosphere with each layer having different grain sizes and material compositions (Figs. 9,10) [courtesy: Diana Juchner]. **Bottom:** Extinction efficiency as function wavelength in the small-particle limit of the Mie-theory (Woitke 2006).

ity (or 'particulate opacity sources') into their atmosphere model which served as outer boundary for brown dwarf evolution models. Tsuji et al (1996a) suggested that dust needs to be taken into account as opacity source for atmosphere models with  $T_{\text{eff}} < 2800\text{K}$ .

The following cloud models are very different from any cloud parametrization used in the classical retrieval methods. Retrieval methods only use a radiative transfer code that is iterated until an externally given set of parameters (local properties like molecular abundances and gas temperatures) allows to fit a set of observed properties (Madhusudhan and Seager 2009; Benneke and Seager 2012; Barstow et al 2013; Lee et al 2013). Different approaches are used to decide with which quality the parameter set fits the observation. Lee et al (2013) and Line et al (2014) assume Gaussian error for single-best fit solutions, Benneke and Seager (2012) derive a full probability distribution and credibility regions for all atmospheric parameters. Both methods require a prior to start the best-fit procedure in a multi-parameter space to ensure that the global minimum can be found.

*i) Tsuji model:* Tsuji (2001) suggested that condensates in cool dwarf atmospheres are present in the form of layers with strict inner and outer boundaries. The inner boundary, associated with a certain temperature denoted by  $T_{\text{cond}}$ , is related to the thermodynamical stability of the cloud particles in the surrounding gas. The upper boundary, parametrized by  $T_{\text{cr}}$ , is related to the assumption that the cloud particles must remain extremely small, because if they would grow too large then they would otherwise settle gravitationally. For  $T_{\text{cond}} > T > T_{\text{cr}}$ , the particles are assumed to be constantly forming and evaporating, thereby circumventing the problem of the gravitational settling (Tsuji 2001, 2002; Tsuji et al 2004; Tsuji 2005). Yamamura et al (2010); Tsuji et al (2011); Sorahana et al (2013) have applied their UNIFIED CLOUDY MODEL to the unique AKARI data set for brown dwarfs. Sorahana et al (2014) interpreted the mismatch with these models as signature of chromospheric activity on brown dwarfs (see Sect. 2.2.2).

*ii) Burrows et al. model:* Cooper et al (2003) (also Burrows et al 2006) assume chemical and phase equilibrium to determine whether cloud particles of a certain kind are thermodynamically stable in a solar composition gas. If  $p_x(T_{\text{gas}}, p_{\text{gas}}) = p_{\text{sat},s}(T_{\text{gas}})$ , i.e. the material  $s$  is thermally stable, the mean size of the particle of a certain homogeneous composition  $s$  is deduced from local time-scale arguments (Rossow 1978), considering growth, coagulation (also named coalescence), precipitation and convective mixing.  $p_x(T_{\text{gas}}, p_{\text{gas}}) = p_{\text{sat},s}(T_{\text{gas}})$  also determines the altitude of cloud layers of composition  $s$ . The amount of dust is prescribed by a free parameter  $S_{\text{max}} \approx 1.01$  (maximum supersaturation) which is the same for all materials. Thereby, the supersaturation ratio of the gases is fixed throughout the atmosphere and the mass of cloud particles present in the atmosphere scales with the saturation vapour pressure  $p_{\text{sat},s}(T)$ , which decreases exponentially with decreasing  $T_{\text{gas}}$ . Consequently, the vertical cloud structure is a dust layer with a strict lower boundary and an exponentially decreasing dust-to-gas ratio above the cloud base. Burrows et al (2011) use this phase-equilibrium approach to search where  $S_s=1.0$  for individual materials  $s$ . A

cloud density function is distributed around this local pressure parametrizing the geometrical cloud extension. For each condensate  $s$  the vertical particle distribution is approximated by a combination of a cloud shape function and exponential fall-offs at the high- and low-pressure ends. The model has been used, for example, in Apai et al (2013b) to suggest the presence of an upper, warm thick cloud and a lower, cool thin cloud as reason for the observed atmospheric variability of two early L/T-transition dwarfs (2M2139, SIMP0136; see Sect.2.3). Different cloud shape functions are tested with constant vertical distribution of particles above the cloud base (B-clouds, same as DUSTY models in Allard et al. 2001), and the modal grain sizes per material are adjusted to provided the best spectral fit.

*iii) Marley et al. model:* Ackerman and Marley (2001) parametrize the efficiency of sedimentation of cloud particles relative to turbulent mixing through a scaling factor,  $f_{\text{sed}}$ . Large values of  $f_{\text{sed}}$  describe rapid particle growth and large mean particle sizes. In this case, sedimentation is efficient, which leads to geometrically and optically thin clouds. When  $f_{\text{sed}}$  is small, particles are assumed to grow more slowly and the amount of condensed matter in the atmosphere is larger and clouds are geometrically more extended. Marley et al. solve a diffusion equation that aims to balance the advection and diffusion of each species vapor,  $p_x(T_{\text{gas}}, p_{\text{gas}})$ , and condensate,  $p_{\text{sat},s}(T_{\text{gas}})$ , at each layer of the atmosphere. It balances the upward transport of vapor and condensate by turbulent mixing with the downward transport of condensate by sedimentation. The downward transport of each condensate is parametrized by  $f_{\text{sed}}$  and the turbulent mixing by an eddy diffusion coefficient,  $K_{zz}$  [ $\text{cm}^2 \text{s}^{-1}$ ]. The partial pressure of each condensate species,  $p_x$ , is compared with the condensate vapour pressure,  $p_{\text{sat},s}$ , the crossing of which defines the lower boundary of the atmosphere above which this particular condensate is thermally stable. The model, as all other aforementioned models, assumes that each material can form by homogeneous condensation. Ackerman and Marley (2001) compute a single, broad log-normal particle size distribution for an assumed modal size that is intended to capture the likely existence of a double-peaked size distribution. Fortney et al (2008) apply this cloud model to planetary atmosphere simulations and, for example, suggest two classes of irradiated planets. Morley et al (2012) applied the Marley et al. model to suggest the presence of an additional cloud layer by moving higher into the atmosphere towards lower temperatures.

*iv) Allard et al. model:* Phase equilibrium between cloud particles and gas is also assumed in this model (Allard et al 2001). This assumption, i.e.  $p_x(T_{\text{gas}}, p_{\text{gas}}) = p_{\text{sat},s}(T_{\text{gas}})$ , is used to determine the cloud base for each condensate individually. Using the time scale for condensation, sedimentation and coalescence (Rossow 1978) in comparison to a prescribed mixing time-scale allows to determine a local mean grain size for a given grain size distribution (Allard et al 2013). The mixing-time scale described the convective overshooting based on a mass exchange frequency guided by Ludwig et al (2002). The BT-SETTL models were applied to learn about variability in brown dwarf atmospheres, for example on Luhman 16 by Crossfield et al (2014).

	grain size	grain composition	gas saturation	fitted parameters
<b>Model atmosphere simulations</b>				
Tsuji <sup>(1)</sup>	$a = 10^{-2} \mu\text{m}$	homog.	$S = 1$	<i>UCM</i> dust between $T_{\text{cr}} < T < T_{\text{cond}}$
Allard & Homeier <sup>(2)</sup>	$f(a) = a^{-3.5}$	homog.	$S = 1$	<i>dusty cond</i> full dusty model
	time scales dep.	homog.	$S = 1.001$	<i>settl</i> dust cleared model
				$K_{\text{zz}}$ time scales
Cooper, Burrows et al. <sup>(3)</sup>	$f(a) \sim \left(\frac{a}{a_0}\right)^6 \times \exp\left[-6\left(\frac{a}{a_0}\right)\right]$	homog.	$S = 1.001$	mixing for non-equilibrium molecules
Barman <sup>(4)</sup>	log-norm. $f(a, a_0)$	homog.	$S = 1$	$P_{\text{min}}, a_0$ dust between $p_{\text{upper}}^{\text{cloud}}, p_{\text{lower}}^{\text{cloud}}$
Ackerman & Marley <sup>(5)</sup>	log-norm. $f(a, z)$	homog.	$S = 1$	$f_{\text{sed}}$ sedimentation
				$K_{\text{zz}}$ mixing for non-equilibrium molecules
Helling & Woitke <sup>(6)</sup>	$f(a, z)$	mixed	$S = S(z, s)$	
<b>Retrieval method (radiative transfer only + fit quality assessment)</b>				
Barstow, Irwin, Fletcher <sup>(7)</sup> + Benneke & Seager <sup>(8)</sup>	$a_1$ log-norm. $f(a_2, z)$	homog.	–	$n_{\text{mix}}(\text{H}_2\text{O}, \text{CO}_2, \text{CH}_4)$ $\tau^{\text{cloud}}(a_1, a_2), R_{\text{PI}}(@ 10 \text{ bar})$
Lee, Heng & Irwin <sup>(9)</sup> + Line, Fortney, Marley, & Sorahana <sup>(10)</sup>	$a = \text{const}$	homog.	–	$P_{\text{up}}^{\text{cloud}}, P_{\text{down}}^{\text{cloud}}, \tau^{\text{cloud}}(Q_{\text{ext}}(a))$ → more parameter possible

**Table 1** <sup>(1)</sup>: Tsuji et al (1996a); Tsuji (2002); Tsuji et al (2004); Tsuji (2005), <sup>(2)</sup>:Allard et al (2001); Barman et al (2001); Allard et al (2013); Rossow (1978), <sup>(3)</sup>:Cooper et al (2003); Burrows et al (2006), <sup>(4)</sup>:Barman et al (2011), <sup>(5)</sup>:Ackerman and Marley (2001); Morley et al (2012), <sup>(6)</sup>:Woitke and Helling (2003, 2004); Helling and Woitke (2006); Helling et al (2008c); Witte et al (2009), <sup>(7)</sup>:Barstow et al (2013); Fletcher et al (2009), <sup>(8)</sup>:Lee et al (2013), <sup>(9)</sup>:Benneke and Seager (2012), <sup>(10)</sup>:Line et al (2014).

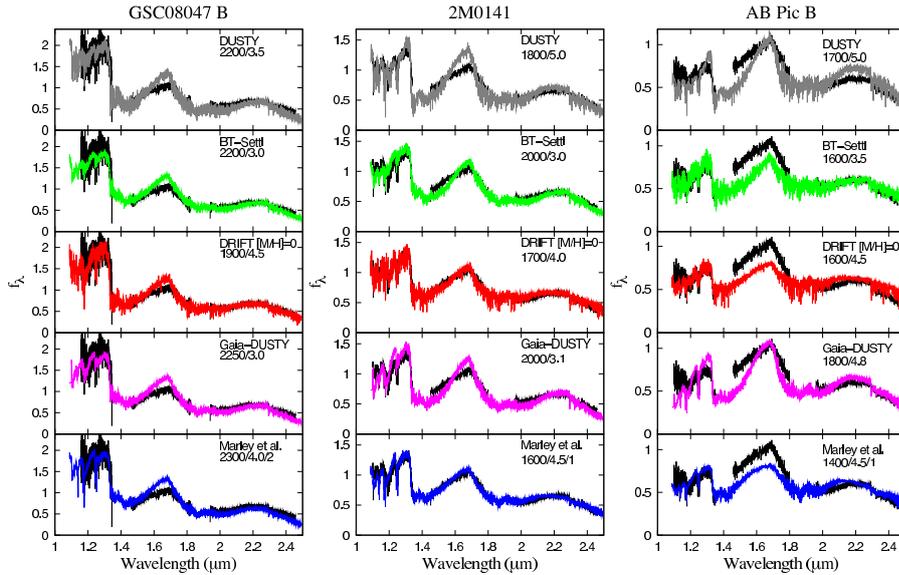
v) *Barman model*: Also Barman et al (2011) assume phase-equilibrium and find the lower boundary of the cloud (cloud base) where the atmospheric ( $T_{\text{gas}}, p_{\text{gas}}$ )-profile intersects the thermal stability curve of a condensate ( $p_{\text{x}}(T_{\text{gas}}) = p_{\text{sat,s}}(T_{\text{gas}})$ ). The particle sizes follow a log-normal distribution with a prescribed modal size,  $a_0$ . The adjustable parameter  $a_0$  can vary between 1 and  $100 \mu\text{m}$  and is the same for each atmospheric height. Prescribing the particle sizes allows to determine the number of cloud particles (equilibrium dust concentration). The cloud height and density above the cloud base is determined by a free parameter  $P_{\text{min}}$ . The equilibrium dust concentration is assumed if  $p_{\text{gas}} \geq P_{\text{min}}$ , and decays exponentially for  $p_{\text{gas}} < P_{\text{min}}$ . If  $P_{\text{min}} > p_{\text{sat,s}}(T_{\text{gas}})$ , then the maximum dusty-to-gas ratio is lowered relative to the equilibrium concentration.

vi) *Woitke & Helling model*: This model is different from all above models i)-v) as it kinetically describes seed formation and growth/evaporation coupled to gravitational settling, convective mixing and element depletion by conservation equations following Sect 3.3.2. These intrinsically time-dependent processes (Helling et al 2001; Woitke and Helling 2003) are treated in a stationary approximation of conservation equations (Woitke and Helling 2004; Helling and Woitke 2006; Helling

et al 2008a) to allow the coupling with a model atmosphere code (DRIFT-PHOENIX, Helling et al 2008b; Witte et al 2009, 2011). The convective mixing with overshooting is parametrized according to a mass exchange frequency (Ludwig et al (2002)). DRIFT-PHOENIX model atmospheres were applied to study early universe, metal-deficient brown dwarfs (Witte et al 2009), and they have recently been used to explore ionization and discharge processes in ultra-cool, cloud-forming atmospheres (Helling et al 2011b,a, 2013; Rimmer and Helling 2013; Stark et al 2013).

### Model approach summary:

- All phase-equilibrium models (i-v) assume that each condensate can form by homogeneous condensation, hence, it is assumed that the monomer exist in the gas phase.
- All phase-equilibrium models (i-v) adjust their element abundances according to by how much the monomer partial pressure exceeds the vapour pressure  $p_s > p_{\text{sat},s}$ . A prescribed size distribution allows the calculation of the cloud particle sizes. Note that the two prescribed distribution functions (power law and log normal) differ strongly in their dust mass distribution due to the relative contribution of the different sizes.
- All phase-equilibrium models (i-v) are relatively easy to implement.
- Table 3.4 provides a comparison of all cloud models, including free parameters for each cloud model.



**Fig. 12** Patience et al (2012) demonstrate spectral fits for varies Brown Dwarfs with synthetic spectra from different model families. Different model families were also used by Dupuy et al (2010) to provide a good error estimate on the derived global parameters. The figure shows that all model atmospheres found it challenging to fit brown dwarfs at the lowest  $T_{\text{eff}}$  depicted.

#### 4 Benchmarking atmosphere models and comparison to observations

A 'benchmark' is per definition a well-defined test case which is performed to understand differences in different approaches to the same problem. Astronomers and Astrophysicists approach this differently.

The observational astronomy, which aims on benchmarking brown dwarf models, follow the original idea that was inspired by stellar binary systems for which one companion's parameters are well known (Pinfield et al 2006; Burningham et al 2013). 'Benchmark brown dwarfs' are objects for which the distance (and thus luminosity), the age and the metallicity can be determined from observations. Their radii and their mass can be derived from evolutionary models if the age is well constrained. The effective temperature and the surface gravity can now be determined from the luminosity and the radius, the mass and radius, respectively. With  $T_{\text{eff}}$ ,  $\log(g)$  and a known metallicity, hence known element abundances, a model atmosphere is well constrained and a synthetic spectrum can be produced. This model spectrum is now compared to the binary target. Obvious places to search for such benchmark objects are open clusters as their age, composition and distance can be well defined through observations of much more luminous cluster members, and near-by kinematic moving groups with well-defined membership, age and composition.

Theoretical astrophysics has two model systems to benchmark in our context of brown dwarfs: the atmosphere models and the evolutionary models. Both model systems are complex. The additional challenge is that both systems are not independent because the model atmospheres serve as outer boundaries during the run of evolutionary models. Benchmarking both systems requires a substantial effort from different research groups world-wide, and it is unlikely to happen in the near future. Ongoing areas of research, however, are dedicated comparison studies that aim to demonstrate the difficulties in using model atmosphere and/or evolutionary grids as 'black boxes' (e.g. Sinclair et al 2010), and to allow the observer community to use an error estimate for model atmospheres (Bozhinova et al 2014) and evolutionary models (Southworth 2009). A sensitive handling of such uncertainties is not only important for our immediate understanding of brown dwarfs, but also for detecting planets around brown dwarfs and M-dwarfs (e.g. Rojas-Ayala et al 2013; Triaud et al 2013).

Model atmosphere test are conducted in various ways. Rajpurohit et al (2012) test different model atmosphere families in finding the stellar parameters for the late M-dwarf LHS 1070. They also including the cloud-free MARCS models in their comparison with the cloud-modelling PHOENIX-families (BTsettl, DRIFT). Dupuy et al (2010) and Patience et al (2012) compare the quality of fits to observations by model atmospheres that describe the same physical problem, a cloud-forming atmosphere (Fig. 12). The authors point out the significant difference in the  $H$ -band spectrum for the different models. This effects decreases with increasing  $T_{\text{eff}}$  but does still impact the  $J$ -band for  $T_{\text{eff}} = 1700\text{K}$ . The primary differences is in the cloud modelling. The cloud models differ in details (grain sizes, material composition) that influence the local opacity of the cloud and also of the gas phase through element depletion. For example does a higher cloud opacity results in less flux in the  $J$ -band as the water abundance decreases and, hence, results in weakened water absorption bands. The approach presented in Dupuy et al (2010) and Patience et al (2012) allows an error

estimate of the derived, global stellar parameters. A more detailed comparison of various brown dwarf model families is presented in Helling et al (2008a). The focus of this paper is comparing cloud model results for prescribed test cases. This also led to more understanding about why the synthetic spectra from different model families differ and which role the cloud modelling plays.

The Virtual Observatory pioneers the incorporation of grids of different model atmosphere families into their data base. A comparison between different model families can provide estimates of the expected systematic errors, which is of interest for the outcome of space missions. Sarro et al (2013) performed the task of predicting how well  $T_{\text{eff}}$  can be determined from GAIA data for Brown Dwarfs based in the BT-Settle model atmosphere grid. The Virtual Observatory is now capable of facilitating a multi-model family approach.

## 5 Increasing completeness and increasing model complexity

It may seem a big leap from a 1D atmosphere code to an atmosphere model that allows the study of time-variable cloud cover, the formation of photochemically driven hydro-carbonaceous macro-molecules, magnetic interactions, and irradiation. All these depend on global parameters like rotational period, magnetic field strength, cosmic ray flux etc. However, several aspects on this list start to emerge in the literature.

### 5.1 Multi-dimensional, dynamical atmosphere simulations

First steps towards a multi-dimensional approach to cloud forming brown dwarf atmospheres were made by 2D hydrodynamical simulations that treat dust formation (nucleation, growth/evaporation, element depletion), turbulence and radiative heating/cooling (Helling et al 2001, 2004), and by large-scale 2D radiative-convection simulations that included the dust growth/evaporation processes for a prescribed number of nucleation seeds (Freitag et al 2010). Both works suggest that clouds will not be present as a homogeneous, carpet-like layer but that cloud particles form, depending on the local temperature and density field, intermittently resulting in patchy cloud structures. Robinson and Marley (2014) came forward with a similar suggestion of local temperature variations to explain brown dwarf variability. Showman and Kaspi (2013b) use a 3D approach to simulate a globally circulating brown-dwarf atmosphere but excluding cloud opacities, turbulence, and radiation. These authors suggest that a hydrodynamically induced horizontal temperature variation of  $\Delta T = 50\text{K}$  can lead to flux variations of  $\Delta F/F \approx 0.02 - 0.2$ . Each of these models addressed a different aspect of a multi-dimensional, dynamical atmosphere simulations. The challenges faced by all simulation is illustrated by comparing the following time scales that are characteristic for interacting processes. The below table demonstrates that it is misleading to consider atmospheric processes as independent from each other, but that for example cloud formation processes could be re-ignited by transport processes like gravitational settling or gas-mixing that provides new condensable material:

$$\text{radiative cooling}^{\diamond}: \quad \tau_{\text{rad}}(\rho_{\text{gas}}) = \left( \frac{4\pi\kappa}{c\nu} \frac{\partial B}{\partial T} \right)^{-1} = 0.5 \dots 100 \text{ days}$$

gravitational settling <sup>†</sup> :	$\tau_{\text{sink}}(a, \rho_{\text{gas}}) = \frac{H_p}{v_{\text{drift}}}$	(with dust    without dust) = 15 min ... 8 month ( $a = 100\mu\text{m} \dots 0.1\mu\text{m}$ )
large-scale convection:	$\tau_{\text{conv}}(\nabla T_{\text{gas}}) = \frac{H_p}{v_{\text{conv}}}$	= 20 min ... 3.5h
diffusive eddy mixing <sup>‡</sup> :	$\tau_{\text{diff}} = \frac{H_p^2}{K_{\text{eddy}}}$	= 3h ... 3 yrs
grain growth:	$\tau_{\text{gr}}(T_{\text{gas}}, \rho_{\text{gas}}) = \frac{a}{v_{\text{gr}}}$	= 0.1s ... 1.5min
wave propagation:	$\tau_{\text{wave}}(T_{\text{gas}}, \rho_{\text{gas}}) = \frac{H_p}{u + c_s}$	= 0.3s ... 3s
seed formation:	$\tau_{\text{nuc}}(T_{\text{gas}}, \rho_{\text{gas}}) = \frac{n_d}{J_*}$	$\approx 10^{-3}\text{s}$

◇ Please refer to Table 1 in Helling et al (2011b) for definitions and values of the absorption coefficient  $\kappa$ ,  $c_V$  specific heat capacity for constant volume and  $B(T)$  the frequency integrated Planck function.

† Please refer to Woitke and Helling (2003, 2004) for definition of  $v_{\text{drift}}$ ,  $v_{\text{gr}}$ , the mean grain size  $a$ , the number of cloud particles  $n_d$ , and the seed formation rate  $J_*$ . Typical values for all other quantities are applied,  $H_p \approx 10^6\text{cm}$ .

‡  $K_{\text{eddy}}$  [ $\text{cm}^2\text{s}^{-1}$ ] (or  $K_{zz}$ ) is the eddy diffusion coefficient ranging between  $10^4 \dots 10^8\text{cm}^2\text{s}^{-1}$ , see Bilger et al (2013)

Diffusion, gravitational settling and convection have the longest time scales in a brown dwarf atmosphere compared to chemical timescales for cloud particle nucleation and growth. The wave propagation time scale can be used as proxy for turbulence acting on small scales where chemical processes would take place. The wave propagation takes still  $100\times$  longer, and hence, cloud particle formation would be given too much time if a numerical scheme uses wave propagation to set integration time-steps. This is problematic as the cloud particle formation determines the remaining gas phase abundance which in turn determines the local gas opacity and with that the local gas temperature, and eventually, the energy transport and the spectral flux. The radiative cooling time scale indicates the impact of the radiative energy transport on the local hydrodynamics through the energy equation. Depending on the local opacity, radiative cooling can be very efficient, even causing local gas volumes to implode (Helling et al 2001).

## 5.2 Gas-phase non-equilibrium effects

Deviations from local chemical gas-phase equilibrium in the upper atmosphere are suggested to be caused by a rapid convective and/or diffusive up-mixing of warm gases from deeper atmospheric layers combined with a slow relaxation into chemical equilibrium (Saumon et al 2000). Other processes that drive the local gas-phase out of chemical equilibrium (and LTE) are photodissociation, or ion-neutral chemistry initiated by cosmic ray impact (Rimmer and Helling 2013). The local chemical composition of the atmosphere is derived from extensive gas-phase rate network calculations under the influence of vertical mixing and photodissociation. Most of these studies are performed for irradiated planets (e.g. Moses et al 2011; Venot et al 2012)<sup>3</sup>. A height in the atmosphere (so-called quenching height) is derived above which the

<sup>3</sup> Venot et al (2012)'s chemical network is publicly available under <http://kida.obs.u-bordeaux1.fr/>.

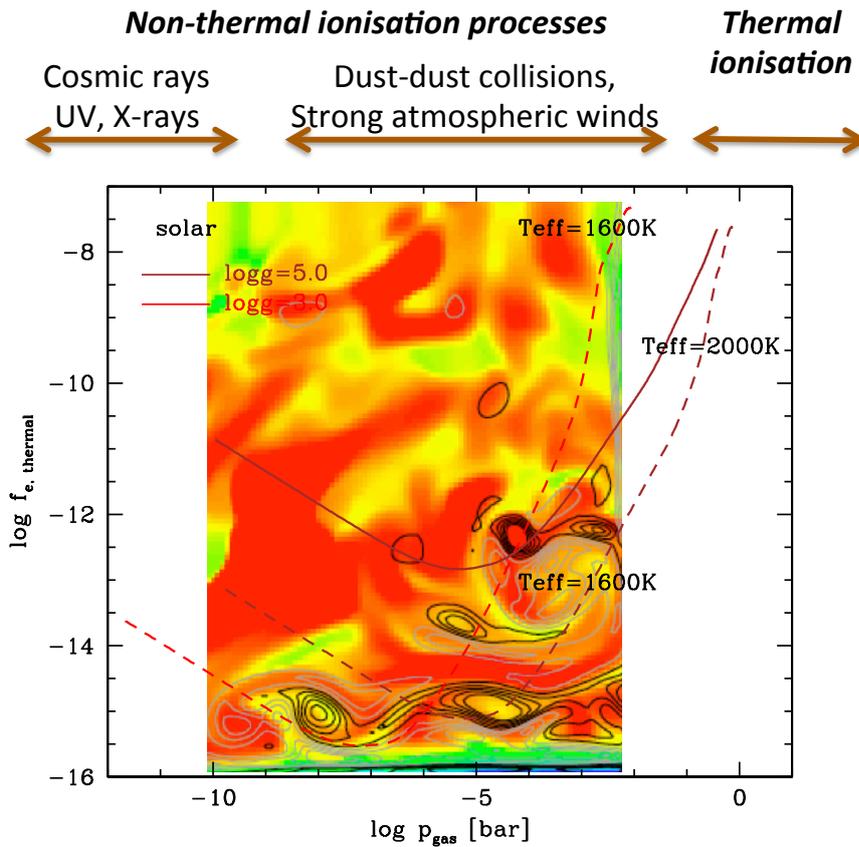
gas kinetic reactions are too slow to considerably change molecular abundances. This idea of modelling time-dependent gas non-equilibrium effects has two shortcomings: First, the diffusive eddy mixing coefficient  $K_{\text{eddy}}$  [ $\text{cm}^2\text{s}^{-1}$ ] (or  $K_{zz}$ ) becomes an additional fitting parameter for model atmospheres to observations (e.g. Cushing et al 2010). Second, reaction rate coefficients differ in the literature leading differences in destruction time scale for example for  $\text{C}_2\text{H}_2$  and  $\text{C}_2\text{H}_6$  (Bilger et al 2013). This is, however, a challenge faced by all gas-kinetic approaches and considerable effort is ongoing to weed-out the respective rates. Rimmer et al (2014) model cosmic ray transport through an brown dwarf atmosphere and they demonstrate how galactic cosmic rays influence the abundance of hydrocarbon molecules through ion-neutral reactions.

## 6 Closing the loop

The first L4 dwarf (GD 165B; Becklin and Zuckerman 1988) was discovered  $\sim 30$  years ago. Since then, spectral classification of these very cool objects led to the introduction of the new spectral classes L, T and Y, with the Y dwarfs having  $T_{\text{eff}}$  typical for planets. Such low temperature immediately suggest that brown dwarf atmospheres must contain a chemically very rich gas from which clouds will form. The evolutionary transition from the L into the T dwarf spectral type are associated with atmospheric variabilities which is attributed to variable cloud coverage. In parallel to the increasing number of observations, atmosphere modellers adopted stellar atmosphere codes for cooler gases by introducing cloud models and additional gas opacity sources (e.g.  $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{NH}_3$ ). More complex processes like kinetic gas chemistry, turbulence and multi-dimensional hydrodynamic simulations were performed but with far less consistency between the processes. The picture that emerged for a brown dwarf atmosphere is that of chemically very active gas that is exposed to phase-changes, turbulence, high and low energy radiation. It also provides a valuable path towards the understanding for brown dwarfs as planetary host stars (Triaud et al 2013) and of climate evolution on extrasolar planets. More and more similarities to planets arise: Radio and X-ray observations suggest brown dwarf atmospheres to be ionized to a certain extend. Theoretical studies on ionization processes support this idea by demonstrating that clouds in brown dwarfs will be charged (Helling et al 2011a,b), that clouds can discharge in form of lighting (Bailey et al 2013), that Cosmic Rays can ionize the upper atmosphere and the upper part of the cloud (Rimmer and Helling 2013, and that hydrodynamic winds can provide a source for gas-ionization (Stark et al 2013). Figure 13 shows that these ionization processes (boxes in figure) do appear with different efficiencies in different parts of the atmosphere, suggesting a brown dwarf atmosphere to be a stratified ionized medium rather than a cold, neutral gas.

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**Fig. 13** A brown dwarf atmosphere is not only stratified by its cloud structure (2D colour overlay). Different non-thermal ionization processes occur in brown dwarf atmospheres (boxes: cosmic rays, dust-dust collisions, strong winds) which produce free charges through the atmosphere with varying efficiency. The local degree of thermal ionization (brown solid and dashed lines) is shown in the background for illustration, a 2D simulation of turbulent dust formation indicates where the cloud is located in the atmosphere. (The 2D colour-coded plot contains contour lines of the local vorticity; see Fig 8 in Helling et al (2004))

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