Atmospheres of Giant Planets from Neptune to Gliese 229B

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Abstract. Stratospheric heating, condensation, convective transport of non-equilibrium species, and deep radiative energy transport are important processes in the atmospheres of the solar jovian planets. They likely affect the atmospheres of extrasolar giant planets and brown dwarfs as well. Stratospheric temperatures control thermal fluxes in strong molecular bands, and may dramatically affect observed spectra. Condensation processes affect the appearance of an object, alter the abundances of atmospheric species, and influence the fluxes of both reflected and emitted radiation. Convection can dredge up non-thermochemical equilibrium species from the deep atmosphere to the observable atmosphere. Finally deep radiative zones can limit the effectiveness of deep convection and alter the boundary condition at which the planet radiates energy to space. Here I discuss the role these processes may play in the atmospheres of brown dwarfs and extrasolar giant planets.

1. Introduction

Two decades of exploration of the outer solar system has given us a sophisticated perspective on the physical processes which shape the observable atmospheres of the jovian planets. Indeed this exploration has taught us a number of lessons about planetary atmospheres which we can take with us as we leave the solar system and begin to study the atmospheres of the extrasolar planets and brown dwarfs. Here I discuss a selection of four processes which play substantial roles in these atmospheres and have the potential to play important roles in the atmospheres of extrasolar giant planets and brown dwarfs as well. These processes are stratospheric heating, condensation, convective transport of non-thermochemical equilibrium species, and deep radiative energy transport. I will discuss both lessons learned about these processes from the atmospheres of the solar jovian planets as well as applications and model results for extrasolar planets and brown dwarfs.

For clarity, I will refer to Jupiter, Saturn, Uranus, and Neptune as the solar jovian or giant planets. I will assume that the objects detected in orbit around other stars by the Doppler method are indeed Jupiter-mass jovian, as opposed to terrestrial, planets and will refer to these objects as extrasolar giant planets (EGPs). This is done simply for economy of expression and is not meant to have any bearing on the question of whether or not some of these objects are in fact
brown dwarfs. The most massive and warmest object considered here is Gliese 229B.

2. Atmosphere Models

Model results presented below are obtained using the modeling procedures of Marley et al. (1996, 1997). Radiative-convective equilibrium temperature profiles are computed for assumed gravities, internal heat fluxes, and incident radiative fluxes. The deposition of incident radiation as a function of vertical position in the atmosphere is self-consistently computed assuming the mean orbital radius of the planet and the spectral type of the primary. No incident flux is assumed for Gliese 229 B. Temperature profiles for all objects are obtained by assuming cloud-free atmospheres.

Molecular opacities are treated using the exponential sum (or k-coefficient) method (Goody et al. 1989; Lacis & Oinas 1991). This technique is widely used in the analysis of planetary atmospheres and is accurate (e.g. Grossman & Grant 1994). It should not be confused with the Opacity Distribution Function (ODF) method. The limiting factor in the model accuracy is knowledge of the molecular opacities, particularly those of methane, at high temperatures and pressures, not the radiative transfer technique.

Computed temperature profiles for a variety of objects are shown in Figure 1. For the EGPs, a typical model with parameters selected from a range of possible values for the surface gravity and internal heat flux for the particular planet (Guillot et al. 1996) is shown. The accuracy of the approach is demonstrated by the close correspondence of the model and actual temperature profiles for Jupiter (Lindal et al. 1981). The Jupiter model profile assumes solar composition and no clouds. Departure of the model from the observed profile at low pressure in the stratosphere is discussed in the next section.

3. Stratospheric Heating

The stratosphere is the region of a planetary atmosphere which is in radiative equilibrium and lies immediately above the troposphere. Unlike the temperature gradient in the troposphere which falls with rising altitude, the stratospheric temperature is either constant or increases with altitude. A hot stratosphere overlying a cold temperature minimum at the top of the troposphere (the tropopause) is indeed a general feature of the solar jovian planets, as well as the Earth, all exceed the skin temperature. Thus the transport of thermal radiation emitted by the lower atmosphere does not solely determine the stratospheric temperature.

If there were no incident radiation or other energy transport mechanism, the stratosphere would have a temperature close to the planetary “skin” temperature (e.g. Chamberlain and Hunten 1987). This is defined as the temperature at zero optical depth in the thermal infrared, \( T_0 = 2^{-1/4} T_e \) where \( T_e \) is the effective temperature. In fact the stratospheric temperatures of the solar jovian planets, as well as the Earth, all exceed the skin temperature. Thus the transport of thermal radiation emitted by the lower atmosphere does not solely determine the stratospheric temperature.

The discrepancy arises from the absorption of incident solar radiation within the stratosphere. On Earth the UV bands of ozone are responsible for strato-
Figure 1. Model temperature profiles for a variety of objects. The extrasolar planet 55 Cnc A c is only suspected from residuals in the orbit of 55 Cnc A b (Butler et al. 1996). Model Jupiter profile is computed in the same way as the other profiles and is compared with observed profile (dotted). Thermochemical equilibrium between N$_2$ and NH$_3$ is denoted by the short dashed line; water condenses along the long dashed line.
spheric heating. In the atmospheres of the jovian planets the near-infrared methane bands play a similar role. Hazes created by the condensation of photochemical products derived from the decomposition of methane by solar UV radiation are also important. The influence of these hazes is complex as they both scatter incident radiation out of the atmosphere and absorb photons. Other mechanisms, including wave breaking, may also deposit energy and be responsible for some stratospheric heating.

The Jupiter model temperature profile shown in Figure 1 is derived for a clear atmosphere. The model does not include the radiative effect of stratospheric hazes and is too cool compared to the observed temperature profile in the stratosphere. The warming effect of hazes is detectable even at Neptune at 30 AU (Appleby 1986).

The model EGP profiles (Fig. 1) also show signs of some stratospheric warming. As with Jupiter, the models likely underestimate the magnitude of this warming as no stratospheric hazes are included. In fact it is exceptionally difficult to model such hazes on an a priori basis as their size and composition (and thus radiative properties) depend upon a complex interplay of eddy diffusion, condensation, and coagulation, which are peculiar to each individual object. Even models constrained to fit spacecraft observations have a difficult time reproducing observed haze properties (e.g. Rages et al. 1991).

Gliese 229 A is sufficiently dim and the brown dwarf lies at such large orbital distance that any stratospheric heating from incident radiation would only amount to a few degrees and would likely be undetectable. Isolated brown dwarfs would also not be expected to exhibit stratospheric warming unless there is a non-radiative energy transport mechanism (such as wave breaking).

Even relatively modest stratospheric heating can produce large effects in the thermal emission spectra. In particular the 7.8 μm methane band is a particularly effective stratospheric temperature indicator. In Jupiter’s atmosphere emission from this strong bands originates in the stratosphere. The cold model stratosphere thus produces substantially less flux in this band (Figure 2). The flux at neighboring wavelengths which arise deeper in the atmosphere where the model more closely follows the actual temperature profile agree much better with the observations.

Mid-infrared spectra of extrasolar giant planets and brown dwarfs will thus provide substantial information about the temperature profile above the tropopause and consequently information on stratospheric heating mechanisms.

4. Condensation

4.1. Solar Jovian Atmospheres

The visual appearance of the solar jovian planets is predominantly controlled by their tropospheric cloud decks and stratospheric hazes. Clouds condense when the partial pressure of a minor constituent exceeds the saturation vapor pressure at a given location in the atmosphere. Figure 1 includes the temperature-pressure profile for Jupiter as well as the vapor pressure curve for water. Clouds are assumed to form where the two lines intersect. It is on the basis of this
Figure 2. Model and observed brightness temperature spectra for Jupiter. The cold model stratosphere (Figure 1) results in substantially less flux in the 7.8 $\mu$m methane band than is the case in the real Jupiter. The lack of cloud opacity in the 5 $\mu$m spectral window allows flux from the model to escape from deeper, hotter layers of the atmosphere than in the real planet.
sort of calculation that the composition of the clouds in jovian atmospheres are inferred.

In Jupiter’s atmosphere the uppermost cloud deck consists of ammonia ice particles. Beneath this cloud is an optically thick layer of condensed NH$_4$SH which in turn likely overlies a water cloud. The global extent of the NH$_4$SH cloud layer is revealed by center-to-limb brightness variations across the disk (West 1979; Chanover 1997) which are inconsistent with a single cloud layer. However, on a local scale the clouds are clearly patchy. The nephelometer on the Galileo atmosphere probe, which penetrated the atmosphere in a relatively cloud free region, did not detect the thick clouds present over most of Jupiter’s disk (Ragent et al. 1996).

Rock forming elements, such as Fe, Si, Ti presumably are condensed as grains far below the visible atmosphere and thus are generally not present in Jupiter’s visible atmosphere (Fegley & Lodders 1994).

The condensation sequence in Saturn’s atmosphere is similar to that at Jupiter. The atmospheres of Uranus and Neptune, however, are substantially colder and their upper cloud layer is instead composed of condensed methane. Below this cloud layer is likely an H$_2$S cloud deck, followed at depth by a sequence similar to that seen at Jupiter and Saturn.

Clouds substantially affect both the appearance and spectra of the jovian planets. First, condensation removes species from the atmosphere above the clouds. It is generally expected that the abundance of condensable species follows a saturation vapor pressure curve above its own cloud tops. While this is approximately true in general, the actual abundance of condensable species above clouds in the solar system is a complex issue (e.g. Lunine and Hunten 1989). Secondly, clouds form reflecting layers which scatter incident solar radiation. An absorbing, Rayleigh-scattering atmosphere with no clouds would look substantially different. Photons streaming downwards at red and longer wavelengths would generally be absorbed before scattering, suppressing the flux in these regions of the spectrum. Thirdly, clouds also may affect the emitted radiation. At Jupiter, most of the thermal emission arises at or above the ammonia cloud tops. However emission in the 5µm spectral window arises from deeper, hotter layers of the atmospheres. A comparison of Hubble Space Telescope visual and IRTF 5µm images of the planet (Chanover 1997) reveals that there is a one-to-one correspondence between holes in the ammonia cloud deck and regions of five-micron emission.

Condensates of low-abundance species produced by photochemistry are also found in all the jovian atmospheres. In Jupiter’s stratosphere methane and ammonia are photolyzed by solar UV radiation. A rich photochemistry ensues that results in compounds such as ethylene (C$_2$H$_4$) and acetylene (C$_2$H$_2$) which condense in the stratosphere, producing an optically thin haze which lies above the ammonia cloud (West 1979). Hazes are particularly apparent in spectral regions of strong methane absorption in the near-infrared (e.g. the 2.3µm band). In these methane bands a portion of the incident solar radiation that would otherwise be almost entirely absorbed instead scatters off the hazes, thereby increasing reflected flux. Thus a small column abundance of hazes can substantially affect a planet’s spectra as well as the stratospheric temperature.
Figure 3. Brightness temperature spectrum for baseline Gl 229 B model of Marley et al. (1996). Temperature is plotted increasing downwards to suggest depth at which flux originates in the atmosphere. Physical temperature at which NH$_3$ - N$_2$ and CH$_4$ - CO are in thermochemical equilibrium are shown by horizontal lines. Also shown is temperature at which enstatite condenses. The radiative-convective boundary in this model is quite deep, below 1700 K.

4.2. Extrasolar Jovian Atmospheres

Condensation will also play an important role in controlling the properties of the EGPs. Figure 1 shows model temperature-pressure profiles for a selection of the extrasolar planets. Of the selected atmospheres, water clouds would be expected to condense in the atmospheres of 47 UMa b and 55 Cnc A c, but not in the atmospheres of 70 Vir b and HD 114762 b.

In atmospheres that are too warm for water condensation, there are few other condensates until about 2000 K when refractory oxides such as CaTiO$_3$ and Mg$_2$SiO$_4$ condense. As shown in Figure 3, such condensates will form well below the observable atmosphere of Gl 229 B. Thus atmospheres in a temperature range from somewhat warmer than Jupiter to somewhat warmer than Gliese 229 B (or 400 < $T_{\text{eff}}$ < 1200K (Guillot et al. 1996)) will lack abundant condensates. Trace compounds such as ZnS and Na$_2$S may condense in these atmospheres, forming low optical depth hazes. Guillot et al. (1996) explore the condensation of trace species further.
Figure 4. Model reflected visible and near-infrared spectra for 70 Vir b, 47 UMa b, and observed Jupiter spectrum. For 47 UMa b two models are shown, one with (solid) and one without (dotted) clouds. The EGP model spectra are preliminary, but demonstrate the substantial sensitivity to clouds. Note the remarkable fall off of reflected flux in the near-infrared in the cloud-free models.

Approximate reflected visible spectra for several extrasolar jovian planets and Jupiter are shown in Figure 4. There is no cloud assumed for the atmosphere of 70 Vir b. For 47 UMa b, two models are shown, one with and one without clouds. The water cloud is simply modeled as a conservatively-scattering grey cloud of optical depth 10, which is typical for terrestrial clouds. The presence or absence of clouds substantially alters the near-infrared reflected spectrum for 47 UMa b. In the absence of clouds, stellar photons from the primary propagate downwards and are typically absorbed before they Rayleigh scatter. Thus the reflected flux beyond 1 micron is quite small. With a cloud layer many more of the photons scatter before they are absorbed and the planet is much brighter in this spectral region.

Clearly the near-infrared reflected flux of the extrasolar jovian planets can provide a first-order measure of the presence of atmospheric condensates. This in turn provides a measure of the atmospheric temperature.

Such a test however, will be complicated by the emitted thermal radiation. For objects warmer than about 400 K, the emitted flux in some bands will
exceed the reflected flux in the 1 to 3 micron region for planets at several AU from typical primaries. If spectra of such objects are obtained, detailed modeling of the reflected and thermal components will be required.

4.3. Brown Dwarfs

In the atmospheres of the cooler brown dwarfs condensation is important more from a chemical perspective than a radiative perspective.

At temperatures near 2000 K in the atmosphere of Gl 229 B, iron and various refractory silicates condense (Fegley and Lodders 1996). Thus in a rising parcel of gas, these materials will form grains and perhaps a discrete layer. The exact behavior will depend on the grain size, grain growth rate, and convective velocities. The primary consequence of grain formation is that refractory elements, such as Ti, V, and Fe are removed from the gaseous atmosphere. For example Ti condenses as CaTiO$_3$, or perovskite. Vanadium dissolves into perovskite and is likewise removed (Fegley and Lodders 1994). Indeed, absorption lines of refractory diatomic molecules, such as TiO are VO are not observed in the atmosphere of Gliese 229 B (e.g. Allard et al. 1996).

The grains themselves, however, are expected to be hidden from view in the atmosphere of Gl 229 B. As shown in Figure 3, the grain formation region (represented in the figure by Mg$_2$SiO$_4$ lies well below the observable atmosphere. Unless grains are convectively transported to the visible portion of the atmosphere, they would not be expected to play a major role in controlling the spectrum. Since most of the acceptable Gl 229 B models of Marley et al. (1996) are radiative at some point between the region of grain condensation and the photosphere, upward transport of grains is unlikely. As with the EGPs discussed above, however, the condensation of minor species may produce detectable hazes in the atmosphere.

5. Non-equilibrium chemistry

To an excellent first approximation, the atmospheres of the solar jovian planets are in thermochemical equilibrium. Thus C, O, and N are predominantly found in the forms of CH$_4$, H$_2$O, and NH$_3$, as would be expected at the temperatures and pressures of the observable atmospheres. Fegley & Lodders report on the abundances of species expected at chemical equilibrium in the atmospheres of Jupiter and Saturn (1994) and Gl 229 B (1996).

However the timescales of convective motion in these planetary atmospheres are sufficiently short compared to chemical equilibration timescales that some non-thermochemical equilibrium species are present in the observable atmospheres of these planets. Species which equilibrate at higher temperatures and pressures deeper into the planet are dredged up to the visible atmosphere by convection.

An example of this process is CO at Jupiter. The carbon monoxide mixing ratio measured in Jupiter’s atmosphere, $1.6 \times 10^{-9}$ (Noll et al. 1988), is more than ten orders of magnitude (Fegley & Lodders 1994) larger than the chemical equilibrium abundance. This discrepancy is explained by the convective transport of CO from depths where the temperature is about 1100 K and the observed abundance of CO is in equilibrium with water and methane.
In elementary mixing length theory (e.g. Clayton 1968) the convective velocity is proportional to the cube root of the convective flux. Thus in Jupiter-mass and larger planets of comparable or lesser age, convective velocities will be comparable to those in Jupiter or greater. Convective transport of non-equilibrium species will likely also be an important process in these atmospheres.

Whether or not convective transport is an important process in the atmosphere of Gl 229 B depends on the mass and gravity. For some models, such as the baseline model of Marley et al. illustrated in Figure 3 ($T_{\text{eff}} = 960$ K and $g = 1000$ m sec$^{-2}$), the radiative/convective boundary is quite deep, below 1700 K and the point at which CO is in chemical equilibrium with CH$_4$. Since the atmosphere is radiative above this point, there would be no upward transport. From Figure 3 it is apparent that the CO 1-0 vibration-rotation band near 4.7 $\mu$m (where CO has been detected in the jovian planets (Noll et al. 1988)) probes to temperatures no deeper than about 800 K and thus CO would be expected to virtually undetectable.

However in other somewhat cooler and less massive models a detached convection zone is predicted to appear near 1 bar. Thus convection could mix air from around 1100 K to the observable atmosphere around 800 K, bringing with it detectable, non-equilibrium, amounts of CO.

Noll and Marley (1997) consider the detectability of non-equilibrium species in Gl 229 B. CO is the most easily detected non-equilibrium species. PH$_3$ is also potentially detectable. If CO is detected, the implied presence of an upper, detached convection zone would help constrain the atmosphere model.

6. Deep Radiative Zones

Prior to work by Guillot et al. (1994), it had long been assumed that the deep atmospheres of the solar jovian planets were fully convective at all depths below the radiative-convective boundary, slightly below the photosphere. The large pressure-induced opacity of H$_2$ as well as the molecular opacities of water, methane, and ammonia, along with free-free and bound-free absorption at depth, would presumably require steep temperature gradients to transport heat by radiation. Since both the conductivity and viscosity of dense hydrogen-helium fluids are low, it was assumed that the adiabatic temperature gradient would always be less steep than the radiative-equilibrium lapse rate and the atmospheres would convect.

However Guillot et al. (1994) demonstrated that the near-infrared windows in the important opacity sources from 1 to 2.4 $\mu$m would create a region from about 1,000 K to about 3,000 K through which a substantial amount of radiation could be transported. The boundaries of this region are controlled by the overlap of the Planck function with the windows in methane, water, and pressure-induced hydrogen opacity. At lower temperatures the Planck function does not substantially overlap the window regions and energy transport is again by convection. At higher temperatures the electron number density grows large enough that free-free and bound-free absorption closes the windows.

The models of Marley et al. (1996) predict that this same process is at work in the atmospheres of brown dwarfs. However since these objects are warmer, the radiative region arises at much lower pressures than on Jupiter. Thus in
models where it is present, the deep radiative zone is found much closer to the observable atmosphere than on Jupiter. Thus its effects may be more important.

The radiative window is important because it disconnects the upper convection zone from the deep interior. Planetary evolution models require as a boundary condition a temperature and pressure within the deep convection zone. Thus models must account for the presence of the radiative window. Furthermore if convection indeed delivers non-equilibrium constituents to the observable atmosphere in the presence of the two zones, the upper zone will dredge only to the bottom of that zone.

7. Summary

When theorists first approach the a new class of objects, like the extrasolar giant planets and the cool brown dwarf Gl 229 B, they are tempted to treat it as a “homogeneous, spherical object”. However the exploration of the solar system has clearly taught us that planets are complex, unexpected objects. Processes which at first seem second order in importance may control first order observable characteristics. For example Jupiter might be expected to have thick, uniform water and ammonia cloud decks, which could prevent any flux from emerging from hot, deep seated regions of the atmosphere. Yet Jupiter’s substantial flux in the five-micron window in molecular opacities emerges through holes in the clouds.

We should not expect the atmospheres of the EGPs and brown dwarfs to be any less complex. The selection of processes discussed here will likely play important roles in at least some of these new atmospheres. The exploration of the solar system has prepared us to learn from these new worlds. Doubtless these worlds will teach us new lessons about unexpected processes that shape their atmospheres.

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