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brown dwarfs and extrasolar planets. 1999-2008

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Author(s): Saumon, D (Saumon, D.); Marley, MS (Marley, Mark S.)

Title: THE EVOLUTION OF L AND T DWARFS IN COLOR-MAGNITUDE DIAGRAMS

Source: ASTROPHYSICAL JOURNAL, 689 (2): 1327-1344 DEC 20 2008

Abstract: We present new evolution sequences for very low mass stars, brown dwarfs, and giant planets and use them to explore a variety of influences on the evolution of these objects. While the predicted adiabatic evolution of luminosity with time is very similar to results of previous work, the remaining disagreements reveal the magnitude of current uncertainty in brown dwarf evolution theory. We discuss the sources of those differences and argue for the importance of the surface boundary condition provided by atmosphere models including clouds. The L- to T-type ultracool dwarf transition can be accommodated within the Ackerman and Marley cloud model by varying the cloud sedimentation parameter. We develop a simple model for the evolution across the L/T transition. By combining the evolution calculation and our atmosphere models, we generate colors and magnitudes of synthetic populations of ultracool dwarfs in the field and in Galactic clusters. We focus on near-infrared color-magnitude diagrams (CMDs) and on the nature of the "second parameter" that is responsible for the scatter of colors along the T-eff sequence. Instead of a single second parameter we find that variations in metallicity and cloud parameters, unresolved binaries, and possibly a relatively young population all play a role in defining the spread of brown dwarfs along the cooling sequence. We also find that the transition from cloudy L dwarfs to cloudless T dwarfs slows down the evolution and causes a pileup of substellar objects in the transition region, in contradiction with previous studies. However, the same model is applied to the Pleiades brown dwarf sequence with less success. Taken at face value, the present Pleiades data suggest that the L/T transition occurs at lower T-eff for lower gravity objects, such as those found in young Galactic clusters. The simulated populations of brown dwarfs also reveal that the phase of deuterium burning produces a distinctive feature in CMDs that should be detectable in similar to 50-100 Myr old clusters.

Author(s): Rowe, JF (Rowe, Jason F.); Matthews, JM (Matthews, Jaymie M.); Seager, S (Seager, Sara); Miller-Ricci, E (Miller-Ricci, Eliza); Sasselov, D (Sasselov, Dimitar); Kuschnig, R (Kuschnig, Rainer); Guenther, DB (Guenther, David B.); Moffat, AFJ (Moffat, Anthony F. J.); Rucinski, SM (Rucinski, Slavek M.); Walker, GAH (Walker, Gordon A. H.); Weiss, WW (Weiss, Werner W.)

Title: THE VERY LOW ALBEDO OF AN EXTRASOLAR PLANET: MOST1 SPACE-BASED PHOTOMETRY OF HD 209458

Source: ASTROPHYSICAL JOURNAL, 689 (2): 1345-1353 DEC 20 2008

Abstract: Measuring the albedo of an extrasolar planet provides insight into its atmospheric composition and its global thermal properties, including heat dissipation and weather patterns. Such a measurement requires very precise photometry of a transiting system, fully sampling many phases of the secondary eclipse. Space-based optical photometry of the transiting system HD 209458 from the MOST (Microvariablity and Oscillations of Stars) satellite, spanning 14 and 44 days in 2004 and 2005, respectively, allows us to set a sensitive limit on the optical eclipse of the hot exosolar giant planet in this system. Our best fit to the observations yields a flux ratio of the planet and star of 7 +/- 9 ppm (parts per million), which corresponds to a geometric albedo through the MOST bandpass (400-700 nm) of A(g) = 0.038 +/- 0.045. This gives a 1 sigma upper limit of 0.08 for the geometric albedo and a 3 sigma upper limit of 0.17. HD 209458b is significantly less reflective than Jupiter (for which A(g)would be about 0.5). This low geometric albedo rules out the presence of bright reflective clouds in this exoplanet's atmosphere. We determine refined parameters for the star and exoplanet in the HD 209458 system based on a model fit to the MOST light curve.

Author(s): Burrows, A (Burrows, A.); Ibgui, L (Ibgui, L.); Hubeny, I (Hubeny, I.)

Title: Optical albedo theory of strongly irradiated giant planets: The case of HD 209458b

Source: ASTROPHYSICAL JOURNAL, 682 (2): 1277-1282 AUG 1 2008

Abstract: We calculate a new suite of albedo models for close-in extrasolar giant planets and compare with the recent stringent upper limit

for HD 209458b of Rowe et al. using MOST. We find that all models without scattering clouds are consistent with this optical limit. We explore the dependence on wavelength and wave band, metallicity, the degree of heat redistribution, and the possible presence of thermal inversions and find a rich diversity of behaviors. Measurements of transiting extrasolar giant planets (EGPs) at short wavelengths by MOST, Kepler, and CoRoT, as well as by proposed dedicated multiband missions, can complement measurements in the near- and mid-IR using Spitzer and JWST. Collectively, such measurements can help determine metallicity, compositions, atmospheric temperatures, and the cause of thermal inversions (when they arise) for EGPs with a broad range of radii, masses, degrees of stellar insolation, and ages. With this paper we reappraise and highlight the diagnostic potential of albedo measurements of hot EGPs shortward of similar to 1.3 mu m.

Author(s): Seager, S (Seager, S.)

Title: Exoplanet transit spectroscopy and photometry

Source: SPACE SCIENCE REVIEWS, 135 (1-4): 345-354 MAR 2008

Abstract: Photometry and spectroscopy of extrasolar planets provides information about their atmospheres and surfaces. From extrasolar planet spectra and photometry we can infer the composition and temperature of the atmospheres as well as the presence of molecular species, including biosignature gases or surface features. So far photometry has been published for three different transiting hot Jupiters (gas giant planets in short-period orbits), opening the era of comparative exoplanetology.

Author(s): Winn, JN (Winn, Joshua N.); Holman, MJ (Holman, Matthew J.); Shporer, A (Shporer, Avi); Fernandez, J (Fernandez, Jose); Mazeh, T (Mazeh, Tsevi); Latham, DW (Latham, David W.); Charbonneau, D (Charbonneau, David); Everett, ME (Everett, Mark E.)

Title: The transit light curve project. VIII. Six occultations of the exoplanet TrES-3

Source: ASTRONOMICAL JOURNAL, 136 (1): 267-271 JUL 2008

Abstract: We present photometry of the exoplanet host star TrES-3 spanning six occultations (secondary eclipses) of its giant planet. No flux decrements were detected, leading to 99%-confidence upper limits on the planet-to-star flux ratio of 2.4 x 10(-4), 5.0 x 10(-4), and 8.6 x 10(-4) in the i-, z-, and R-bands respectively. The corresponding upper limits on the planet's geometric albedo are 0.30, 0.62, and 1.07. The upper limit in the i-band rules out the presence of highly reflective clouds, and is only a factor of 2-3 above the predicted level of thermal radiation from the planet.

Author(s): Pont, F (Pont, F.); Knutson, H (Knutson, H.); Gilliland, RL (Gilliland, R. L.); Moutou, C (Moutou, C.); Charbonneau, D (Charbonneau, D.)

Title: Detection of atmospheric haze on an extrasolar planet: the 0.55-1.05 mu m transmission spectrum of HD 189733b with the Hubble Space Telescope

Source: MONTHLY NOTICES OF THE ROYAL ASTRONOMICAL SOCIETY, 385 (1): 109-118 MAR 21 2008

Abstract: The nearby transiting planet HD 189733b was observed during three transits with the Advanced Camera for Surveys of the Hubble Space Telescope in spectroscopic mode. The resulting time-series of 675 spectra covers the 550-1050 nm range, with a resolution element of similar to 8 nm, at extremely high accuracy (signal-to-noise ratio up to 10 000 in 50-nm intervals in each individual spectrum). Using these data, we disentangle the effects of limb darkening, measurement systematics and spots on the surface of the host star, to calculate the wavelength dependence of the effective transit radius to an accuracy of similar to 50 km. This constitutes the 'transmission spectrum' of the planetary atmosphere. It indicates at each wavelength at what height the planetary atmosphere becomes opaque to the grazing stellar light during the transit. In this wavelength range, strong features due to sodium, potassium and water are predicted by atmosphere models for a planet like HD 189733b, but they can be hidden by broad absorption from clouds or hazes higher up in the atmosphere.
We observed an almost featureless transmission spectrum between 550 and 1050 nm, with no indication of the expected sodium or potassium atomic absorption features. Comparison of our results with the transit radius observed in the near and mid-infrared (2-8 mu m), and the slope of the

spectrum, suggest the presence of a haze of submicrometre particles in the upper atmosphere of the planet.

Author(s): Palle, E (Palle, E.); Ford, EB (Ford, Eric B.); Seager, S (Seager, S.); Montanes-Rodriguez, P (Montanes-Rodriguez, P.); Vazquez, M (Vazquez, M.)

Title: Identifying the rotation rate and the presence of dynamic weather on extrasolar earth-like planets from photometric observations

Source: ASTROPHYSICAL JOURNAL, 676 (2): 1319-1329 APR 1 2008

Abstract: With the recent discoveries of hundreds of extrasolar planets, the search for planets like Earth and life in the universe is quickly gaining momentum. In the future, large space observatories could directly detect the light scattered from rocky planets, but they would not be able to spatially resolve a planet's surface. Using reflectance models and real cloud data from satellite observations, here we show that, despite Earth's dynamic weather patterns, the light scattered by the Earth to a hypothetical distant observer as a function of time contains sufficient information to accurately measure Earth's rotation period. This is because ocean currents and continents result in relatively stable averaged global cloud patterns. The accuracy of these measurements will vary with the viewing geometry and other observational constraints. If the rotation period can be measured with accuracy, data spanning several months could be coherently combined to obtain spectroscopic information about individual regions of the planetary surface. Moreover, deviations from a periodic signal can be used to infer the presence of relatively short-lived structures in its atmosphere (i. e., clouds). This could provide a useful technique for recognizing exoplanets that have active weather systems, changing on a timescale comparable to their rotation. Such variability is likely to be related to the atmospheric temperature and pressure being near a phase transition and could support the possibility of liquid water on the planet's surface.

Author(s): Tinetti, G (Tinetti, Giovanna); Vidal-Madjar, A (Vidal-Madjar, Alfred); Liang, MC (Liang, Mao-Chang); Beaulieu, JP (Beaulieu, Jean-Philippe); Yung, Y (Yung, Yuk); Carey, S (Carey, Sean); Barber, RJ (Barber, Robert J.); Tennyson, J (Tennyson, Jonathan); Ribas, I (Ribas,

Ignasi); Allard, N (Allard, Nicole); Ballester, GE (Ballester, Gilda E.); Sing, DK (Sing, David K.); Selsis, F (Selsis, Franck)

Title: Water vapour in the atmosphere of a transiting extrasolar planet

Source: NATURE, 448 (7150): 169-171 JUL 12 2007

Abstract: Water is predicted to be among the most abundant (if not the most abundant) molecular species after hydrogen in the atmospheres of close-in extrasolar giant planets ('hot Jupiters')(1,2). Several attempts have been made to detect water on such planets, but have either failed to find compelling evidence for it(3,4) or led to claims that should be taken with caution(5). Here we report an analysis of recent observations of the hot Jupiter HD 189733b (ref. 6) taken during the transit, when the planet passed in front of its parent star. We find that absorption by water vapour is the most likely cause of the wavelength-dependent variations in the effective radius of the planet at the infrared wavelengths 3.6 mu m, 5.8 mu m (both ref. 7) and 8 mu m (ref. 8). The larger effective radius observed at visible wavelengths(9) may arise from either stellar variability or the presence of clouds/hazes. We explain the report of a non-detection of water on HD 189733b (ref. 4) as being a consequence of the nearly isothermal vertical profile of the planet's atmosphere.

Author(s): Bailey, J (Bailey, Jeremy)

Title: Rainbows, polarization, and the search for habitable planets

Source: ASTROBIOLOGY, 7 (2): 320-332 APR 2007

Abstract: Current proposals for the characterization of extrasolar terrestrial planets rest primarily on the use of spectroscopic techniques. While spectroscopy is effective in detecting the gaseous components of a planet's atmosphere, it provides no way of detecting the presence of liquid water, the defining characteristic of a habitable planet. In this paper, I investigate the potential of an alternative technique for characterizing the atmosphere of a planet using polarization. By looking for a polarization peak at the "primary rainbow" scattering angle, it is possible to detect the presence of liquid droplets in a planet's atmosphere and constrain the nature of the liquid through its refractive index. Single scattering calculations are presented to show that a well-defined rainbow scattering peak is present over the full range of

likely cloud droplet sizes and clearly distinguishes the,presence of liquid droplets from solid particles such as ice or dust. Rainbow scattering has been used in the past to determine the nature of the cloud droplets in the Venus atmosphere and by the POLarization and Directionality of Earth Reflectances (POLDER) instrument to distinguish between liquid and ice clouds in the Earth atmosphere. While the presence of liquid water clouds does not guarantee the presence of water at the surface, this technique could complement spectroscopic techniques for characterizing the atmospheres of potential habitable planets. The disk-integrated rainbow peak for Earth is estimated to be at a degree of polarization of 12.7% or 15.5% for two different cloud cover scenarios. The observation of this rainbow peak is shown to be feasible with the proposed Terrestrial Planet Finder Coronograph mission in similar total integration times to those required for spectroscopic characterization.

Author(s): Kaltenegger, L (Kaltenegger, Lisa); Traub, WA (Traub, Wesley A.); Jucks, KW (Jucks, Kenneth W.)

Title: Spectral evolution of an Earth-like planet

Source: ASTROPHYSICAL JOURNAL, 658 (1): 598-616 Part 1 MAR 20 2007

Abstract: We have developed a characterization of the geological evolution of the Earth's atmosphere and surface in order to model the observable spectra of an Earth-like planet through its geological history. These calculations are designed to guide the interpretation of an observed spectrum of such a planet by future instruments that will characterize exoplanets. Our models focus on planetary environmental characteristics whose resultant spectral features can be used to imply habitability or the presence of life. These features are generated by H2O, CO2, CH4, O-2, O-3, N2O, and vegetation- like surface albedos. We chose six geological epochs to characterize. These epochs exhibit a wide range in abundance for these molecules, ranging from a CO2-rich early atmosphere, to a CO2/CH4-rich atmosphere around 2 billion years ago, to a present-day atmosphere. We analyzed the spectra to quantify the strength of each important spectral feature in both the visible and thermal infrared spectral regions, and the resolutions required to optimally detect the features for each epoch. We find a wide range of spectral resolutions required for observing the different features. For example, H2O and O-3 can be observed with relatively low resolution, while O-2 and N2O require higher resolution. We also find that the inclusion of clouds in our models significantly affects both the strengths of all spectral features and the resolutions required to observe all these.

Author(s): Fortney, JJ

Title: The effect of condensates on the characterization of transiting planet atmospheres with transmission spectroscopy

Source: MONTHLY NOTICES OF THE ROYAL ASTRONOMICAL SOCIETY, 364 (2): 649-653 DEC 1 2005

Abstract: Through a simple physical argument we show that the slant optical depth through the atmosphere of a 'hot Jupiter' planet is similar to 35-90 times greater than the normal optical depth. This not unexpected result has direct consequences for the method of transmission spectroscopy for characterizing the atmospheres of transiting giant planets. The atmospheres of these planets likely contain minor condensates and hazes, which at normal viewing geometry have negligible optical depth, but at slant viewing geometry have appreciable optical depth that can obscure absorption features of gaseous atmospheric species. We identify several possible condensates. We predict that this is a general masking mechanism for all planets, not just for HD 209458b, and will lead to weaker than expected or undetected absorption features. Constraints on an atmosphere from transmission spectroscopy are not the same as constraints on an atmosphere at normal viewing geometry.

Author(s): Sudarsky, D; Burrows, A; Hubeny, I; Li, AG

Title: Phase functions and light curves of wide-separation extrasolar giant planets

Source: ASTROPHYSICAL JOURNAL, 627 (1): 520-533 Part 1 JUL 1 2005

Abstract: We calculate self-consistent extrasolar giant planet (EGP) phase functions and light curves for orbital distances ranging from 0.2 to 15 AU. We explore the dependence on wavelength, cloud condensation, and Keplerian orbital elements. We find that the light curves of EGPs depend strongly on wavelength, the presence of clouds, and cloud particle sizes. Furthermore, the optical and infrared colors of most EGPs are

phase-dependent, tending to be reddest at crescent phases in V - R and R - I. Assuming circular orbits, we find that at optical wavelengths most EGPs are 3 - 4 times brighter near full phase than near greatest elongation for highly inclined (i. e., close to edge-on) orbits. Furthermore, we show that the planet/star flux ratios depend strongly on the Keplerian elements of the orbit, particularly inclination and eccentricity. Given a sufficiently eccentric orbit, an EGP's atmosphere may make periodic transitions from cloudy to cloud-free, an effect that may be reflected in the shape and magnitude of the planet's light curve. Such elliptical orbits also introduce an offset between the time of the planet's light-curve maximum and the time of full planetary phase, and for some sets of orbital parameters, this light-curve maximum can be a steeply increasing function of eccentricity. We investigate the detectability of EGPs by proposed space-based direct-imaging instruments.

Author(s): Guillot, T
Editor(s): Penny, A; Artymowicz, P; Lagrance, AM; Russell, S

Title: Atmospheric circulation of hot Jupiters

Source: PLANETARY SYSTEMS IN THE UNIVERSE OBSERVATION, FORMATION AND EVOLUTION, (202): 261-268 2004
Book series title: IAU SYMPOSIA

Abstract: About 40% of the extrasolar giant planets discovered so far have orbital distances smaller than 0.2 AU. These "hot Jupiters" are expected to be in synchronous rotation with their star. The ability to measure their radii prompts a careful reexamination of their structure. I show that their atmospheric structure is complex and that thermal balance cannot be achieved through radiation only but must involve heat advection by large-scale circulation. A circulation model inspired from Venus is proposed, involving a relatively strong zonal wind (with a period that can be as short as 1 day). It is shown that even this strong wind is incapable of efficiently redistributing heat from the day side to the night side. Temperature variations of 200K or more are to be expected, even at pressures as large as 10 bar. As a consequence, clouds should be absent on the day side, allowing more efficient absorption of the stellar light. The global chemical composition of the atmosphere should also be greatly affected by the presence of large temperature variations. Finally, stellar tides may also be important in their ability to deposit heat at levels untouched by stellar radiation, thereby slowing further the cooling of the

planets.

Author(s): Marley, MS; Ackerman, AS
Editor(s): Penny, A; Artymowicz, P; Lagrance, AM; Russell, S

Title: The role of clouds in brown dwarf and extrasolar giant planet atmospheres

Source: PLANETARY SYSTEMS IN THE UNIVERSE OBSERVATION, FORMATION AND EVOLUTION, (202): 269-276 2004
Book series title: IAU SYMPOSIA

Abstract: Clouds and hazes are important throughout our solar system and in the atmospheres of brown dwarfs and extrasolar giant planets. Among the brown dwarfs, clouds control the colors and spectra of the L-dwarfs; the disappearance of clouds helps herald the arrival of the T-dwarfs. The structure and composition of clouds will be among the first remote-sensing results from the direct detection of extrasolar giant planets.

Author(s): Tsuji, T

Title: Dust in the photospheric environment. III. A fundamental element in the characterization of ultracool dwarfs

Source: ASTROPHYSICAL JOURNAL, 621 (2): 1033-1048 Part 1 MAR 10 2005

Abstract: Recent photometry of L and T dwarfs revealed that the infrared colors show a large variation at a given effective temperature, and within the framework of our unified cloudy model (UCM), this result can be interpreted as due to a sporadic variation of the critical temperature (T-cr), which is essentially a measure of the thickness of the dust cloud. In our previous applications of the UCMs, we assumed that T-cr is constant at about 1800 K in all the L and T dwarfs, but in view of the new observing result, we now allow T-cr to vary between the surface temperature (T-0) and the condensation temperature (T-cond) at given T-eff and log g. Then, the two-color diagram and the color-magnitude diagram can be well explained by the effects of T-eff, log g, and T-cr, but not by the effects of T-eff and log g alone. This result implies that T-cr is one of the important parameters needed for characterization of dusty dwarfs. The

effects of T-eff and T-cr on individual spectra, however, are difficult to discriminate, since T-eff at fixed T-cr on one hand and T-cr at fixed T-eff on the other essentially have the same effect on the spectra. We show that the degeneracy of T-eff and T-cr can be removed to some extent by the analysis of the spectral energy distribution on an absolute scale. The reanalysis of a selected sample of spectra revealed that the L-T spectral sequence may not necessarily be a sequence of T-eff, but may reflect a change in the thickness of the dust cloud, represented by T-cr in our UCM. Although this unexpected result is based on a limited sample, an odd "brightening" of the absolute J magnitudes plotted against the L-T spectral types may also be an indication that the L-T spectral sequence is not necessarily a temperature sequence. This is because M-bol based on the same photometry data also shows a similar brightening. Thus, the "J-brightening" might not be due to any atmospheric effect and hence should not be a problem to be solved by model atmospheres, including the UCMs. Thus, almost all the available observed data are reasonably well interpreted by the UCMs, whose full capability emerges once T-cr is introduced as the fifth parameter in addition to the usual four parameters (i.e., chemical composition, T-eff, log g, and microturbulent velocity) needed to characterize stellar spectra in general.

Author(s): Dyudina, UA; Sackett, PD; Bayliss, DDR; Seager, S; Throop, HB; Dones, L

Title: Phase light curves for extrasolar Jupiters and Saturns

Source: ASTROPHYSICAL JOURNAL, 618 (2): 973-986 Part 1 JAN 10 2005

Abstract: We predict how a remote observer would see the brightness variations of giant planets similar to those in our solar system as they orbit their central stars. Our models are the first to use measured anisotropic scattering properties of solar system giants and the first to consider the effects of eccentric orbits. We model the geometry of Jupiter, Saturn, and Saturn's rings for varying orbital and viewing parameters, using scattering properties for the (forward scattering) planets and (backward scattering) rings as measured by the Pioneer and Voyager spacecraft at 0.6-0.7 mum. Images of the planet with and without rings are simulated and used to calculate the disk-averaged luminosity varying along the orbit; that is, a light curve is generated. We find that the different scattering properties of Jupiter and Saturn (without rings) make a substantial difference in the shape of their light curves.

Saturn-sized rings increase the apparent luminosity of a planet by a factor of 2-3 for a wide range of geometries, an effect that could be confused with a larger planet size. Rings produce asymmetric light curves that are distinct from the light curve that the planet would have without rings, which could resolve this confusion. If radial velocity data are available for the planet, the effect of the ring on the light curve can be distinguished from effects due to orbital eccentricity. Nonringed planets on eccentric orbits produce light curves with maxima shifted relative to the position of the maximum phase of the planet. Given radial velocity data, the amount of the shift restricts the planet's unknown orbital inclination and therefore its mass. A combination of radial velocity data and a light curve for a nonringed planet on an eccentric orbit can also be used to constrain the surface scattering properties of the planet and thus describe the clouds covering the planet. We summarize our results for the detectability of exoplanets in reflected light in a chart of light-curve amplitudes of nonringed planets for different eccentricities, inclinations, and azimuthal viewing angles of the observer.

Author(s): Helling, C; Klein, R; Woitke, P; Nowak, U; Sedlmayr, E

Title: Dust in brown dwarfs - IV. Dust formation and driven turbulence on mesoscopic scales

Source: ASTRONOMY & ASTROPHYSICS, 423 (2): 657-675 AUG 2004

Abstract: Dust formation in brown dwarf atmospheres is studied by utilising a model for driven turbulence in the mesoscopic scale regime. We apply a pseudo-spectral method where waves are created and superimposed within a limited wavenumber interval. The turbulent kinetic energy distribution follows the Kolmogoroff spectrum which is assumed to be the most likely value. Such superimposed, stochastic waves may occur in a convectively active environment. They cause nucleation fronts and nucleation events and thereby initiate the dust formation process which continues until all condensible material is consumed. Small disturbances are found to have a large impact on the dust forming system. An initially dust-hostile region, which may, originally be optically thin, becomes optically thick in a patchy way showing considerable variations in the dust properties during the formation process. The dust appears in lanes and curls as a result of the interaction with waves, i.e. turbulence, which form larger and larger structures with time. Aiming at a physical understanding of the variability of brown dwarfs, related to structure

formation in substellar atmospheres, we work out first necessary criteria
for small-scale closure models to be applied in macroscopic simulations of
dust-forming astrophysical systems.

Author(s): Burrows, A; Sudarsky, D; Hubeny, I

Title: Spectra and diagnostics for the direct detection of wide-separation
extrasolar giant planets

Source: ASTROPHYSICAL JOURNAL, 609 (1): 407-416 Part 1 JUL 1 2004

Abstract: We calculate as a function of orbital distance, mass, and age
the theoretical spectra and orbit-averaged planet/star flux ratios for
representative wide-separation extrasolar giant planets (EGPs) in the
optical, near-infrared, and mid-infrared. Stellar irradiation of the
planet's atmosphere and the effects of water and ammonia clouds are
incorporated and handled in a consistent fashion. We include predictions
for 12 specific known EGPs. In the process, we derive physical diagnostics
that can inform the direct EGP detection and remote sensing programs now
being planned or proposed. Furthermore, we calculate the effects of
irradiation on the spectra of a representative companion brown dwarf as a
function of orbital distance.

Author(s): Knapp, GR; Leggett, SK; Fan, X; Marley, MS; Geballe, TR;
Golimowski, DA; Finkbeiner, D; Gunn, JE; Hennawi, J; Ivezic, Z; Lupton,
RH; Schlegel, DJ; Strauss, MA; Tsvetanov, ZI; Chiu, K; Hoversten, EA;
Glazebrook, K; Zheng, W; Hendrickson, M; Williams, CC; Uomoto, A; Vrba,
FJ; Henden, AA; Luginbuhl, CB; Guetter, HH; Munn, JA; Canzian, B;
Schneider, DP; Brinkmann, J

Title: Near-infrared photometry and spectroscopy of L and T dwarfs: The
effects of temperature, clouds, and gravity

Source: ASTRONOMICAL JOURNAL, 127 (6): 3553-3578 JUN 2004

Abstract: We present new JHK photometry on the MKO-NIR system and JHK
spectroscopy for a large sample of L and T dwarfs. Photometry has been
obtained for 71 dwarfs, and spectroscopy for 56. The sample comprises
newly identified very red objects from the Sloan Digital Sky Survey (SDSS)

and known dwarfs from the SDSS and the Two Micron All Sky Survey (2MASS). Spectral classification has been carried out using four previously defined indices from Geballe et al. that measure the strengths of the near infrared water and methane bands. We identify nine new L8 - 9.5 dwarfs and 14 new T dwarfs from SDSS, including the latest yet found by SDSS, the T7 dwarf SDSS J175805.46+463311.9. We classify 2MASS J04151954 - 0935066 as T9, the latest and coolest dwarf found to date. We combine the new results with our previously published data to produce a sample of 59 L dwarfs and 42 T dwarfs with imaging data on a single photometric system and with uniform spectroscopic classification. We compare the near-infrared colors and absolute magnitudes of brown dwarfs near the L - T transition with predictions made by models of the distribution and evolution of photospheric condensates. There is some scatter in the Geballe et al. spectral indices for L dwarfs, suggesting that these indices are probing different levels of the atmosphere and are affected by the location of the condensate cloud layer. The near-infrared colors of the L dwarfs also show scatter within a given spectral type, which is likely due to variations in the altitudes, spatial distributions, and thicknesses of the clouds. We have identified a small group of late-L dwarfs that are relatively blue for their spectral type and that have enhanced FeH, H2O, and K I absorption, possibly due to an unusually small amount of condensates. The scatter seen in the H - K color for late-T dwarfs can be reproduced by models with a range in surface gravity. The variation is probably due to the effect on the K-band flux of pressure-induced H-2 opacity. The correlation of H - K color with gravity is supported by the observed strengths of the J-band K I doublet. Gravity is closely related to mass for field T dwarfs with ages greater than 10(8) yr and the gravities implied by the H - K colors indicate that the T dwarfs in our sample have masses in the range 15 - 75M(Jupiter). One of the SDSS dwarfs, SDSS J111010.01+ 011613.1, is possibly a very low mass object, with log g similar to 4.2 - 4.5 and mass similar to 10 - 15M(Jupiter).

Author(s): Sanchez-Lavega, A; Perez-Hoyos, S; Hueso, R

Title: Clouds in planetary atmospheres: A useful application of the Clausius-Clapeyron equation

Source: AMERICAN JOURNAL OF PHYSICS, 72 (6): 767-774 JUN 2004

Abstract: The Clausius-Clapeyron equation is used to do a comparative study of the properties of the clouds that form in planetary atmospheres.

Simple static atmospheric models for various planets, the satellite Titan, and the extrasolar planet HD209458b are used together with the saturation vapor pressure curves of the different kinds of molecules to determine the pressure, density, and scale height of the clouds in each body. This application of the Clausius-Clapeyron equation extends our knowledge of terrestrial water clouds to different exotic clouds present in other planets.

Author(s): Green, D; Matthews, J; Seager, S; Kuschnig, R

Title: Scattered light from close-in extrasolar planets: Prospects of detection with the MOST satellite

Source: ASTROPHYSICAL JOURNAL, 597 (1): 590-601 Part 1 NOV 1 2003

Abstract: The ultraprecise photometric space satellite MOST (Microvariability and Oscillations of STars) will provide the first opportunity to measure the albedos and scattered light curves from known short-period extrasolar planets. Because of the changing phases of an extrasolar planet as it orbits its parent star, the combined light of the planet-star system will vary on the order of tens of micromagnitudes. The amplitude and shape of the resulting light curve is sensitive to the planet's radius and orbital inclination, as well as the composition and size distribution of the scattering particles in the planet's atmosphere. To predict the capabilities of MOST and other planned space missions, we have constructed a series of models of such light curves, improving upon earlier work by incorporating more realistic details such as limb darkening of the star, intrinsic granulation noise in the star itself, tidal distortion and back-heating, higher angular resolution of the light scattering from the planet, and exploration of the significance of the angular size of the star as seen from the planet. We use photometric performance simulations of the MOST satellite, with the light-curve models as inputs, for one of the mission's primary targets, tau Bootis. These simulations demonstrate that, even adopting a very conservative signal detection limit of 4.2 mumag in amplitude (not power), we will be able to either detect the tau Bootis planet light curve or put severe constraints on possible extrasolar planet atmospheric models.

Author(s): Burrows, A; Sudarsky, D; Lunine, JI

Title: Beyond the T dwarfs: Theoretical spectra, colors, and detectability
of the coolest brown dwarfs

Source: ASTROPHYSICAL JOURNAL, 596 (1): 587-596 Part 1 OCT 10 2003

Abstract: We explore the spectral and atmospheric properties of brown dwarfs cooler than the latest known T dwarfs. Our focus is on the yet-to-be-discovered free-floating brown dwarfs in the T-eff range from similar to800 to similar to130 K and with masses from 25 to 1 M-J. This study is in anticipation of the new characterization capabilities enabled by the launch of the Space Infrared Telescope Facility (SIRTF) and the eventual launch of the James Webb Space Telescope (JWST). In addition, it is in support of the continuing ground-based searches for the coolest substellar objects. We provide spectra from similar to0.4 to 30 mum, highlight the evolution and mass dependence of the dominant H2O, CH4, and NH3 molecular bands, consider the formation and effects of water ice clouds, and compare our theoretical flux densities with the putative sensitivities of the instruments on board SIRTF and JWST. The latter can be used to determine the detection ranges from space of cool brown dwarfs. In the process, we determine the reversal point of the blueward trend in the near-infrared colors with decreasing T-eff (a prominent feature of the hotter T dwarf family), the T-eff's at which water and ammonia clouds appear, the strengths of gas-phase ammonia and methane bands, the masses and ages of the objects for which the neutral alkali metal lines (signatures of L and T dwarfs) are muted, and the increasing role as T-eff decreases of the mid-infrared fluxes longward of 4 mum. These changes suggest physical reasons to expect the emergence of at least one new stellar class beyond the T dwarfs. Furthermore, studies in the mid-infrared could assume a new, perhaps transformational, importance in the understanding of the coolest brown dwarfs. Our spectral models populate, with cooler brown dwarfs having progressively more planet-like features, the theoretical gap between the known T dwarfs and the known giant planets. Such objects likely inhabit the Galaxy, but their numbers are as yet unknown.

Author(s): Cooper, CS; Sudarsky, D; Milsom, JA; Lunine, JI; Burrows, A

Title: Modeling the formation of clouds in brown dwarf atmospheres

Source: ASTROPHYSICAL JOURNAL, 586 (2): 1320-1337 Part 1 APR 1 2003

Abstract: Because the opacity of clouds in substellar mass object (SMO) atmospheres depends on the composition and distribution of particle sizes within the cloud, a credible cloud model is essential for accurately modeling SMO spectra and colors. We present a one-dimensional model of cloud particle formation and subsequent growth based on a consideration of basic cloud microphysics. We apply this microphysical cloud model to a set of synthetic brown dwarf atmospheres spanning a broad range of surface gravities and effective temperatures (g(surf) = 1.78 x 10(3)-3 x 10(5) cm s(-2) and T-eff = 600-1600 K) to obtain plausible particle sizes for several abundant species (Fe, Mg2SiO4, and Ca2Al2SiO7). At the base of the clouds, where the particles are largest, the particle sizes thus computed range from similar to5 to over 300 mum in radius over the full range of atmospheric conditions considered. We show that average particle sizes decrease significantly with increasing brown dwarf surface gravity. We also find that brown dwarfs with higher effective temperatures have characteristically larger cloud particles than those with lower effective temperatures. We therefore conclude that it is unrealistic when modeling SMO spectra to apply a single particle size distribution to the entire class of objects.

Author(s): Sengupta, S

Title: Explaining the observed polarization from brown dwarfs by single dust scattering

Source: ASTROPHYSICAL JOURNAL, 585 (2): L155-L158 Part 2 MAR 10 2003

Abstract: Recent observation of linear optical polarization from brown dwarfs confirms the dust hypothesis in the atmospheres of brown dwarfs with effective temperature higher than 1400 K. The observed polarization could arise because of dust scattering in the rotation induced oblate photosphere or because of the scattering by nonspherical grains in the spherical atmosphere or by the anisotropic distribution of dust clouds. Assuming single scattering by spherical grains in a slightly oblate photosphere consistent with the projected rotational velocity, the observed optical linear polarization is modeled by taking grains of different sizes located at different pressure height and of different number density. Minimum possible oblateness of the object due to rotation is considered in order to constrain the grain size. It is shown that the observed polarization from the L dwarfs 2MASSW J0036+1821 and DENIS-P

J0255-4700 can be well explained by several sets of dust parameters and with the minimum possible oblateness. Models for the observed polarization constrain the maximum size of grains. It is emphasized that future observation of polarization at the blue region will further constrain the grain size.

Author(s): Burrows, A; Burgasser, AJ; Kirkpatrick, JD; Liebert, J; Milsom, JA; Sudarsky, D; Hubeny, I

Title: Theoretical spectral models of T dwarfs at short wavelengths and their comparison with data

Source: ASTROPHYSICAL JOURNAL, 573 (1): 394-417 Part 1 JUL 1 2002

Abstract: We have generated new, self-consistent spectral and atmosphere models for the effective temperature range 600 1300 K thought to encompass the known T dwarfs. For the first time, theoretical models are compared with a family of measured T dwarf spectra at wavelengths shortward of similar to1.0 mum. By defining spectral indices and standard colors in the optical and very near-infrared, we explore the theoretical systematics with T-eff, gravity, and metallicity. We conclude that the short-wavelength range is rich in diagnostics that complement those in the near-infrared now used for spectral subtyping. We also conclude that the wings of the Na D and K I (7700 Angstrom) resonance lines and aggressive rainout of heavy metals (with the resulting enhancement of the sodium and potassium abundances at altitude) are required to fit the new data shortward of 1.0 mum. Furthermore, we find that the water bands weaken with increasing gravity, that modest decreases in metallicity enhance the effect in the optical of the sodium and potassium lines, and that at low values of T e, in a reversal of the normal pattern, optical spectra become bluer with further decreases in T-eff. Moreover, we conclude that T dwarf subtype is not a function of T-eff alone but that it is a nontrivial function of gravity and metallicity as well. As do Marley and coworkers in their 2002 work, we see evidence in early T dwarf atmospheres of a residual effect of clouds. With cloudless models, we obtain spectral fits to the two late T dwarfs with known parallaxes, but a residual effect of clouds on the emergent spectra of even late T dwarfs cannot yet be discounted. However, our focus is not on detailed fits to individual objects but on the interpretation of the overall spectral and color trends of the entire class of T dwarfs, as seen at shorter wavelengths.

Author(s): Charbonneau, D; Brown, TM; Noyes, RW; Gilliland, RL

Title: Detection of an extrasolar planet atmosphere

Source: ASTROPHYSICAL JOURNAL, 568 (1): 377-384 Part 1 MAR 20 2002

Abstract: We report high-precision spectrophotometric observations of four planetary transits of HD 209458, in the region of the sodium resonance doublet at 589.3 nm. We find that the photometric dimming during transit in a bandpass centered on the sodium feature is deeper by (2.32 +/- 0.57) x 10(-4) relative to simultaneous observations of the transit in adjacent bands. We interpret this additional dimming as absorption from sodium in the planetary atmosphere, as recently predicted from several theoretical modeling efforts. Our model for a cloudless planetary atmosphere with a solar abundance of sodium in atomic form predicts more sodium absorption than we observe. There are several possibilities that may account for this reduced amplitude, including reaction of atomic sodium into molecular gases and/or condensates, photoionization of sodium by the stellar flux, a low primordial abundance of sodium, and the presence of clouds high in the atmosphere.

Author(s): Burrows, A; Hubbard, WB; Lunine, JI; Liebert, J

Title: The theory of brown dwarfs and extrasolar giant planets

Source: REVIEWS OF MODERN PHYSICS, 73 (3): 719-765 JUL 2001

Abstract: Straddling the traditional realms of the planets and the stars, objects below the edge of the main sequence have such unique properties, and are being discovered in such quantities, that one can rightly claim that a new field at the interface of planetary science and astronomy is being born. This article extends the previous review of Burrows and Liebert (1993) and describes the essential elements of the theory of brown dwarfs and giant planets. It discusses their evolution, atmospheric composition, and spectra, including the new spectroscopic classes L and T. Particular topics which are important for an understanding of the spectral properties include the effects of condensates, clouds, molecular abundances, and atomic opacities. Moreover, it discusses the distinctive features of these extrasolar giant planets that are irradiated by a

central primary, in particular, their reflection spectra, albedos, and transits. Overall, the theory explains the basic systematics of substellar-mass objects over three orders of magnitude in mass and age, and a factor of 30 in temperature.

Author(s): Brown, TM

Title: Transmission spectra as diagnostics of extrasolar giant planet atmospheres

Source: ASTROPHYSICAL JOURNAL, 553 (2): 1006-1026 Part 1 JUN 8 2001

Abstract: Atmospheres of transiting extrasolar giant planets (EGPs) such as HD 209458b must impose features on the spectra of their parent stars during transits; these features contain information about the physical conditions and chemical composition of the atmospheres. The most convenient observational index showing these features is the "spectrum ratio" R(lambda), deDned as the wavelength-dependent ratio of spectra taken in and out of transit. The principal source of structure in R is the variation with wavelength of the height at which the EGP atmosphere first becomes opaque to tangential rays-one may think of the planet as having different radii, and hence different transit depths, at each wavelength. The characteristic depth of absorption lines in R scales with the atmospheric scale height and with the logarithm of the opacity ratio between continuum and strong lines. For close-in EGPs, line depths of 10(-3) relative to the stellar continuum can occur. The atmospheres of EGPs probably consist mostly of molecular species, including H-2, CO, H2O, and CH4, while the illuminating flux is characteristic of a Sun-like star. Thus, the most useful diagnostics are likely to be the near-infrared bands of these molecules, and the visible/near-IR resonance lines of the alkali metals. I describe a model that estimates R(lambda) for EGPs with prescribed radius, mass, temperature structure, chemical composition, and cloud properties. This model assumes hydrostatic and chemical equilibrium in an atmosphere with chemistry involving only H, C, N, and O. Other elements (He, Na, K, Si) are included as nonreacting minor constituents. Opacity sources include Rayleigh scattering, the strongest lines of Na and K, collision-induced absorption by scattering by cloud particles, and molecular lines of CO, H2O, and CH4. The model simulates Doppler shifts from height-dependent winds and from planetary rotation, and deals in a schematic way with photoionization of Na and K by the stellar UV flux. Using this model, I investigated the diagnostic potential of various spectral features for planets similar to HD 209458b. Clouds are the most important determinants of the depth of features in R; they decrease the strength of all features as they reach higher in the atmosphere. The relative strengths of molecular lines provide diagnostics for the heavy-element abundance, temperature, and the vertical temperature structure, although diagnostics for different physical properties tend to be somewhat degenerate. Planetary rotation with likely periods leaves a clear signature on the line profiles, as do winds with speeds comparable to that of rotation. Successful use of these diagnostics will require spectral observations with signal-to-noise ratio (S/N) of 10(3) or better and resolving power R = lambda/delta lambda ranging from 10(3) to 10(6), depending on the application. Because of these stringent demands, it will be important to evolve analysis methods that combine information from many lines into a few definitive diagnostic indices.

Author(s): Sudarsky, D; Burrows, A; Pinto, P

Title: Albedo and reflection spectra of extrasolar giant planets

Source: ASTROPHYSICAL JOURNAL, 538 (2): 885-903 Part 1 AUG 1 2000

Abstract: We generate theoretical albedo and reflection spectra for a full range of extrasolar giant planet (EGP) models, from Jovian to 51 Pegasi class objects. Our albedo modeling utilizes the latest atomic and molecular cross sections, Mie theory treatment of scattering and absorption by condensates, a variety of particle size distributions, and an extension of the Feautrier technique, which allows for a general treatment of the scattering phase function. We find that, because of qualitative similarities in the compositions and spectra of objects within each of five broad effective temperature ranges, it is natural to establish five representative EGP albedo classes. At low effective temperatures (T-eff less than or similar to 150 K) is a class of "Jovian" objects (class I) with tropospheric ammonia clouds. Somewhat warmer class II, or "water cloud," EGPs are primarily affected by condensed H2O. Gaseous methane absorption features are prevalent in both classes. In the absence of nonequilibrium condensates in the upper atmosphere, and with sufficient H2O condensation, class II objects are expected to have the highest visible albedos of any class. When the upper atmosphere of an EGP is too hot for H2O to condense, radiation generally penetrates more deeply. In these objects, designated class III or "clear" because of a lack of condensation in the upper atmosphere, absorption lines of the

alkali metals, sodium and potassium, lower the albedo significantly throughout the visible. Furthermore, the near-infrared albedo is negligible, primarily because of strong CH4 and H2O molecular absorption and collision-induced absorption (CIA) by H-2 molecules. In those EGPs with exceedingly small orbital distance ("roasters") and 900 K less than or similar to T-eff less than or similar to 1500 K (class IV), a tropospheric silicate layer is expected to exist. In all but the hottest (T-eff greater than or similar to 1500 K) or lowest gravity roasters, the effect of this silicate layer is likely to be insignificant because of the very strong absorption by sodium and potassium atoms above the layer. The resonance lines of sodium and potassium are expected to be salient features in the reflection spectra of these EGPs. In the absence of nonequilibrium condensates, we find, in contrast to previous studies, that these class IV roasters likely have the lowest visible and Bond albedos of any class, rivaling the lowest albedos of our solar system. For the small fraction of roasters with T-eff greater than or similar to 1500 K and/or low surface gravity (less than or similar to 10(3) cm s(-2); class V), the silicate layer is located very high in the atmosphere, reflecting much of the incident radiation before it can reach the absorbing alkali metals and molecular species. Hence, the class V roasters have much higher albedos than those of class IV. In addition, for class V objects, UV irradiation may result in significant alkali metal ionization, thereby further weakening the alkali metal absorption lines. We derive Bond albedos (A(B)) and T-eff estimates for the full set of known EGPs. A broad range in both values is found, with T-eff ranging from similar to 150 to nearly 1600 K, and A(B) from -0.02 to 0.8. We find that variations in particle size distributions and condensation fraction can have large quantitative, or even qualitative, effects on albedo spectra.
In general, less condensation, larger particle sizes, and wider size distributions result in lower albedos. We explore the effects of nonequilibrium condensed products of photolysis above or within principal cloud decks. As in Jupiter, such species can lower the UV/blue albedo substantially, even if present in relatively small mixing ratios.

Author(s): Stephens, DC; Marley, M; Gelino, CR; Lunine, JI

Title: The effect of clouds on the visible spectra of extrasolar giant planets

Source: EARTH MOON AND PLANETS, 81 (1): 105-106 1998

Author(s): Gelino, CR; Marley, M; Stephens, D; Lunine, J; Freedman, R

Title: Model bond albedos of extrasolar giant planets

Source: PHYSICS AND CHEMISTRY OF THE EARTH PART C-SOLAR-TERRESTIAL AND PLANETARY SCIENCE, 24 (5): 573-578 1999

Abstract: The atmospheres of extrasolar giant planets are modeled with various effective temperatures and gravities, with and without clouds. Bond albedos are computed by calculating the ratio of the flux reflected by a planet (integrated over wavelength) to the total stellar flux incident on the planet. This quantity is useful for estimating the effective temperature and evolution of a planet. We find it is sensitive to the stellar type of the primary. For a 5 M-Jup planet the Bond albedo varies from 0.4 to 0.3 to 0.06 as the primary star varies from A5V to G2V to M2V in spectral type. It is relatively insensitive to the effective temperature and gravity for cloud-free planets. Water clouds increase the reflectivity of the planet in the red, which increases the Bond albedo. The Bond albedo increases by an order of magnitude for a 13 M-Jup planet with an M2V primary when eater clouds are present. Silicate clouds, on the other hand, can either increase or decrease the Bond albedo, depending on whether there are many small grains (the former) or few large grains (the latter). (C) 1999 Elsevier Science Ltd. All rights reserved.

Author(s): Burrows, A; Sharp, CM

Title: Chemical equilibrium abundances in brown dwarf and extrasolar giant planet atmospheres

Source: ASTROPHYSICAL JOURNAL, 512 (2): 843-863 Part 1 FEB 20 1999

Abstract: We explore detailed chemical equilibrium abundance profiles for a variety of brown dwarf and extra-solar giant planet atmosphere models, focusing in particular on Gl 229B, and derive the systematics of the changes in the dominant reservoirs of the major elements with altitude and temperature. We assume an Anders & Grevesse solar composition of 27 chemical elements and track 330 gas-phase species, including the monatomic forms of the elements, as well as about 120 condensates. In our fiducial, limiting reference model, we do not assume that condensation sequesters

elements at depth and present true chemical equilibrium calculations for the solar element mix. However, there is evidence in the atmosphere of Gliese 229B that it is depleted in heavy elements. To explore depletion and rainout, which are fundamentally nonequilibrium processes, we perform a series of rainout calculations in which refractory elements are withdrawn from the equilibrium in stoichiometric ratios via an ad hoc algorithm. Then we compare the true equilibrium results with the rainout results, with an eye to understanding the near-infrared spectrum of Gliese 229B, as well as the new "L dwarfs" with T-eff's above similar to 1500 K. We address the issue of the formation and composition of clouds in the cool atmospheres of substellar objects. We conclude that the opacity of clouds of low-temperature (less than or equal to 900 K), small-radius condensables (specific chlorides and sulfides, not silicates), may in part be responsible for the steep spectrum of G1 229B observed in the near-IR below 1 mu m We assemble a temperature sequence of chemical transitions in substellar atmospheres that may be used to anchor and define a sequence of spectral types for substellar objects with T-eff's from similar to 2200 to similar to 100 K.

Author(s): Marley, MS; Gelino, C; Stephens, D; Lunine, JI; Freedman, R

Title: Reflected spectra and albedos of extrasolar giant planets. I. Clear and cloudy atmospheres

Source: ASTROPHYSICAL JOURNAL, 513 (2): 879-893 Part 1 MAR 10 1999

Abstract: The reflected spectra of extrasolar giant planets are primarily influenced by Rayleigh scattering, molecular absorption, and atmospheric condensates. We present model geometric albedo and phase-integral spectra and Bond albedos for planets and brown dwarfs with masses between 0.8 and 70 Jupiter masses. Rayleigh scattering predominates in the blue while molecular absorption removes most red and infrared photons. Thus cloud-free atmospheres, found on giant planets with effective temperatures exceeding about 400 K, are quite dark in reflected light beyond 0.6 mu m. In cooler atmospheres, first water clouds and then other condensates provide a bright reflecting layer. Only planets with cloudy atmospheres will be detectable in reflected light beyond 1 mu m. Thermal emission dominates the near-infrared for warm objects with clear atmospheres. However the presence of other condensates, not considered here, may brighten some planets in reflected near-infrared light and darken them in the blue and UV. Bond albedos, the ratio of the total reflected to incident power, are sensitive to the spectral type of the primary. Most incident photons from early-type stars will be Rayleigh scattered, while most incident photons from late-type stars will be absorbed. The Bond albedo of a given planet thus may range from 0.4 to 0.05, depending on the primary type. Condensation of a water cloud may increase the Bond albedo of a planet by up to a factor of 2. The spectra of cloudy planets are strongly influenced by poorly constrained cloud microphysical properties, particularly particle size and supersaturation. Both Bond and geometric albedos are comparatively less sensitive to variations in planet mass and effective temperature.