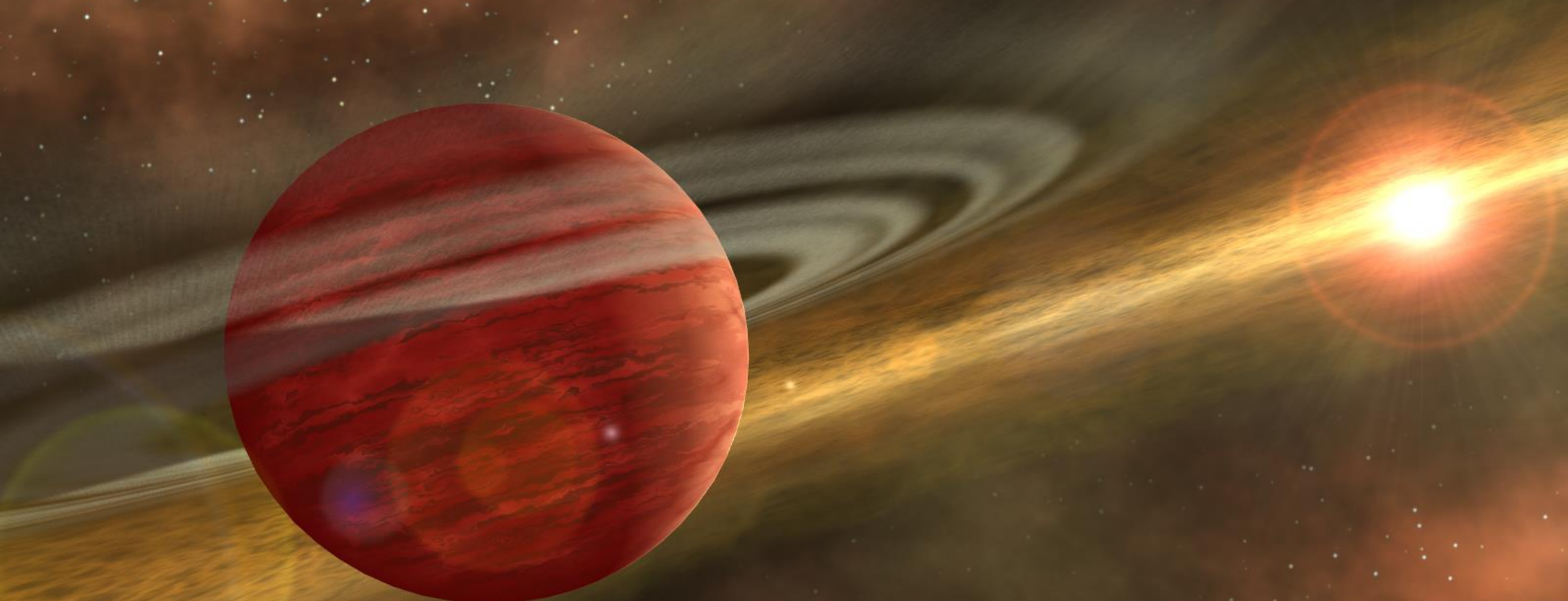
Atmospheric Chemistry on Substellar Objects



Channon Visscher
Lunar and Planetary Institute, USRA
UHCL Spring Seminar Series 2010

Image Credit: NASA/JPL-Caltech/R. Hurt

Outline

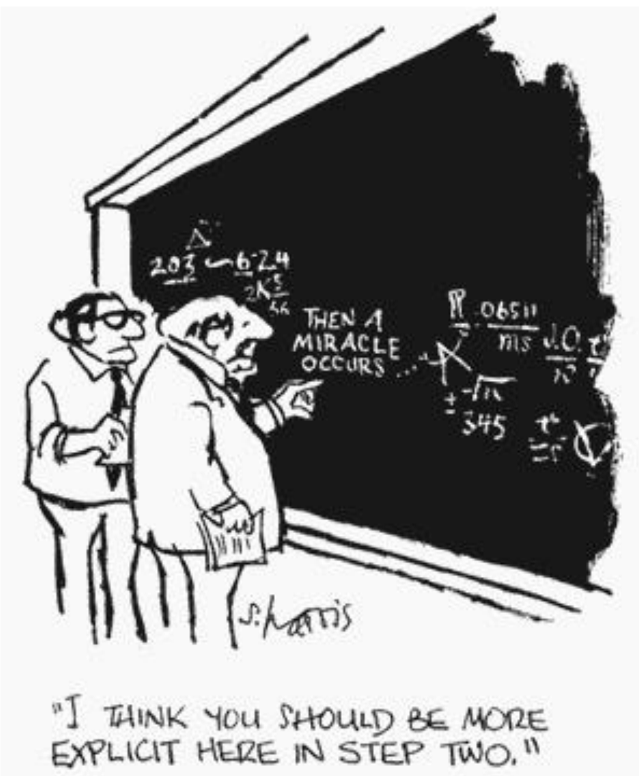
- introduction to substellar objects; recent discoveries
  - *what can exoplanets tell us about the formation and evolution of planetary systems?*

- clouds and chemistry in substellar atmospheres
  - role of thermochemistry and disequilibrium processes
    - Jupiter's bulk water inventory
    - chemical regimes on brown dwarfs and exoplanets

- *understanding the underlying physics and chemistry in substellar atmospheres is essential for guiding, interpreting, and explaining astronomical observations of these objects*

Methods of inquiry

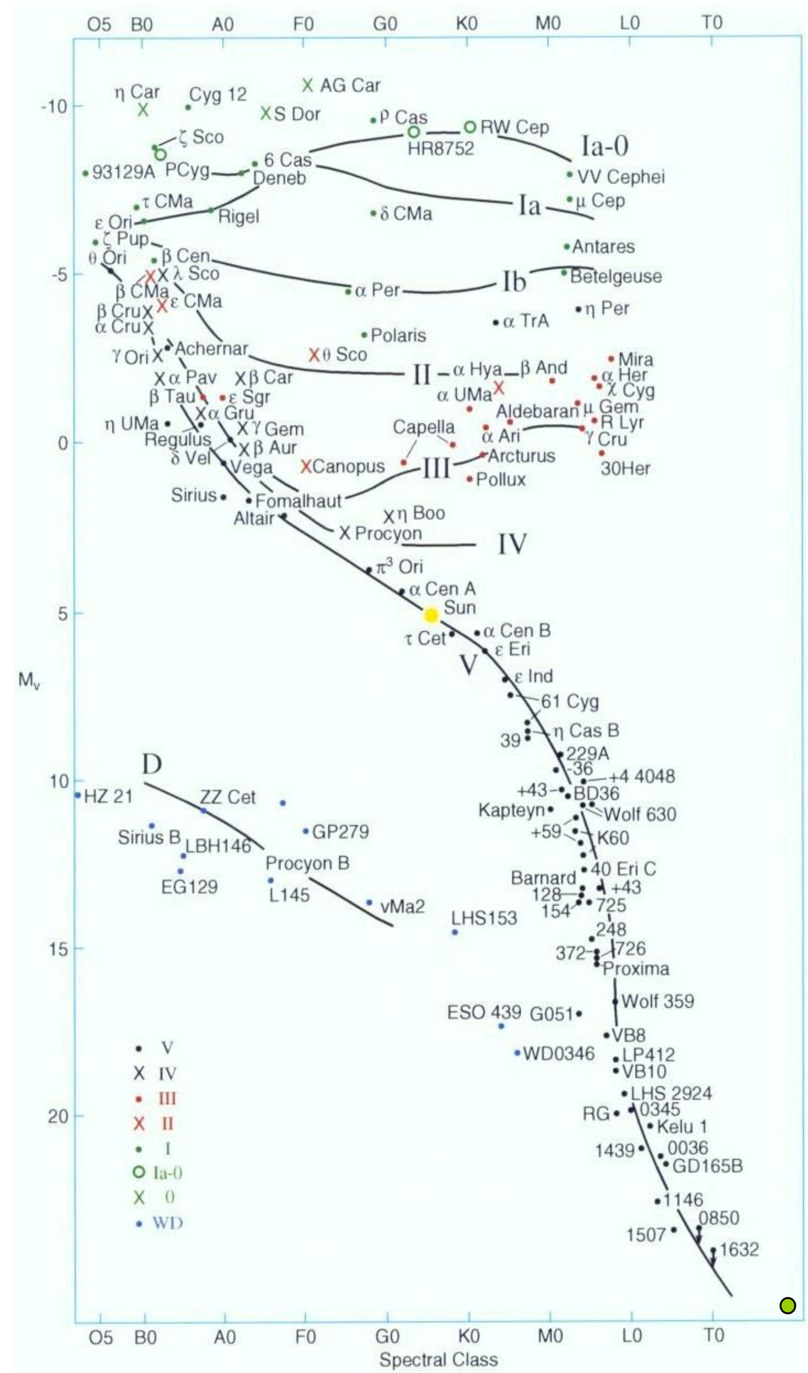
- telescopic observations (*Hubble, Spitzer*, *Kepler*, etc)
- spacecraft exploration (*Voyager, Galileo, Cassini*, etc)
- assume same physical principles apply throughout universe
  - allows the use of *models* to interpret observations



A simple model; Ike vs. the Great Red Spot

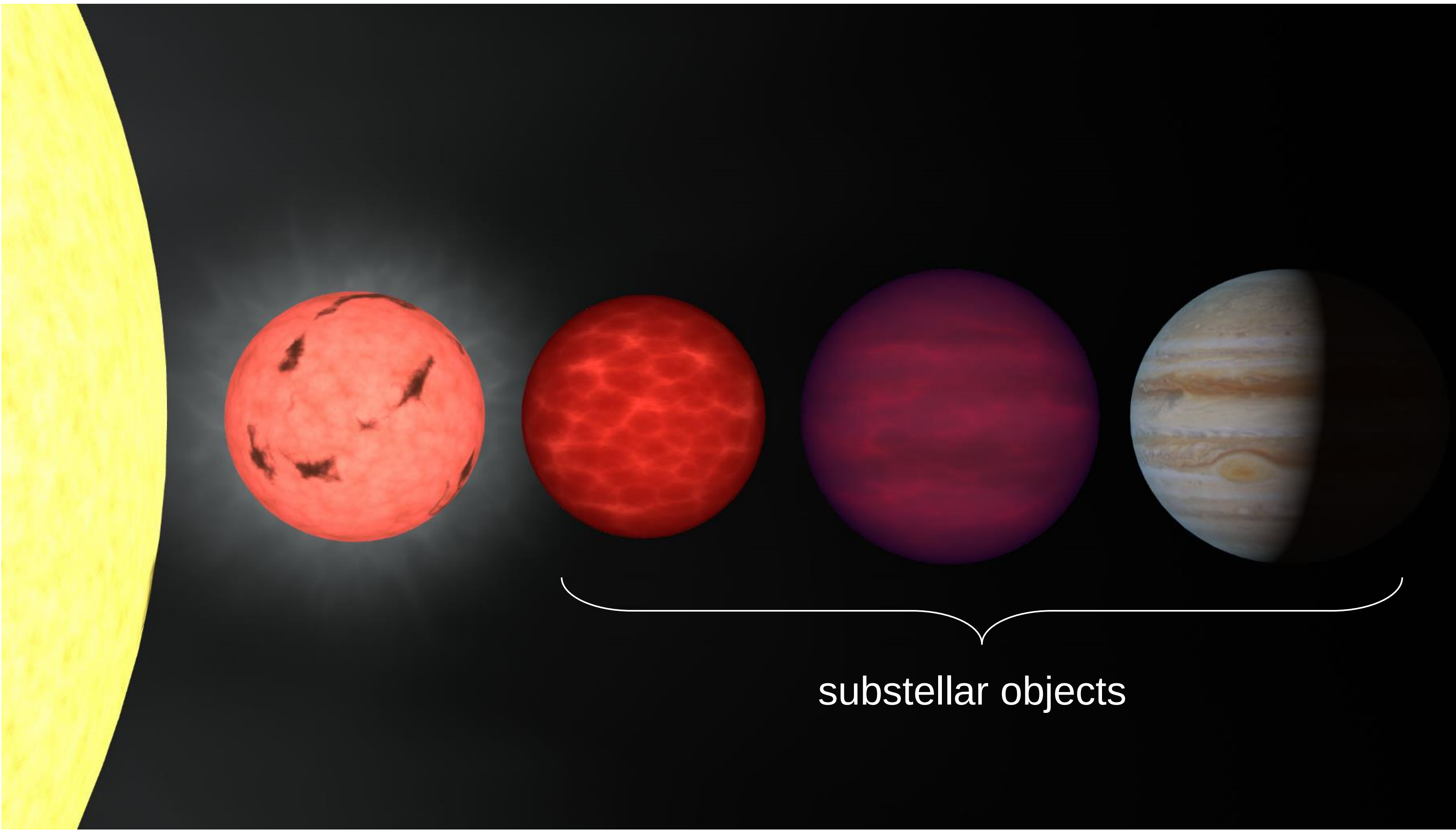
Field of study

- **stars**:
    - sustained H fusion
    - spectral classes OBAFGKM
    - > 75 M_{Jup} (0.07 M_{Sun})
- **substellar objects:**
    - *brown dwarfs* (~750)
        - temporary D fusion
        - spectral classes L and T
        - 13 to 75 M_{Jup}
    - *planets* (~450)
        - no fusion
        - < 13 M_{Jup}



Field of study

- Sun (5800 K), M (3200-2300 K), L (2500-1400 K), T (1400-700 K), Jupiter (124 K)
- upper atmospheres of substellar objects are cool enough for interesting chemistry!



Dr. Robert Hurt, Infrared Processing and Analysis Center

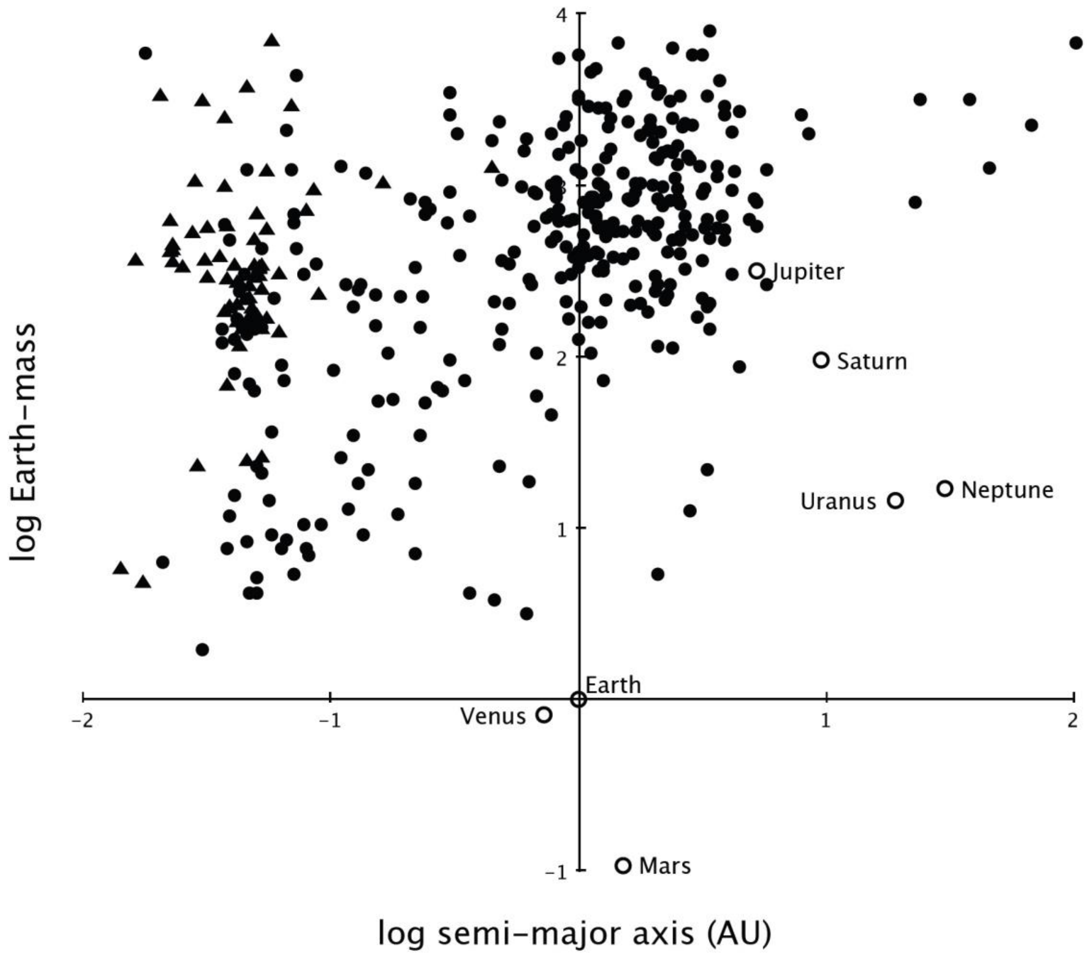
Worlds without end…

- prehistory: (Earth), Venus, Mars, Jupiter, Saturn
- 1400 BC: Mercury
- 1781: Uranus
- 1801: Ceres
- 1846: Neptune
- 1930: Pluto – *first and largest Kuiper Belt object*
- 1992: PSR 1257+12 b - *first extrasolar planet (orbiting a pulsar)*
- 1995: 51 Pegasi b - *first extrasolar planet around solar-type star*
- 1995: Gliese 229b – *first 'bona fide' (methane) brown dwarf*
- 1997: *first confirmed multi-planet systems*
- 1999: HD209458b – *first transiting extrasolar planet*
- 2000: *50 known exoplanets*
- 2003: Eris – *largest dwarf planet in Solar System*
- 2004: 2M1207b – *first exoplanet around brown dwarf, first imaged (IR)*
- 2005: *180 known exoplanets*
- 2007: Gliese 581d – *7x Earth mass planet in habitable zone*
- 2008: Fomalhaut b – *first exoplanet directly imaged at visible wavelengths*
- *2010: 445 confirmed exoplanets (as of this morning), 750 brown dwarfs*

Source: Google; Extrasolar Planets Encyclopaedia

Worlds without end…

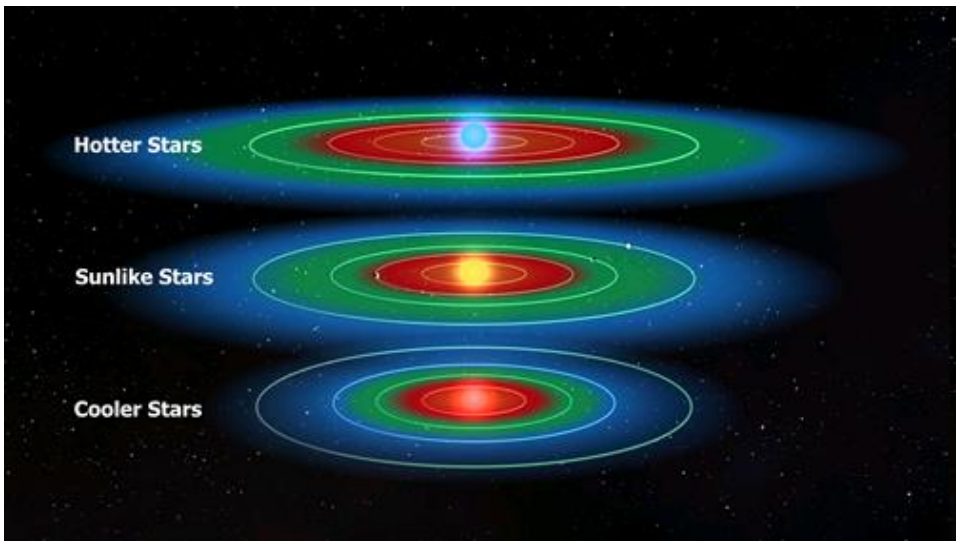
- there remains a strong observational bias toward large, close-in planets

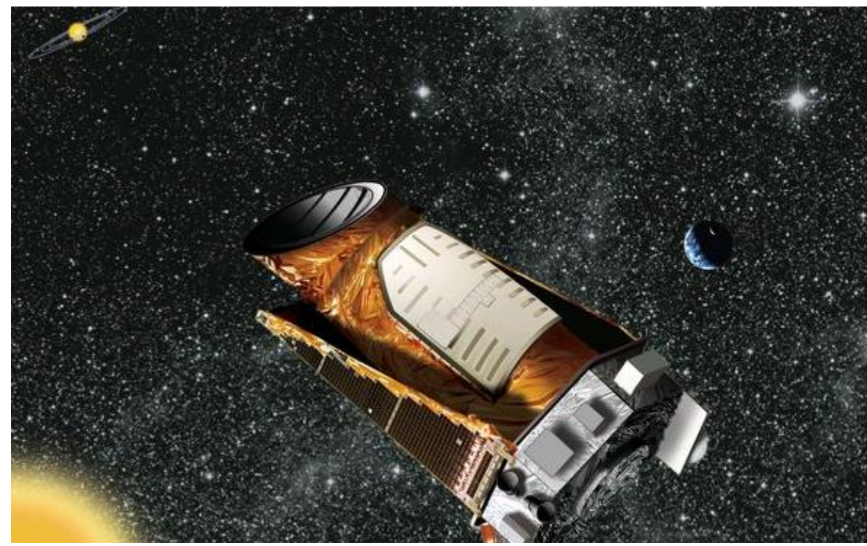


Mass and orbit of exoplanets, normalized to Earth

Worlds without end…

- current objective Earth-mass planets or large satellites in habitiable zone
  - *habitable zone*: temperatures allow existence of liquid water

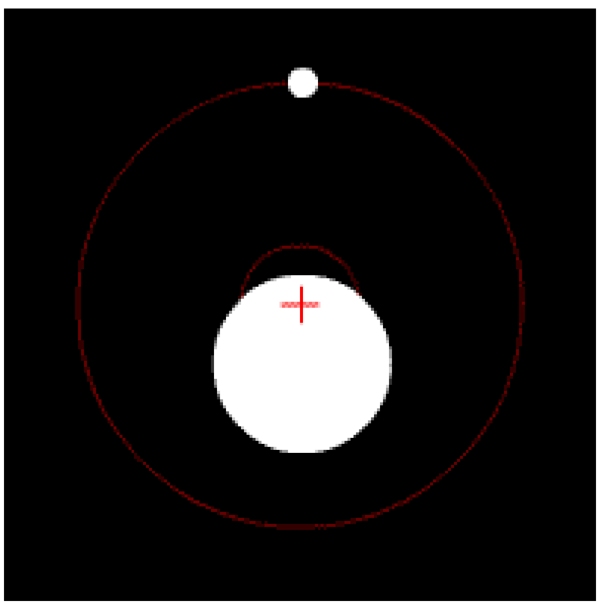


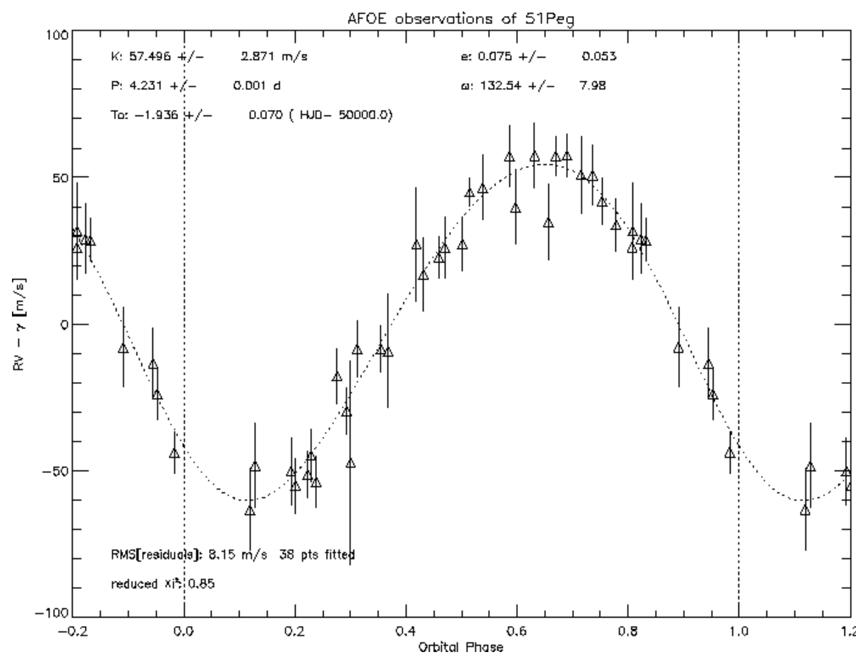


relative location of habitable zone; Kepler spacecraft

Exoplanet detection methods

- *radial velocity method* (80% of exoplanets)
  - planet's gravity causes wobble in star's rotation
  - measurement bias:
    - 2/3 of extrasolar planets are 1 Jupiter mass or greater
    - 2/3 of extrasolar planets are within 1 AU of their star

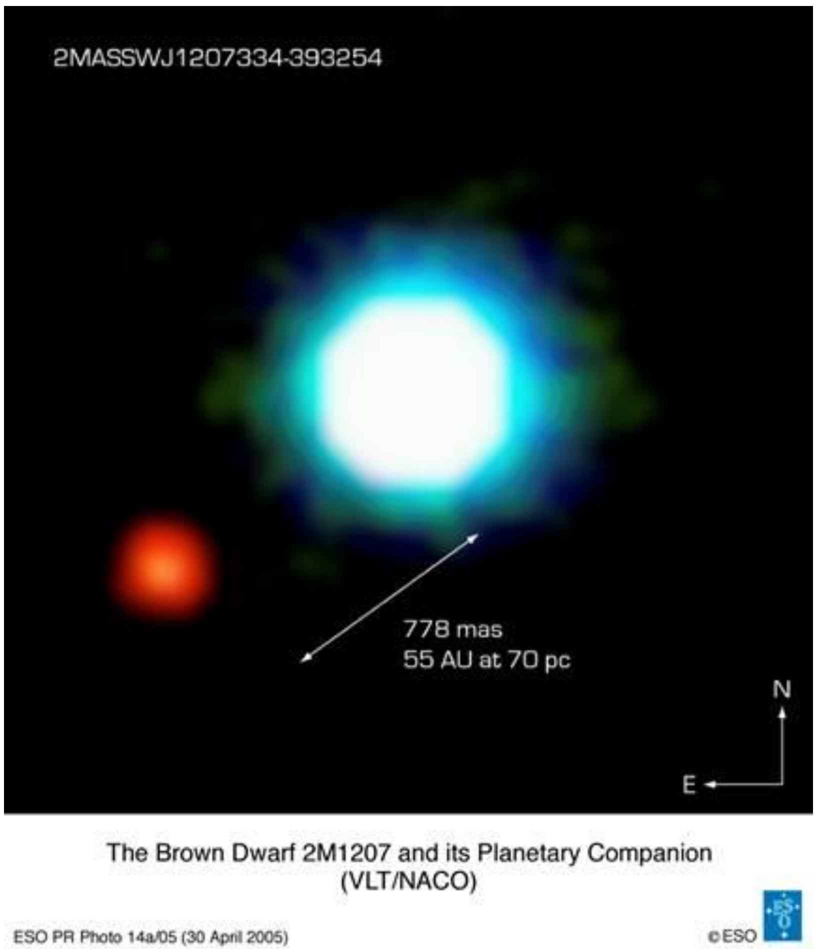


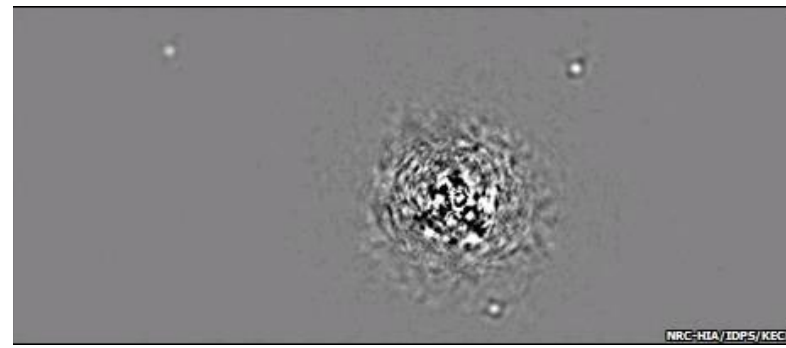


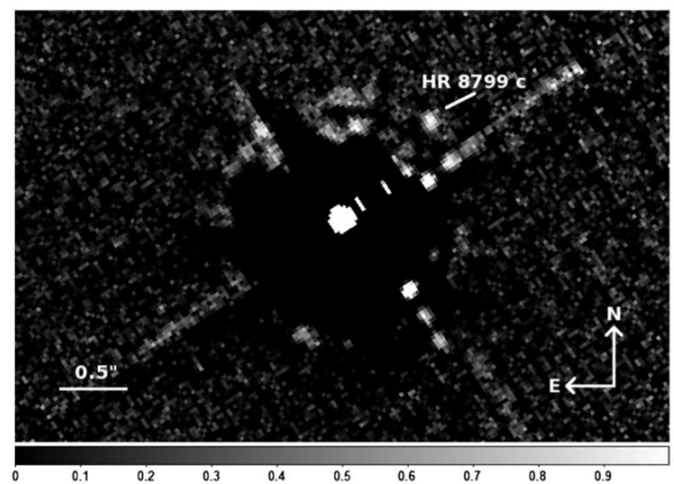
Star & planet orbit a common center of gravity; radial velocity for 51 Pegasi

Exoplanet detection methods

- *direct imaging* (~12 planets) – infrared
  - 2M1207b: brown dwarf 3-10 M_{Jup} companion at 40 AU
  - HR8799: young main sequence star with three planets



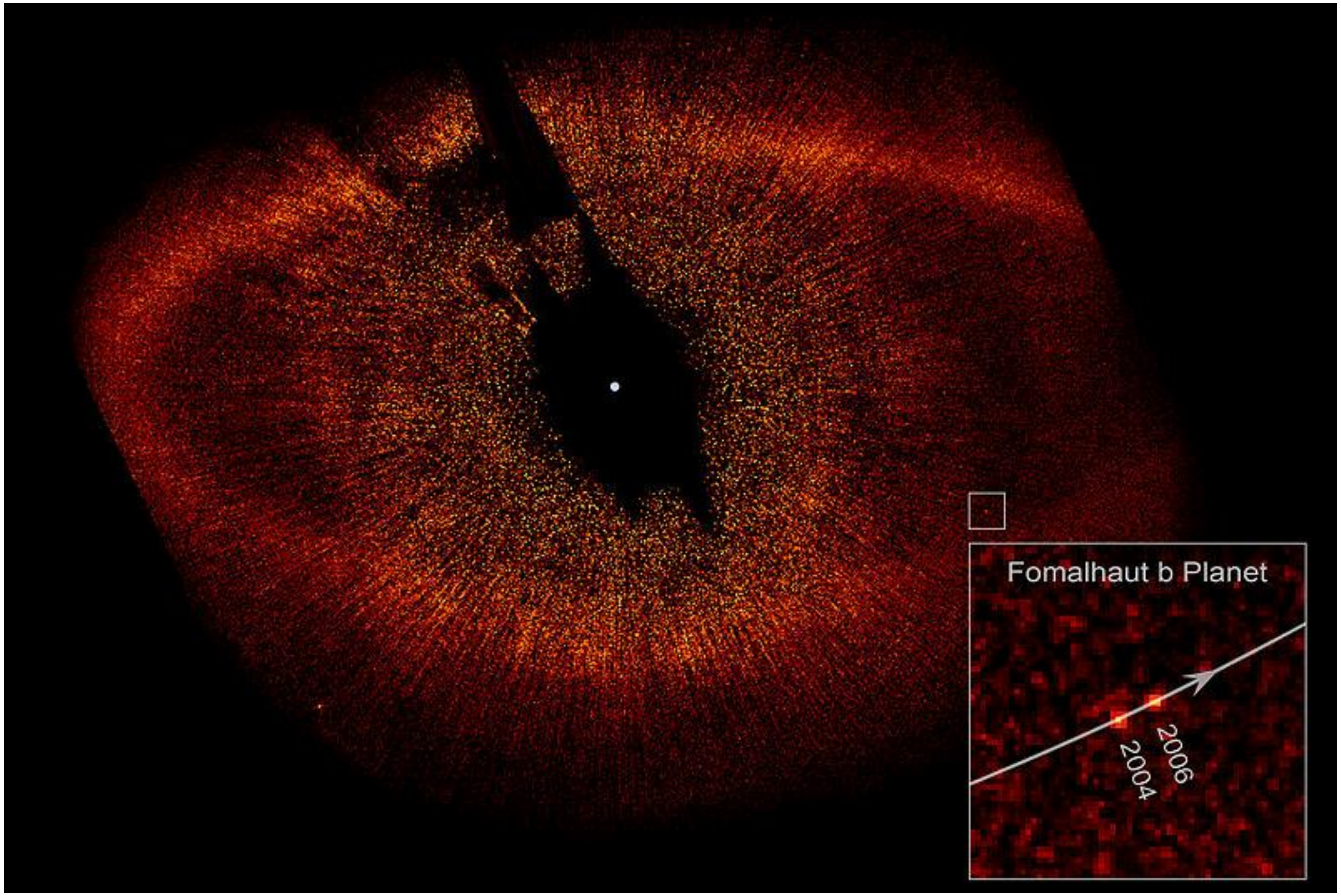




*2M1207b (ESO); HR 8799*c (Janson et al 2010)

Exoplanet detection methods

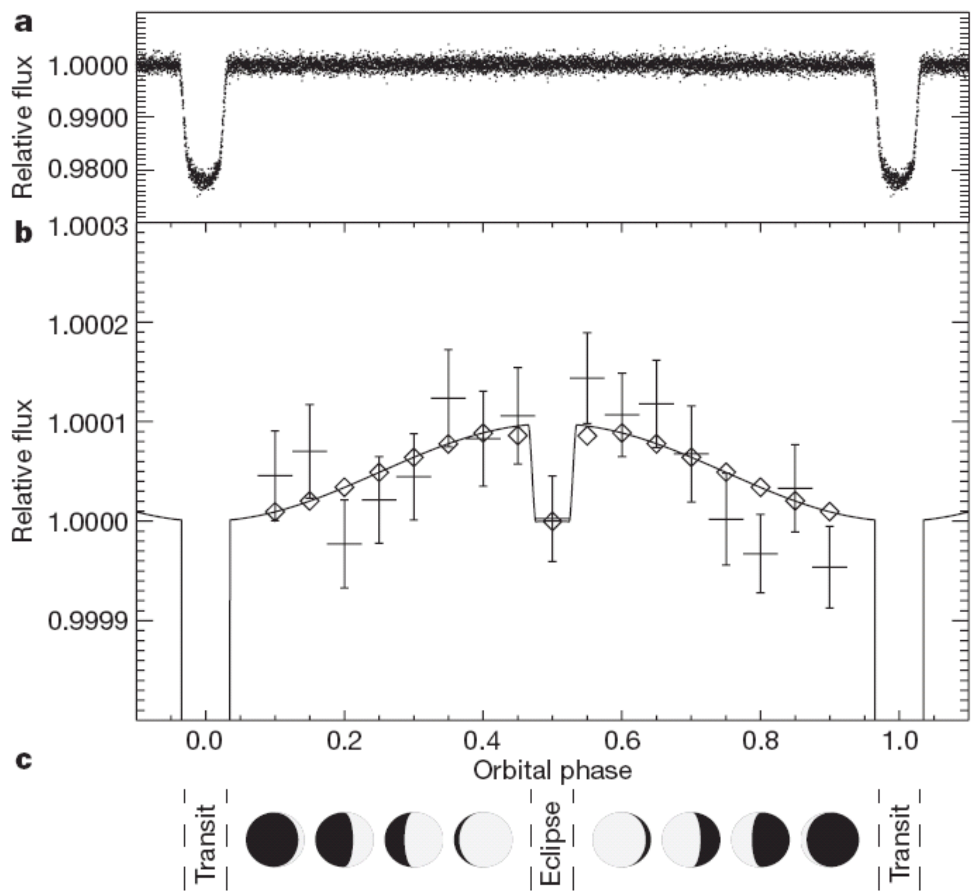
- *direct imaging* (~12 planets) – visible!
  - Fomalhaut b: ~3 M_{Jup} planet orbiting A3V star at 115 AU, at inner edge of debris disk



Fomalhaut b discovery; Kalas et al 2005

Exoplanet detection methods

- *planetary transits* (16% of exoplanets)
  - planet cross the disk of the star, from our perspective
  - allows determination of radius and (sometimes) planetary spectra



Optical phase variation for CoRoT-1b, Snellen et al 2009

Exoplanet detection methods

- *planetary transits* (16% of exoplanets)
  - planet cross the disk of the star, from our perspective
  - allows determination of radius and (sometimes) planetary spectra
  - HD209458b: 0.7 M_{Jup} planet orbiting G star at 0.05 AU

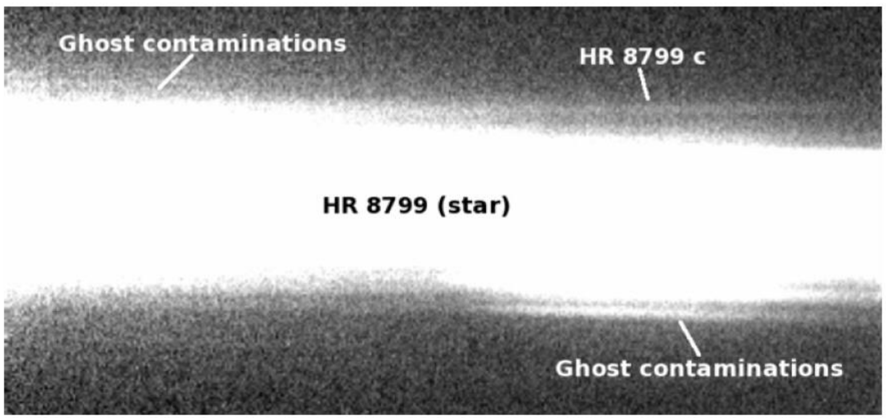
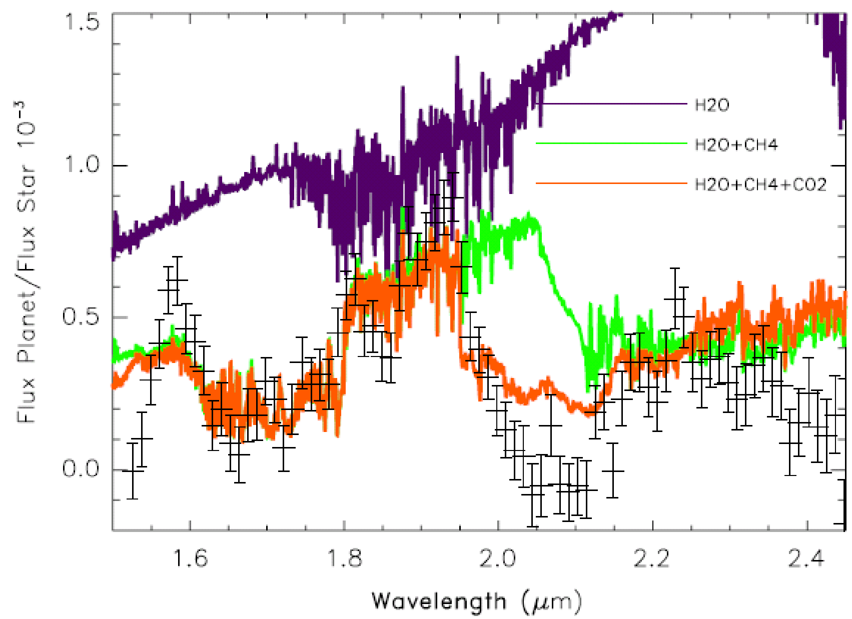


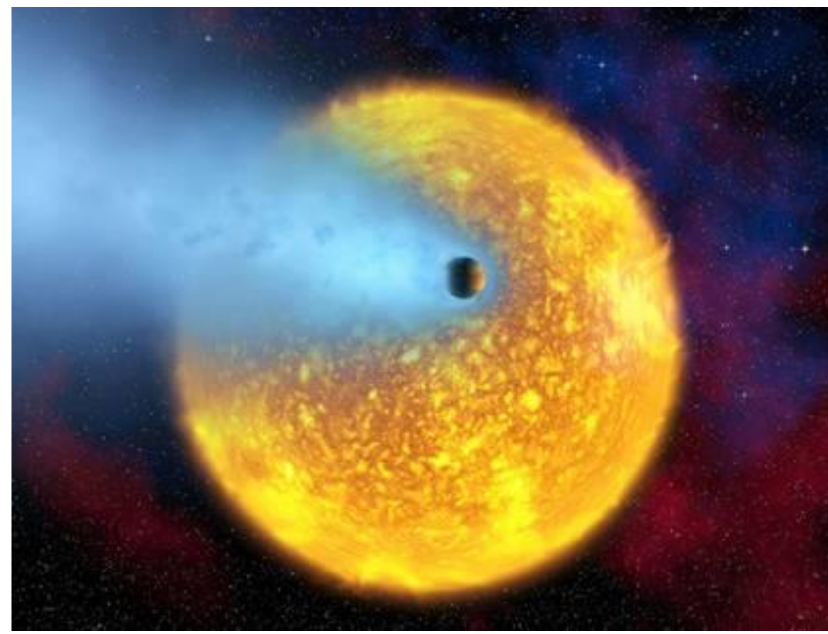
Figure 2. Image with the HR 8799 c spectrum before extraction. The spatial direction along the star–planet axis is vertical. The spectral direction is horizontal, with wavelength increasing from left to right.



Janson et al 2010 HR8799c spectra; Swain et al 2009 HD209458b spectra

Planetary formation & migration

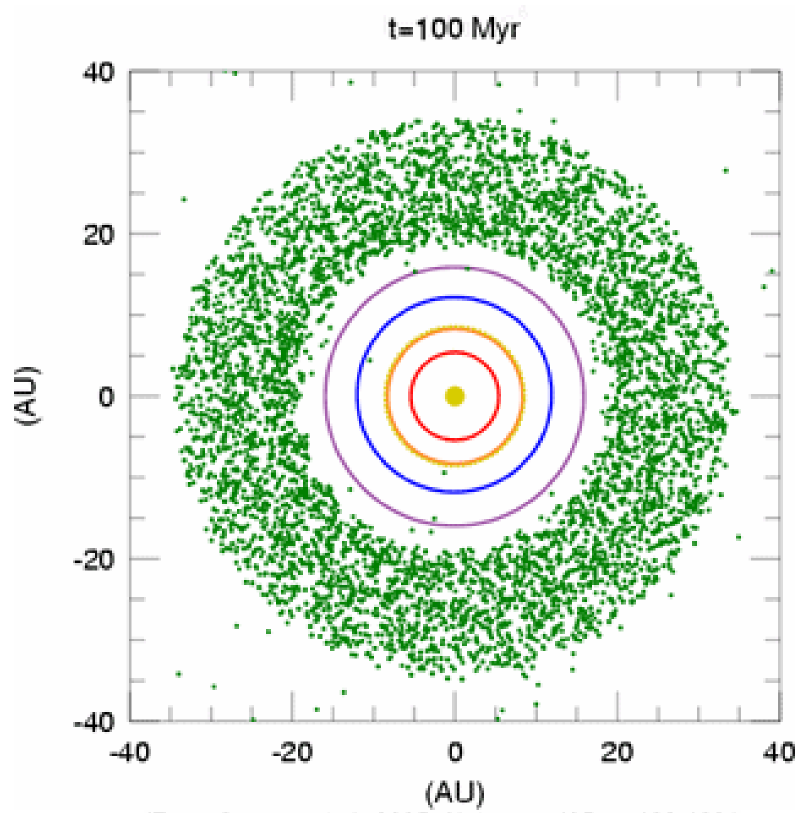
- close-in exoplanets suggest *planetary migration*
  - too close and too hot for "normal" planet formation
    - Corot-7b: 5 M_{Earth} 0.017 AU orbit around main sequence G star
    - high density suggests atmosphere was stripped away
    - evidence for atmospheric loss from HD209458b



Corot-7b; Gomes et al. "Nice model"; evaporation from HD209458b

Planetary formation & migration

- reanalysis of migration in the Solar System
  - migration of Jupiter, Saturn, Uranus, Neptune
  - responsible for late-heavy bombardment in ~4 billion years ago?

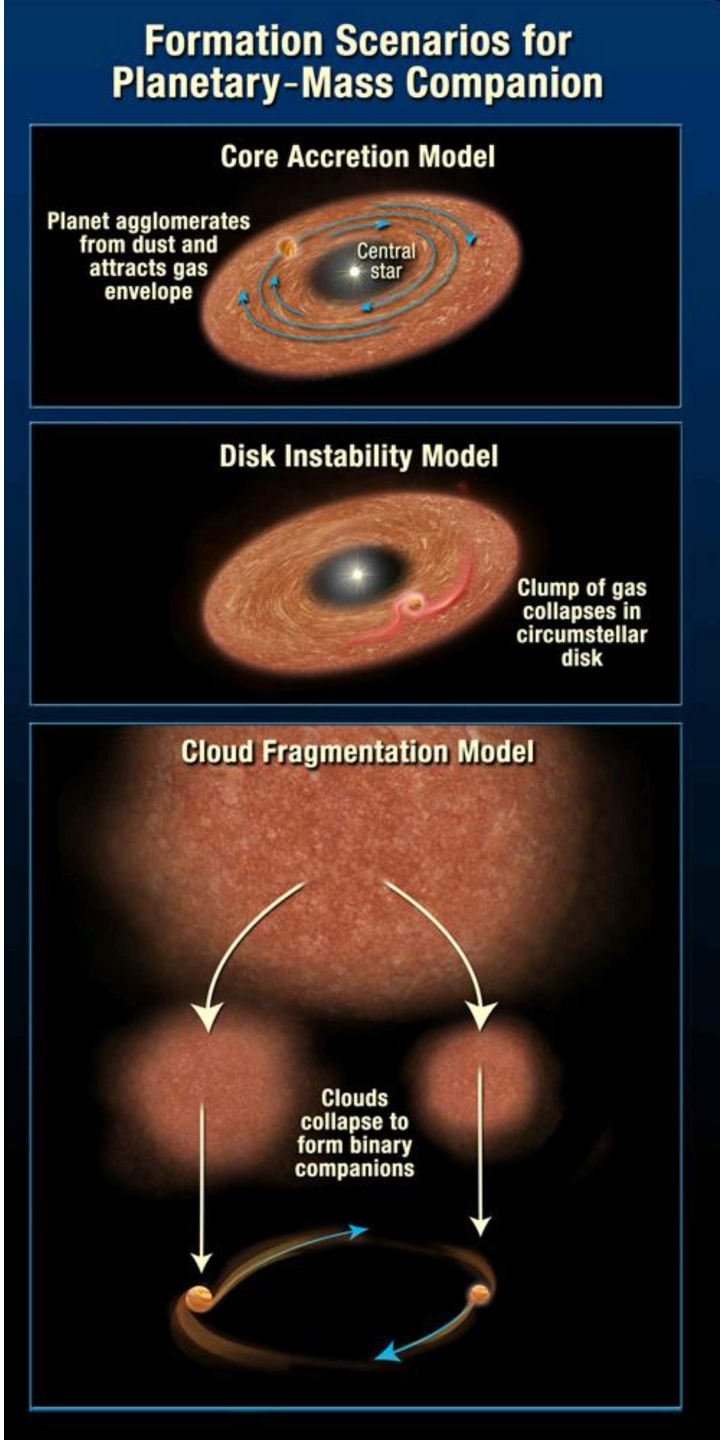


(From Gomes, *et al.*, 2005, *Nature*, v. 435, p. 466-469.)

Gomes et al. "Nice model"

Planetary formation

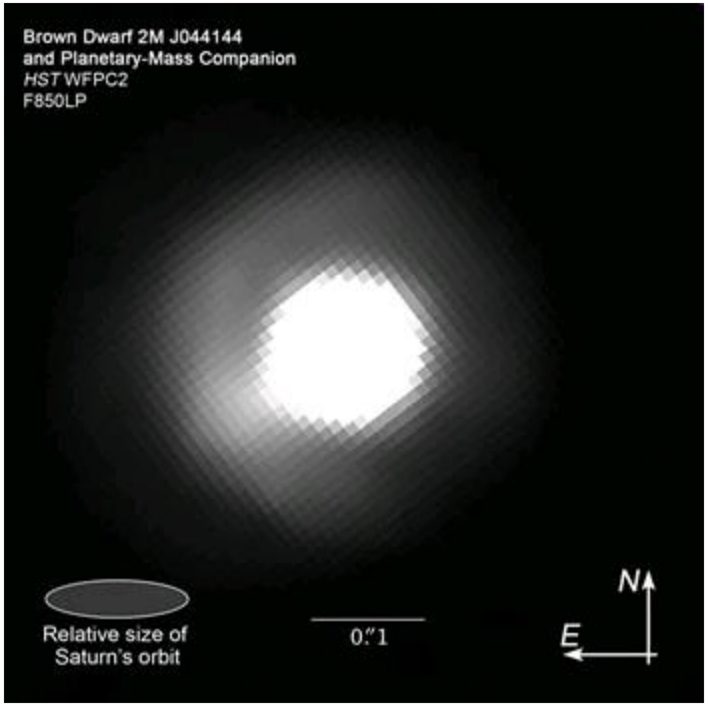
- reanalysis of planetary formation theories
- planetary formation
  - core accretion (slowest)
  - disk instability
  - cloud collpase (?)
- both core accretion & disk instability have been suggested for Jupiter



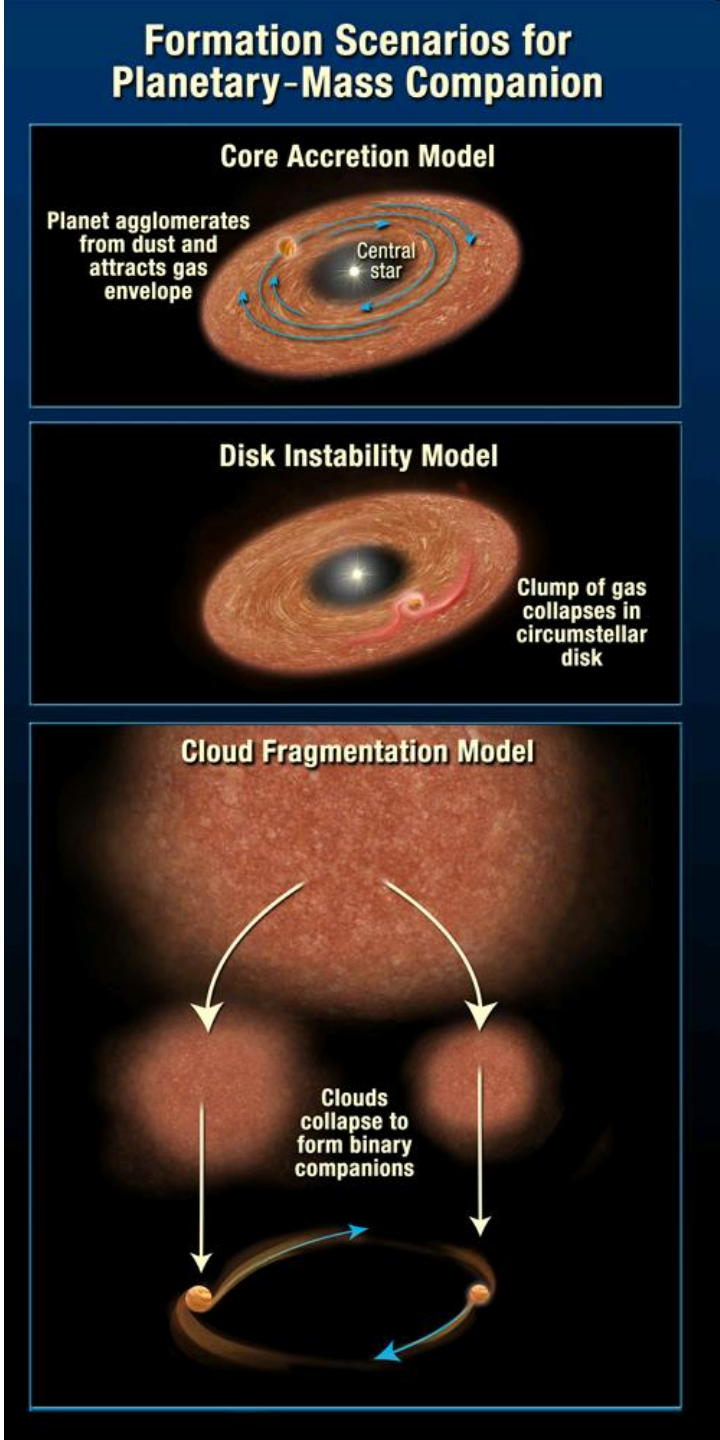
hubblesite.org

Planetary formation

- 2M J044144 system
  - 7 M_{Jup} companion orbiting at 24 AU
  - too young (1 Ma) for core accretion
  - not enough material for disk instability
  - suggests cloud collapse (like a star)

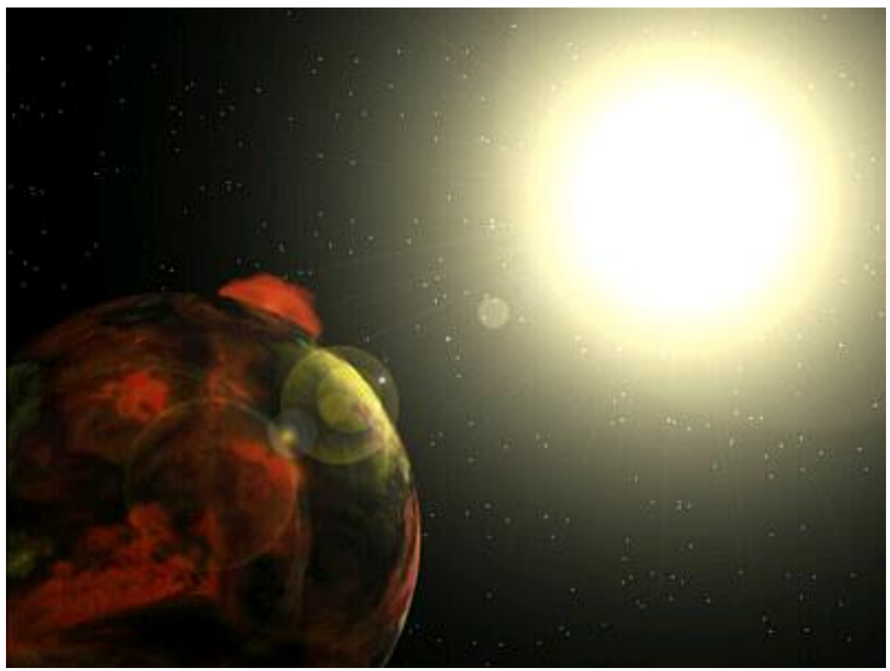


hubblesite.org;Todorov et al 2010



Extrasolar planet properties

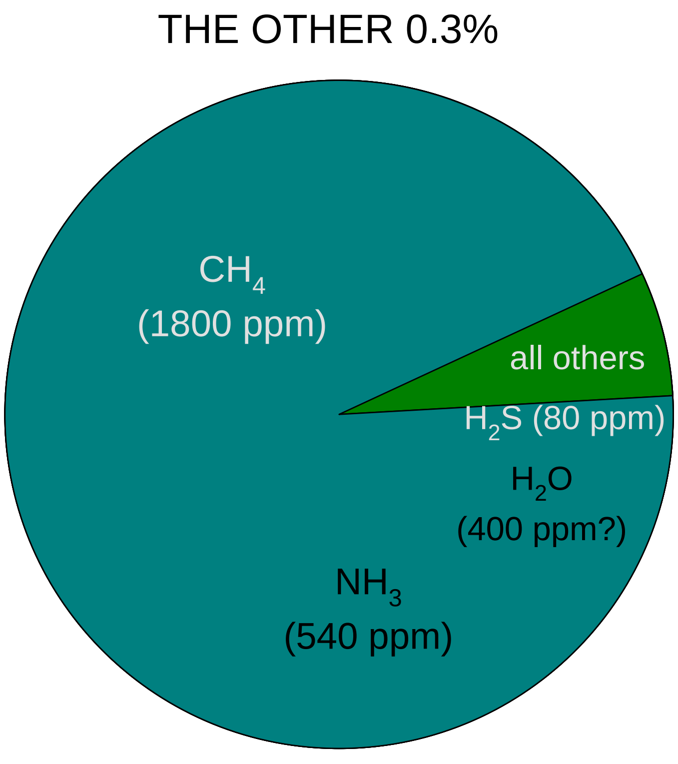
- radius and mass suggest most are gas giants with ‘solar’ composition (H, He)
- orbital properties suggest variety of formation histories
- what’s controlling what we see on the planets themselves?
  - clouds & chemistry operating in different environments
  - may expect similar physical & chemical processes as on Jupiter

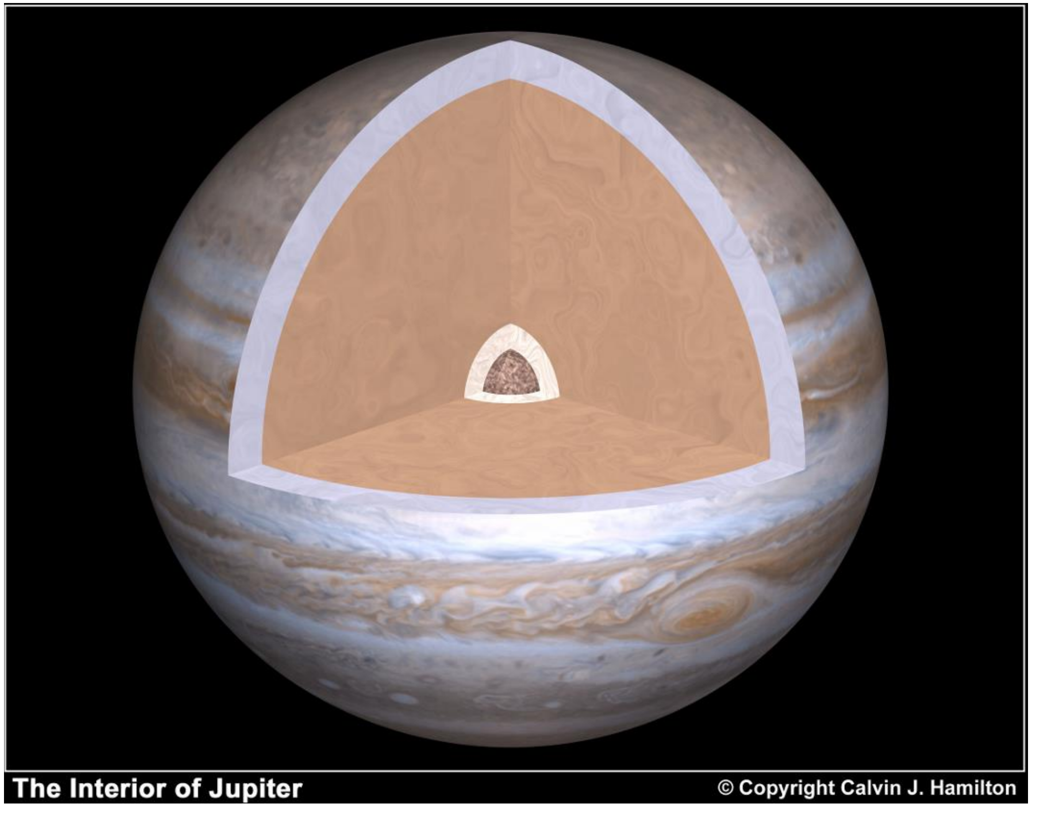


artists’ conceptions of 55 Pegasi b

Introduction to Jupiter

- 86% H_2, 14% He and 0.3% heavy elements
- outer molecular envelope, H metal "mantle", ice/rock core
- emits 2x radiation as it receives from Sun: warm convective interior



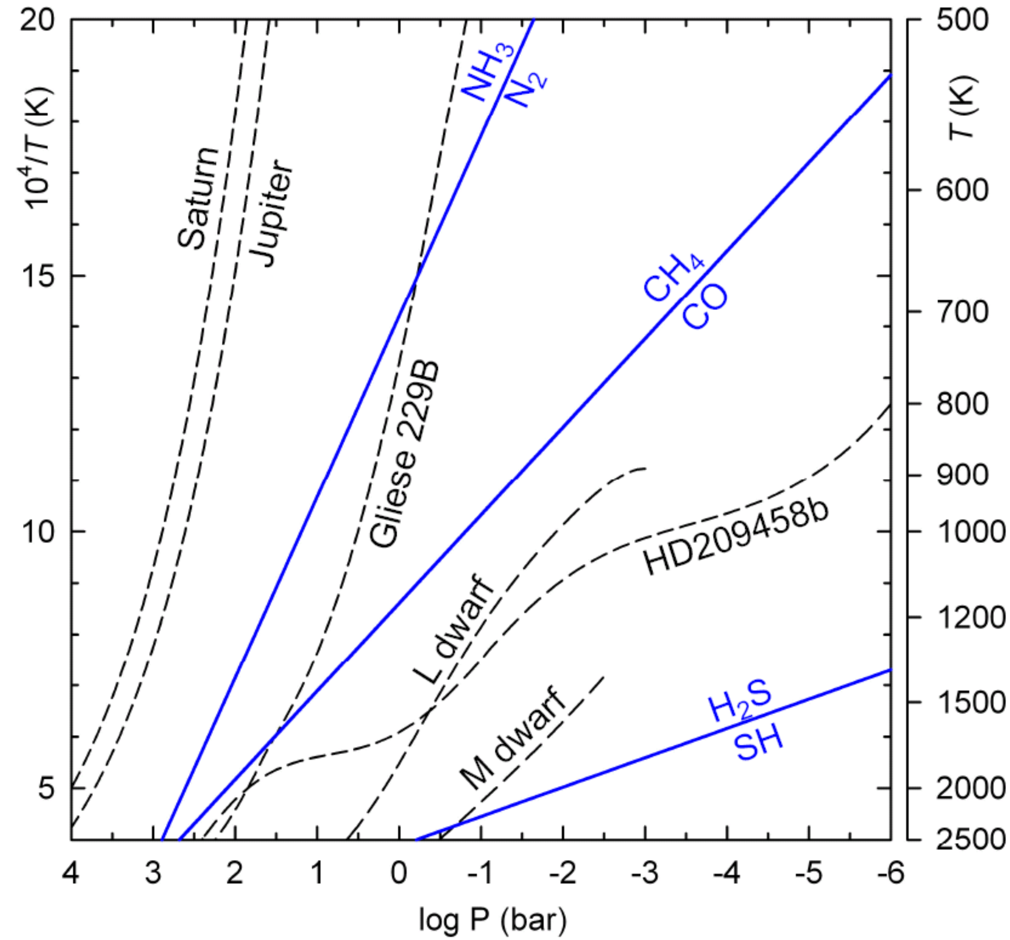


major element chemistry on Jupiter; interior model of Jupiter;

Gas chemistry

- Chemistry 101: major gases predicted by thermodynamic equilibrium for a given P, T, X (1:1 abundance lines shown)

- carbon is mostly found as…
  - CO on L dwarfs
  - CO/CH_4 on T dwarfs (Gl229b)
  - CH_4 on Jupiter, Saturn
  - *this is observed*



equilibrium gas chemistry in substellar objects, cf. Visscher et al. 2006

Cloud chemistry

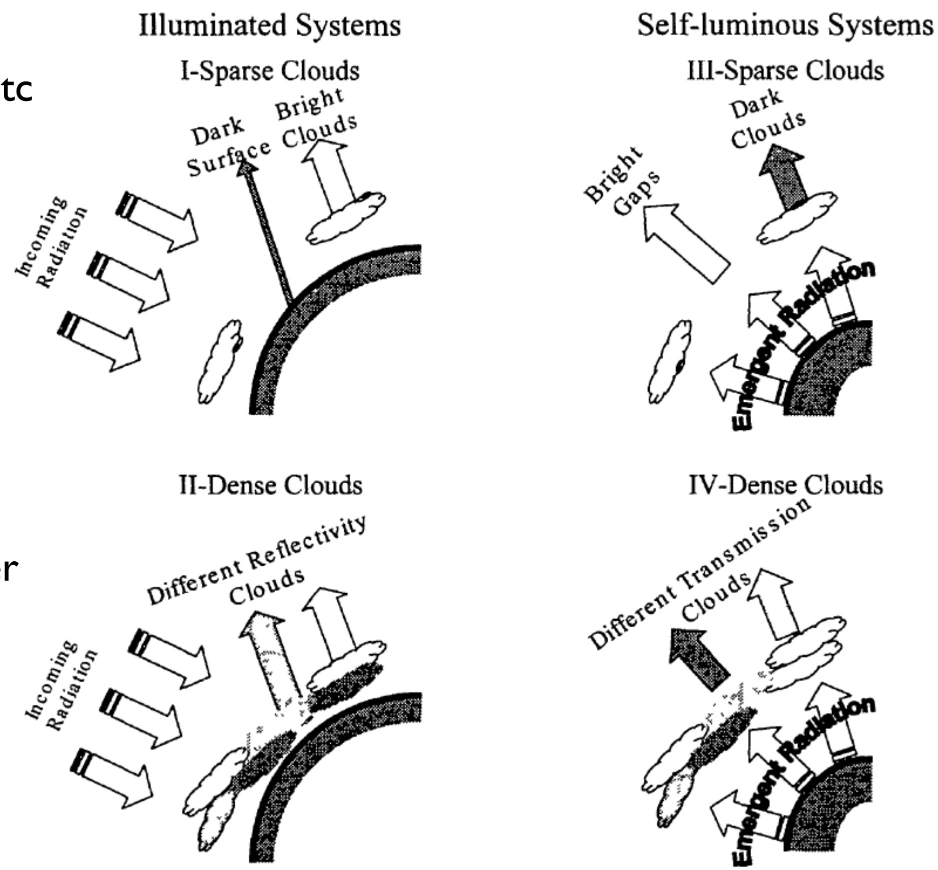
- clouds strongly affect what we can observe:
  - remove atoms and molecules from the gas phase
  - introduce particulate matter (reflection & scattering)

Earth, Mars, etc

Jupiter hotspots

gas giants, Jupiter

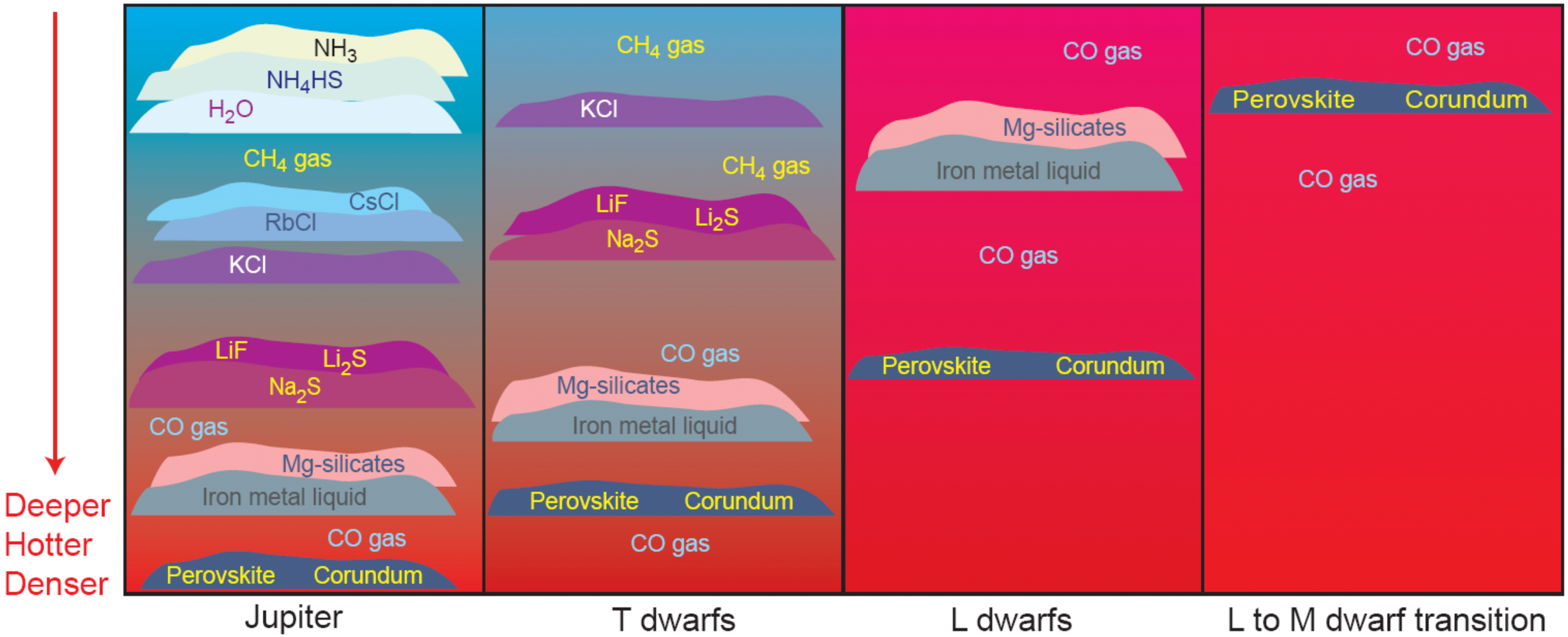
brown dwarfs?



from Tinney (2000)

Cloud chemistry

- numerous deep cloud layers are predicted by equilibrium
- *strong effect on spectral observations*
    - note: Na_2S cloud disappears in warmer objects
    - note: CH_4 dominant at high altitudes in cooler objects

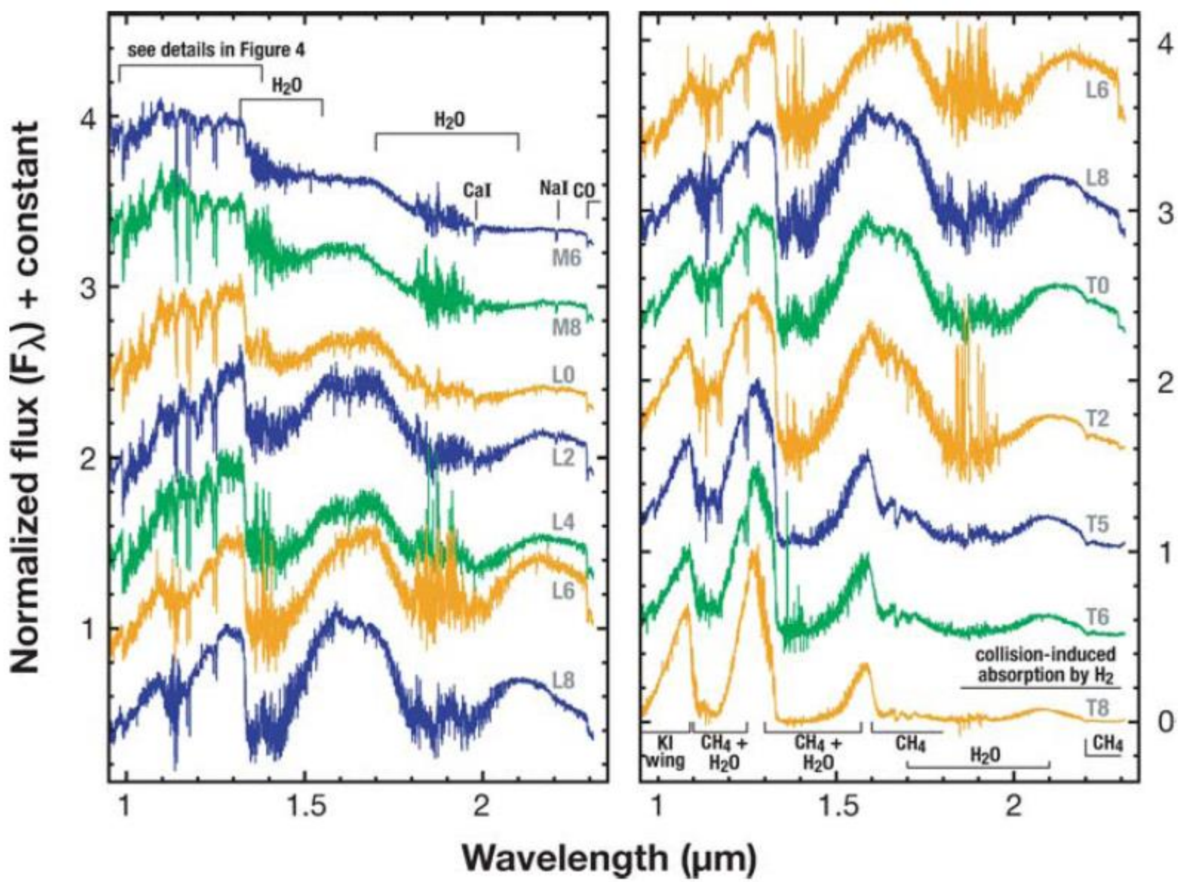


A cloudy picture. Cloud layers for Jupiter, T dwarfs, L dwarfs, and objects near the transition from L to M dwarfs. The layers are progressively stripped off as the temperature of the object increases.

Lodders (2004)

Spectral observations and chemistry

- basic thermochemistry is confirmed by spectral observations
  - disappearance of Na in later (cooler) types – removed by cloud
  - appearance of CH_4 in later (cooler) types – change in gas chemistry



Kirkpatrick (2000)

Predicting chemistry in substellar objects

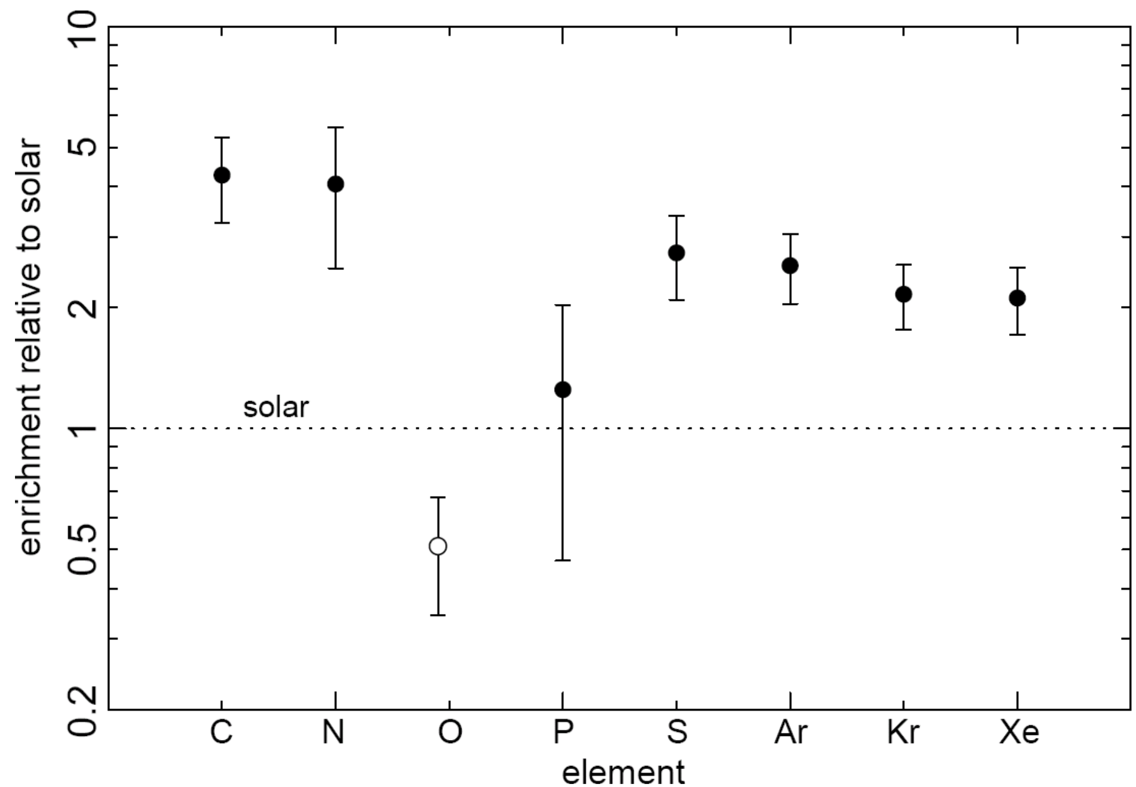
- thermochemical equilibrium is useful first approximation, but…
- *substellar atmospheres are not in complete equilibrium:*
  - atmospheric mixing (convection)
  - photochemistry (UV-driven reactions)
  - these effects must be included in chemical models

- new approach: numerical model which simultaneously considers thermochemistry, photochemistry, and mixing
  - based upon JPL/Caltech KINETICS code (Allen et al. 1981)
  - includes >100 species and >900 forward/reverse reaction pairs
  - in principle, can be applied to any object

Application 1: Jupiter's water abundance

- what is Jupiter's atmospheric water abundance? why do we care?
  - water vapor is expected to be relatively abundant (>1000 ppm)
  - plays large role in Jupiter's weather and transfer of energy
  - formation models: how were heavy elements delivered to Jupiter?

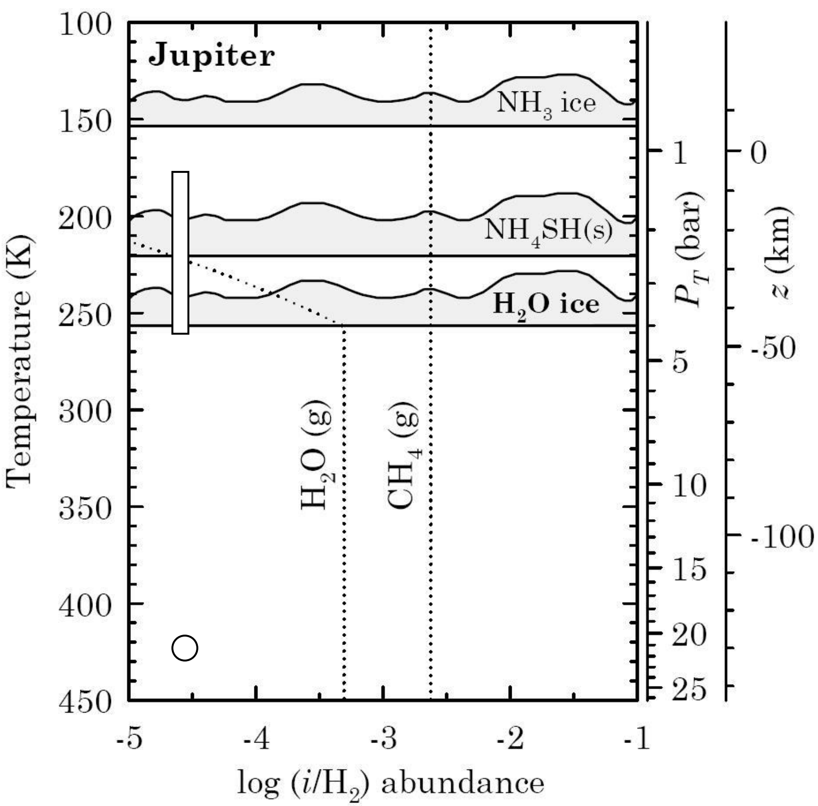
$$\text{enrichment} = \frac{\left(M/H_2\right)_{Jupiter}}{\left(M/H_2\right)_{solar}}$$



Heavy element enrichments in Jupiter's atmosphere, relative to solar M/H_2

Jupiter's water abundance: difficulties

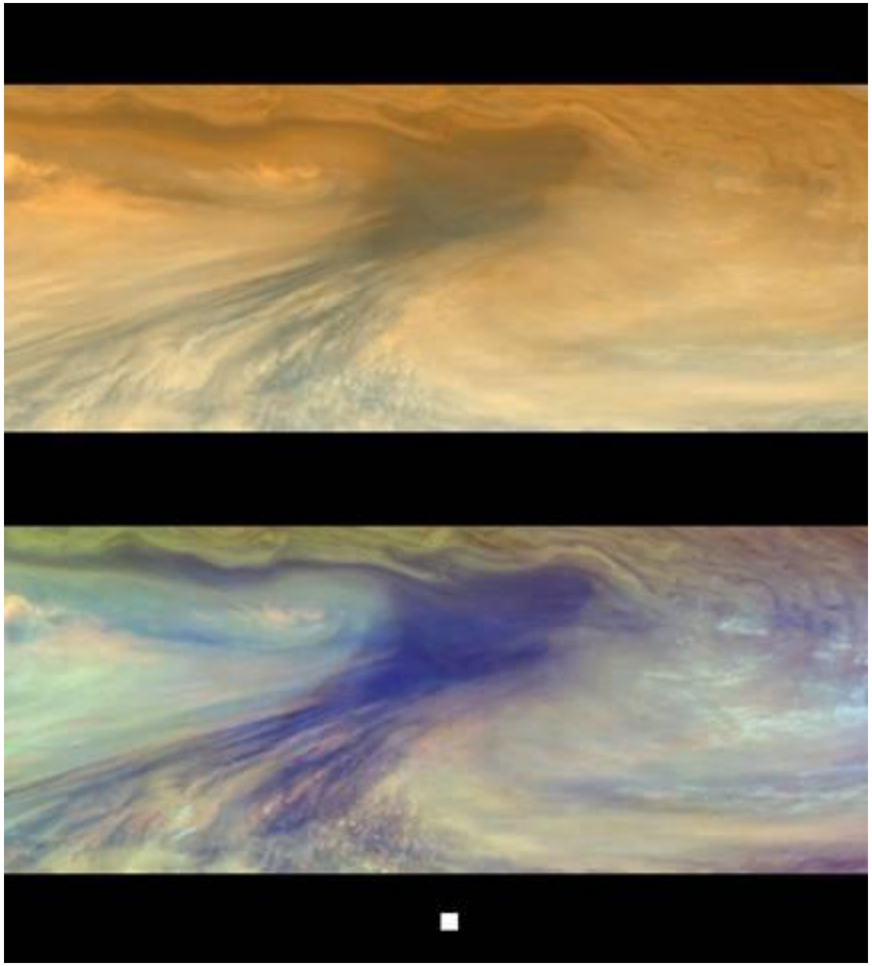
- H_2O difficult to measure by because of cloud formation
- solution: *Galileo* probe (December 7, 1995)
  - survived to 420 K, 20 bar level
  - measured a low H_2O abundance (400 ppm), that increased with depth!?



getting at the deep water abundance; the Galileo entry probe

Why the low water abundance?

- probe entered a *hotspot*
  - localized regions of downwelling material
  - unusually dry with relatively thin clouds



Infrared image showing hotspots; clouds near hotspot region – white square has area of Texas

Using a chemical model

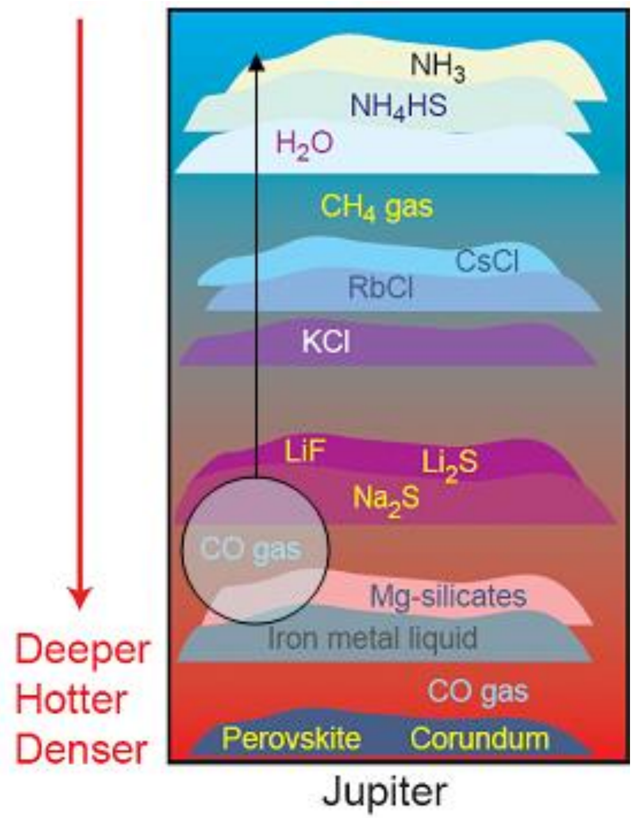
- study how H_2O affects chemistry of things which we *can* observe on Jupiter
- carbon monoxide (CO) is tied to H_2O abundance

$$CH_4 + H_2O = CO + 3H_2$$

- we expect negligible CO in upper atmosphere, but observe 1 ppb CO observed on Jupiter: *need to consider atmospheric mixing*

CO abundance depends upon:

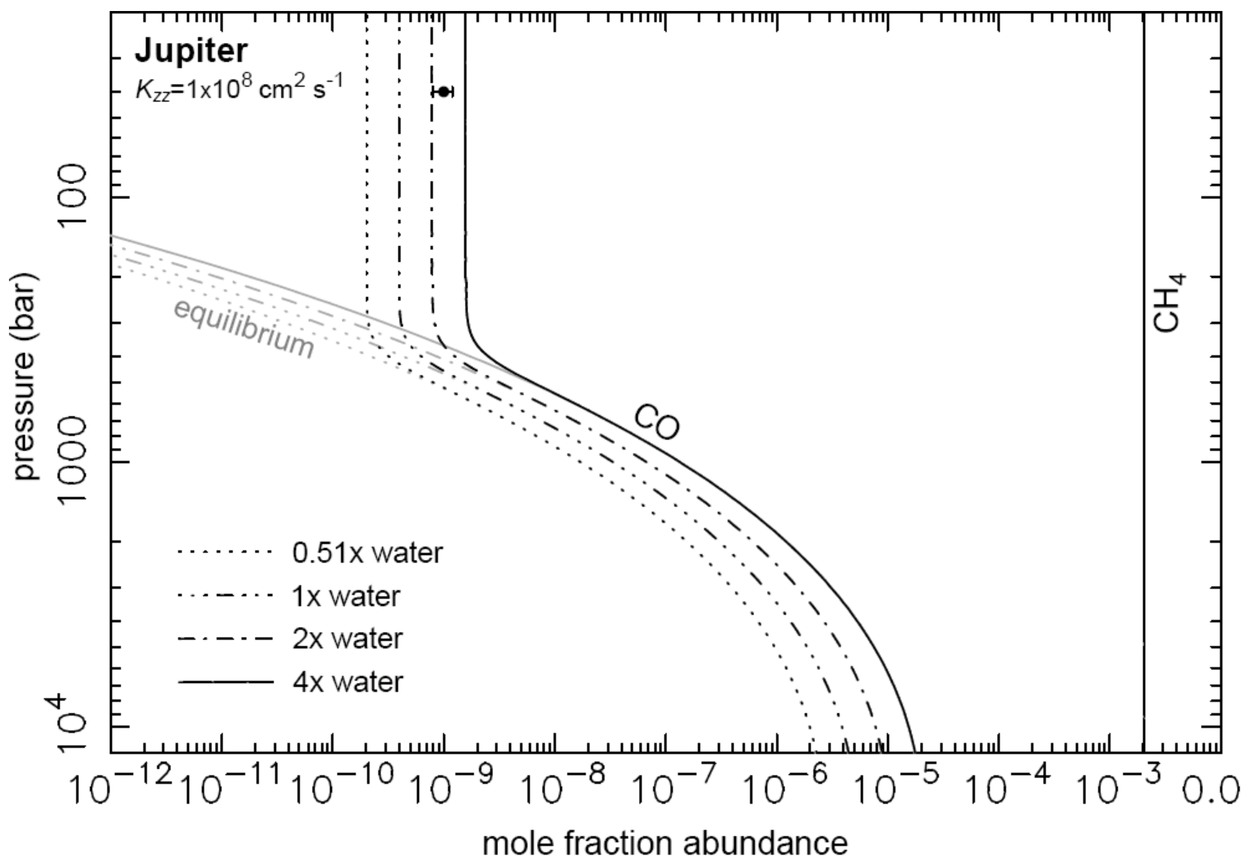
- rate of mixing
- rate of chemical reactions
- water abundance



after Lodders (2004); CO equilibrium chemistry on Jupiter

Jupiter's water abundance: results

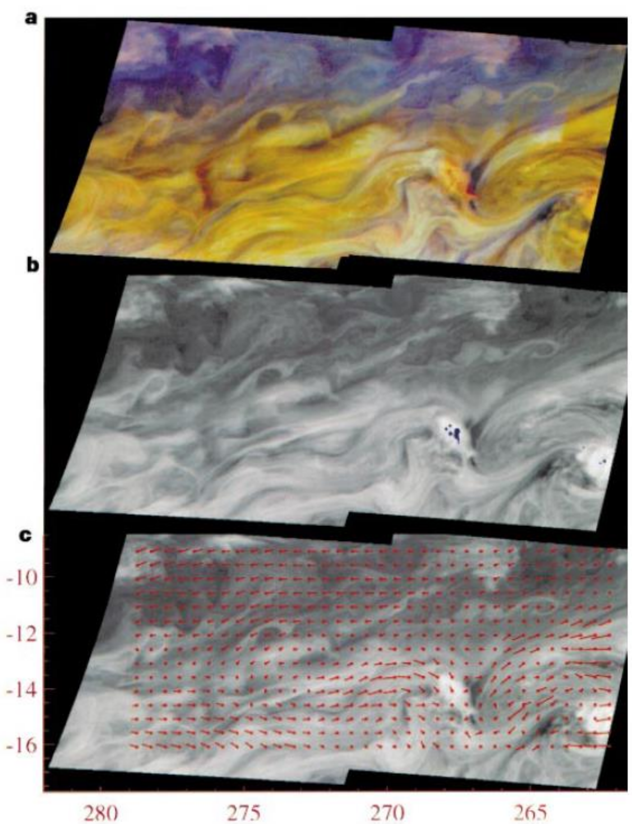
- our results suggest a water enrichment of 2-3x solar, consistent with other heavy elements
- rules out formation mechanisms which require large (>8x) amounts of water

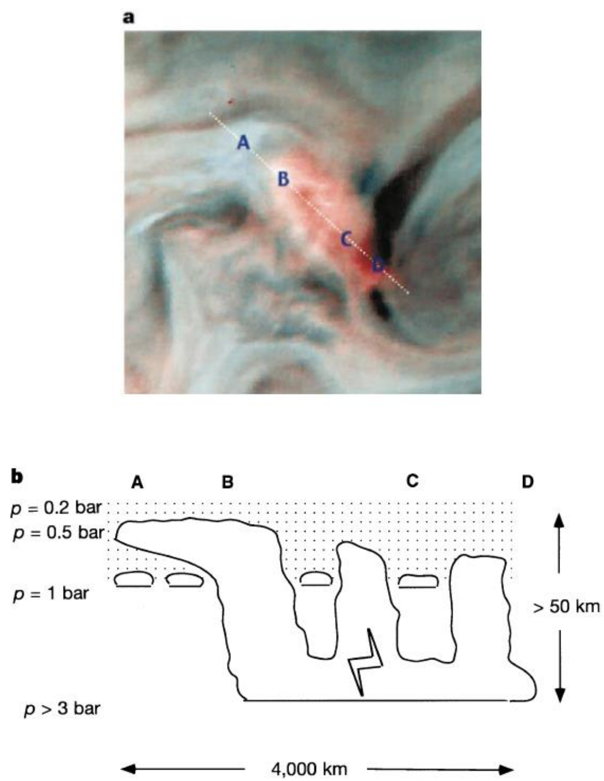


Visscher et al. 2010 (in press); CO observation from Bezard et al. 2002

Some familiar clouds: Jovian thunderstorms

- evidence for moist, convective thunderstorms on Jupiter
  - towering, cumulonimbus-type cloud structures
  - upper level divergence consistent with cloud updraft
- our results are roughly in agreement with estimated cloud base temperatures

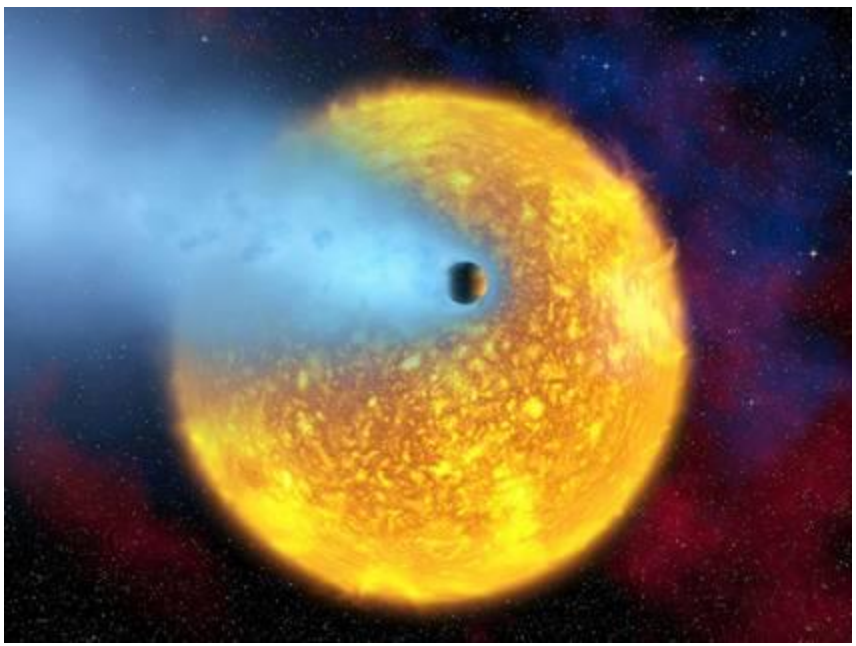


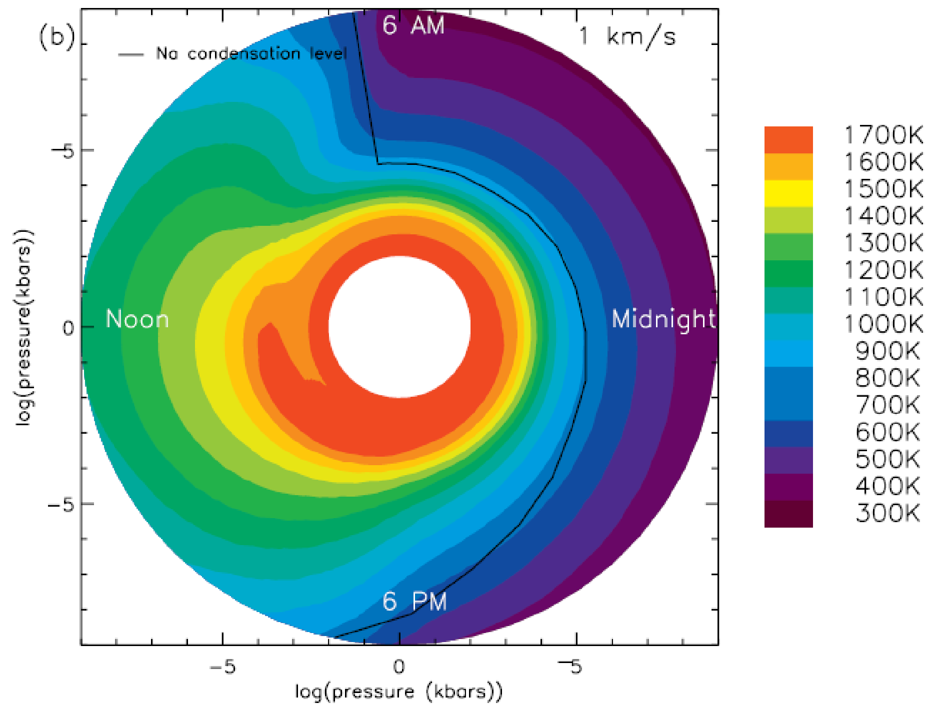


Storm region and interpretation from Gierasch et al (2000); a terrestrial analog?

Application 2: substellar photochemistry

- close-in exoplanets experience **intense** stellar irradiation
  - atmosphere evaporation (HD20948b, Corot-7b?)
  - large day/night differences
  - dramatic effect on weather
- what are relative roles of thermochemistry vs. photochemistry?

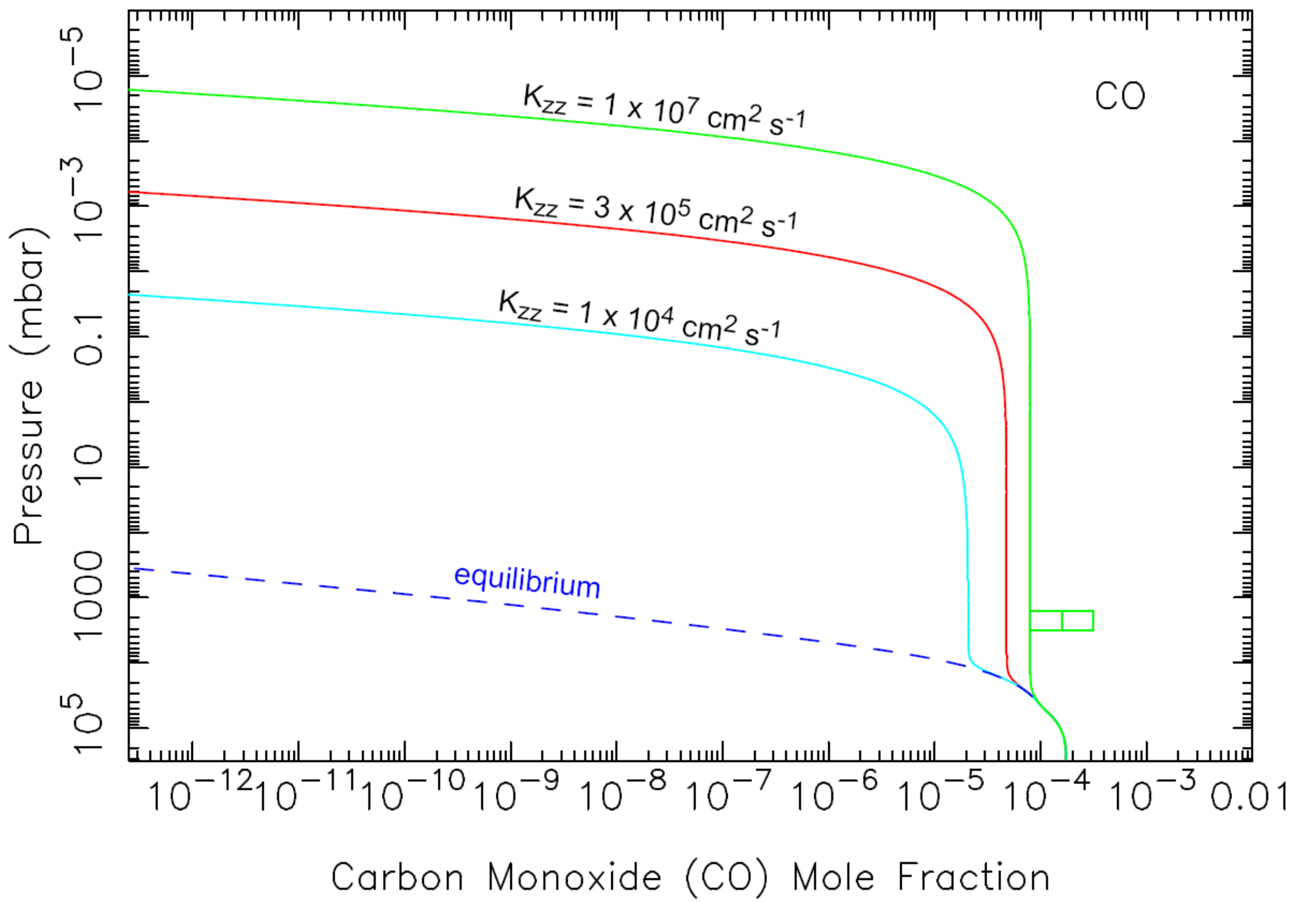




artist's concept of evaporating atmosphere around HD209458b; temperature differences from Iro et al (2005)

CO chemistry: Gliese 229b

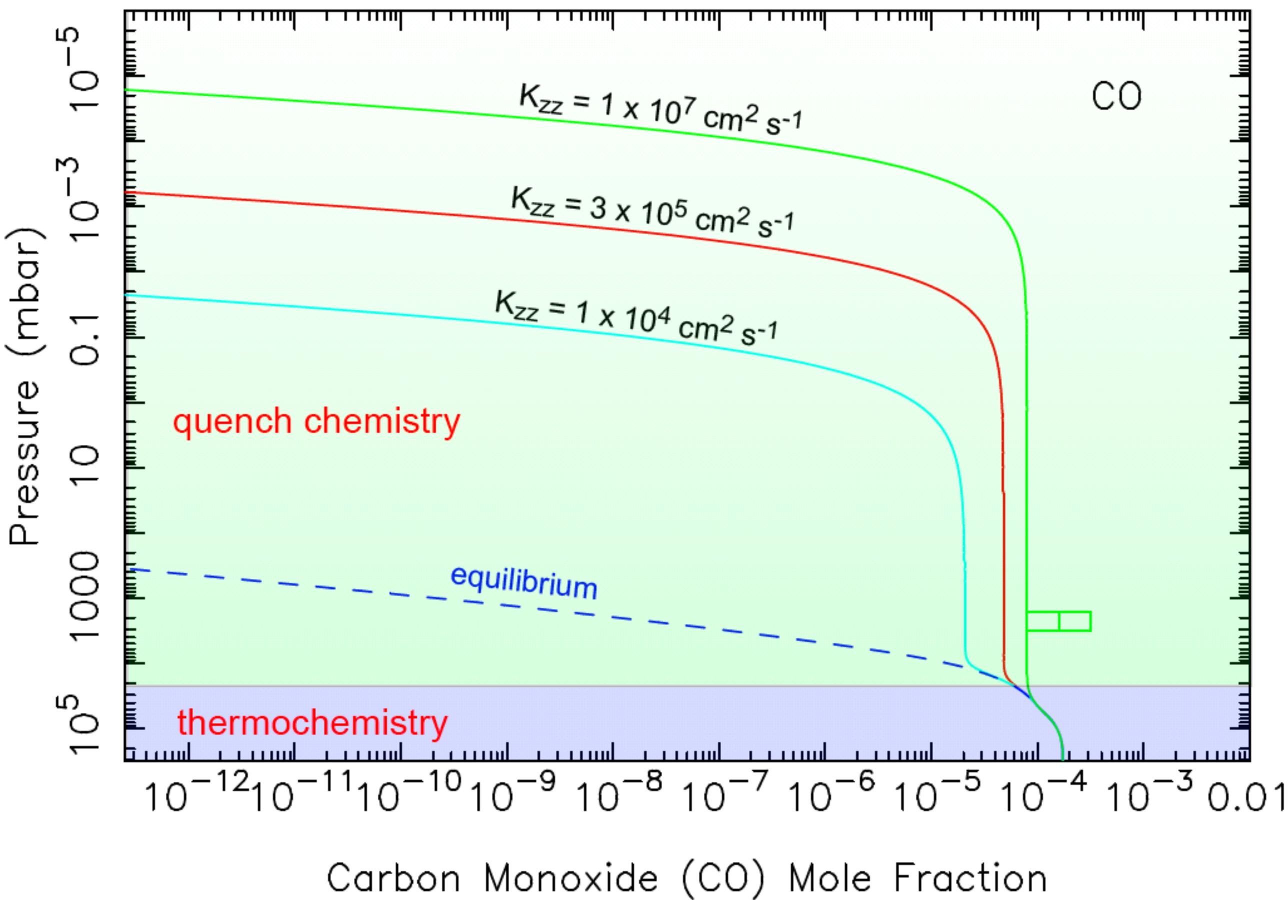
- two regimes evident: thermochemistry and quench chemistry



CO chemistry on Gliese 229B with observed abundance (cf. Saumon et al. 2000)

CO chemistry: Gliese 229b

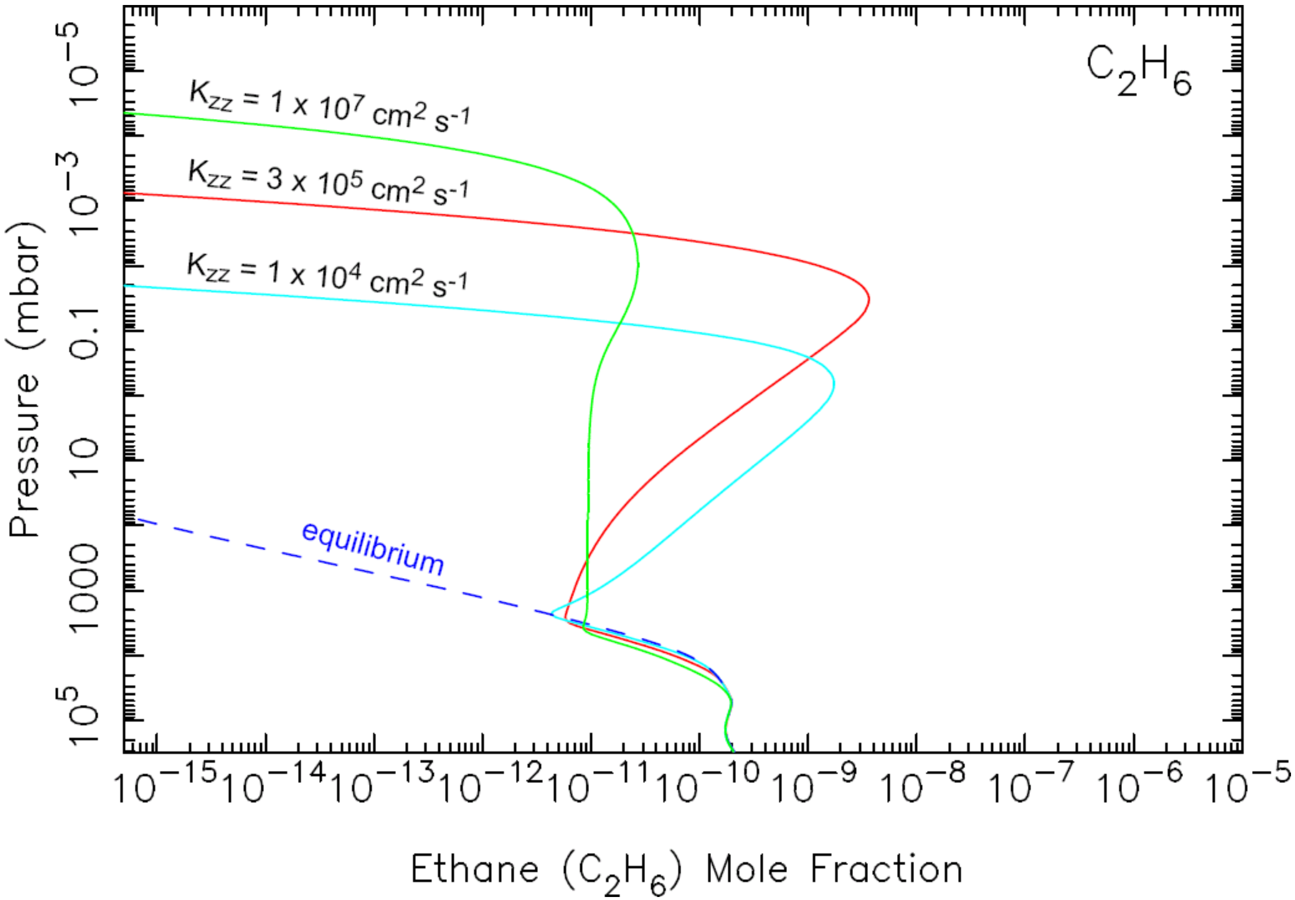
- two regimes evident: thermochemistry and quench chemistry



CO chemistry on Gliese 229B with observed abundance (cf. Saumon et al. 2000)

C_2H_6 chemistry: Gliese 229b

- three regimes: thermochemistry, quench chemistry, photochemistry



C_2H_6 chemistry on Gliese 229B

C_2H_6 chemistry: Gliese 229b

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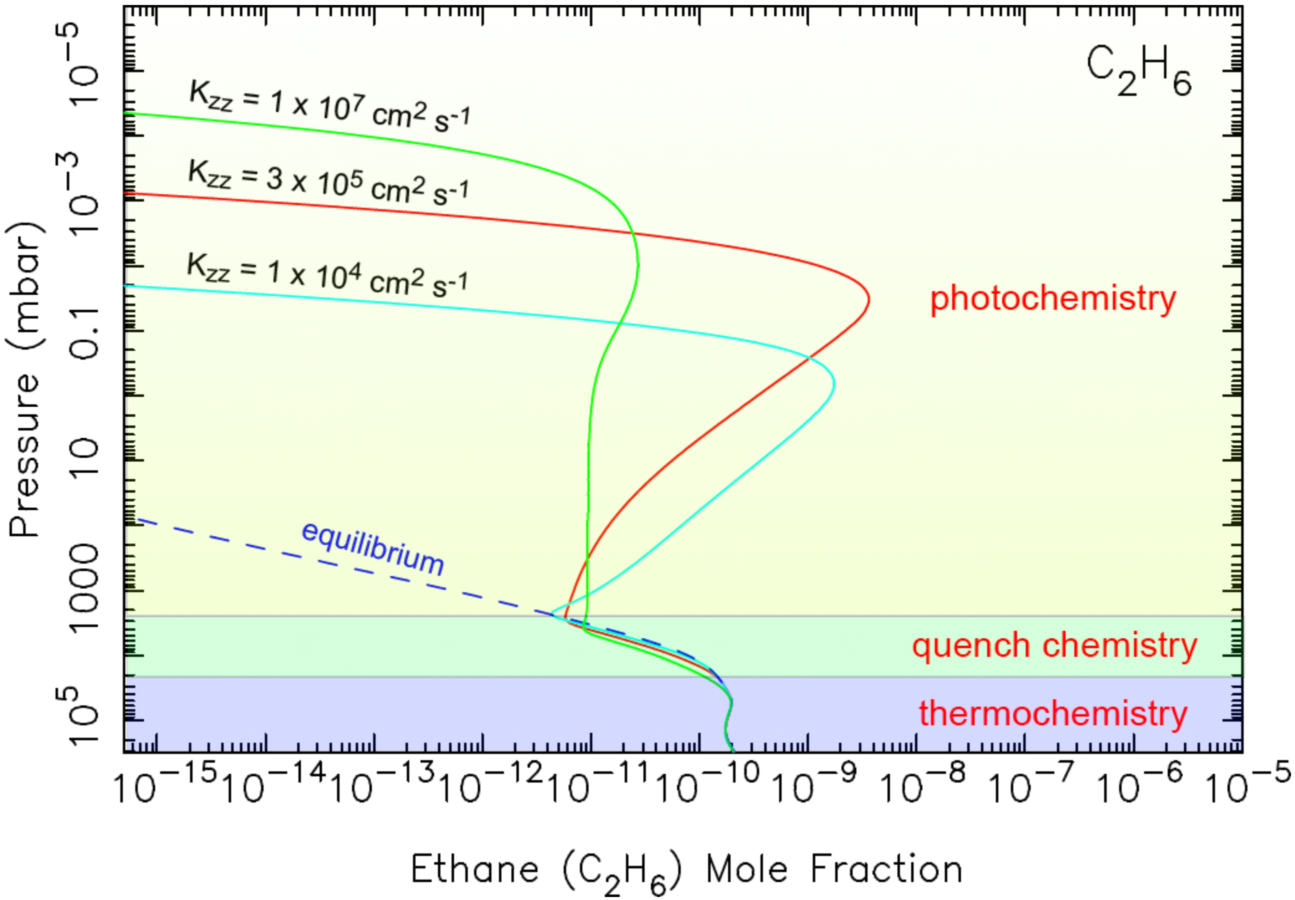


C_2H_6 chemistry on Gliese 229B

Exoplanet chemistry

- close-in exoplanets dominated by photochemical regime
  - UV flux 10,000x for HD209458b than for Jupiter
- very few photochemical models exist
  - Liang et al. 2003, 2004: simple hydrocarbons
  - Zahnle et al. 2010: sulfur chemistry
- how deep is thermochemical/photochemical crossover?

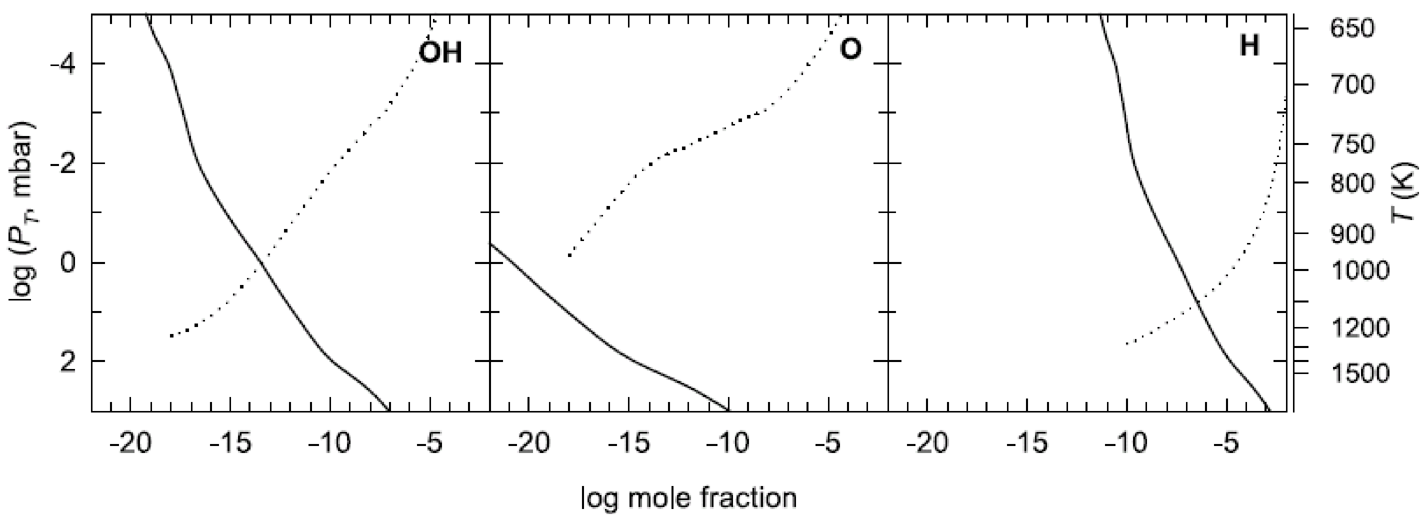
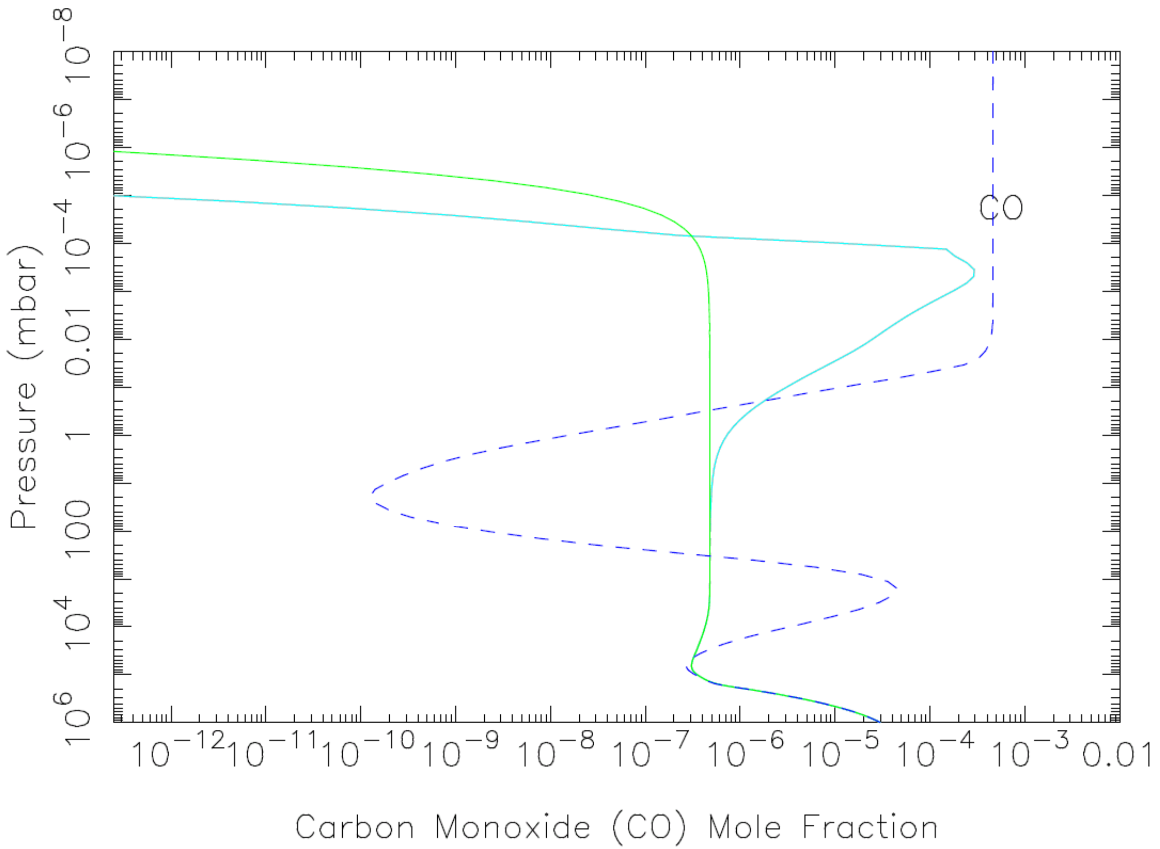


Figure 8, Visscher et al. 2006. HD209458b, solid lines: equilibrium, dotted lines: Liang et al 2003

Exoplanet chemistry: GJ436b

- GJ436b: transiting "hot Neptune": 22 M_{Earth}, 0.03 AU orbit around M dwarf
  - blue dashed line: equilibrium (reflects the unusual P-T profile)
  - green line: photochemistry turned off
  - blue line: photochemistry turned on – *very large flux*



Preliminary model results for GJ436b

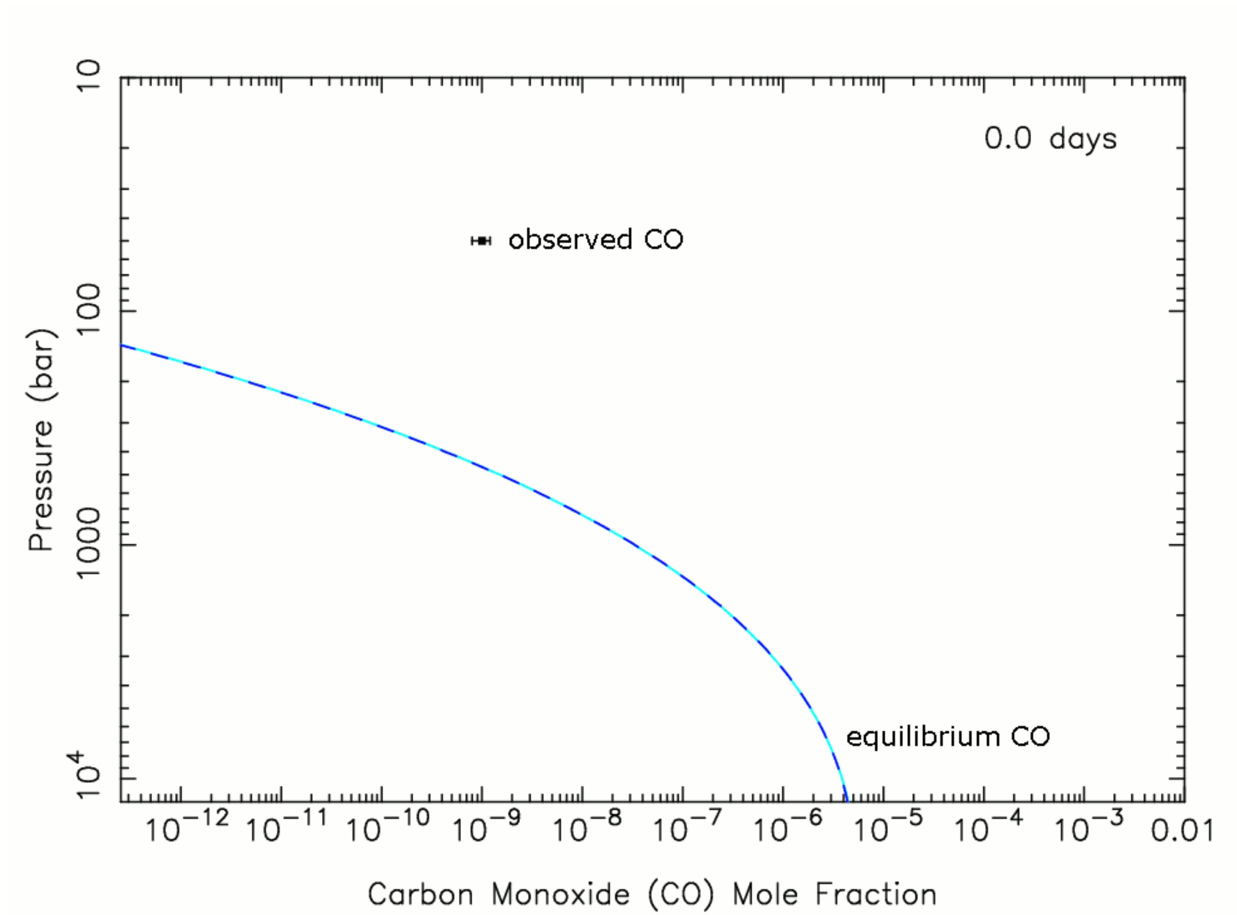
Outlook

- observed chemical behavior of any given substellar object depends upon atmospheric structure, atmospheric dynamics, and available UV flux
- cloud formation and disequilibrium effects have a strong influence on the spectral appearance of substellar objects
- exoplanet discoveries are driving planetary research:
  - how do planets evolve over time?
  - how do planetary systems form and evolve?
  - what atmospheric processes influence what we observe?
- current and future work: characterization of exoplanet atmospheres

Thank you

CO quenching chemistry

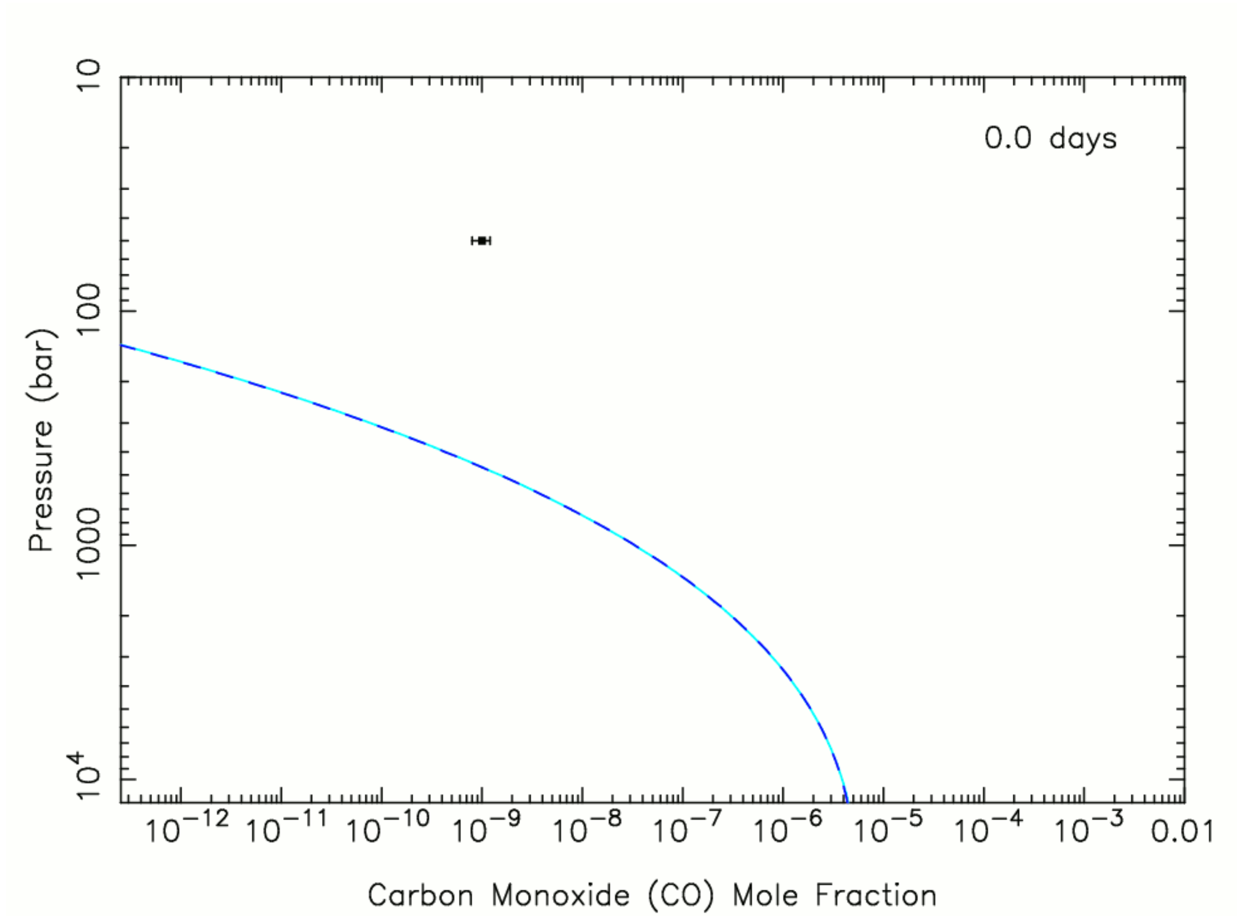
- atmospheric transport drives CO out of equilibrium
  - *quenching*: rate of mixing is faster than chemical reaction rates



CO chemistry in Jupiter's atmosphere at 1000 ppm water

CO quenching chemistry

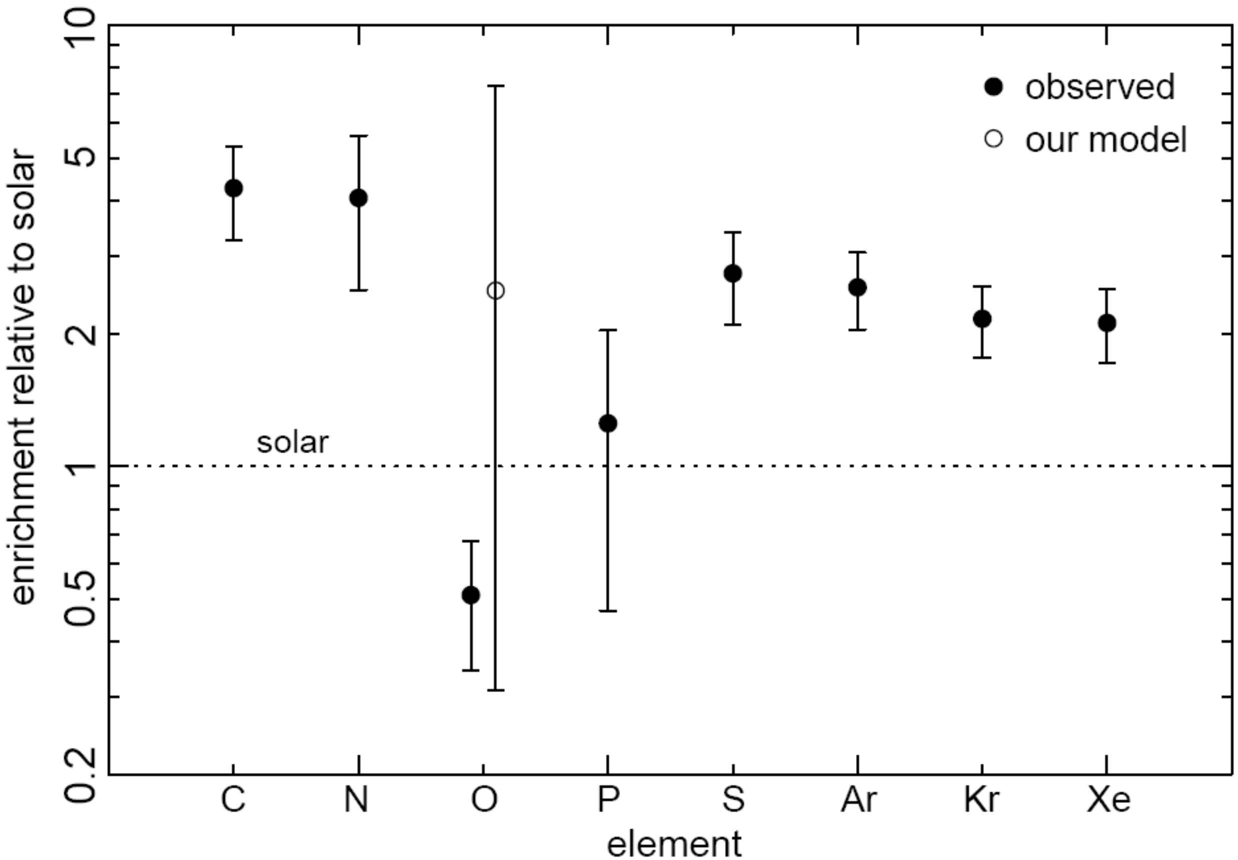
- atmospheric transport drives CO out of equilibrium
  - *quenching*: rate of mixing is faster than chemical reaction rates



CO chemistry in Jupiter's atmosphere at 1000 ppm water

Jupiter's Water Abundance: Results

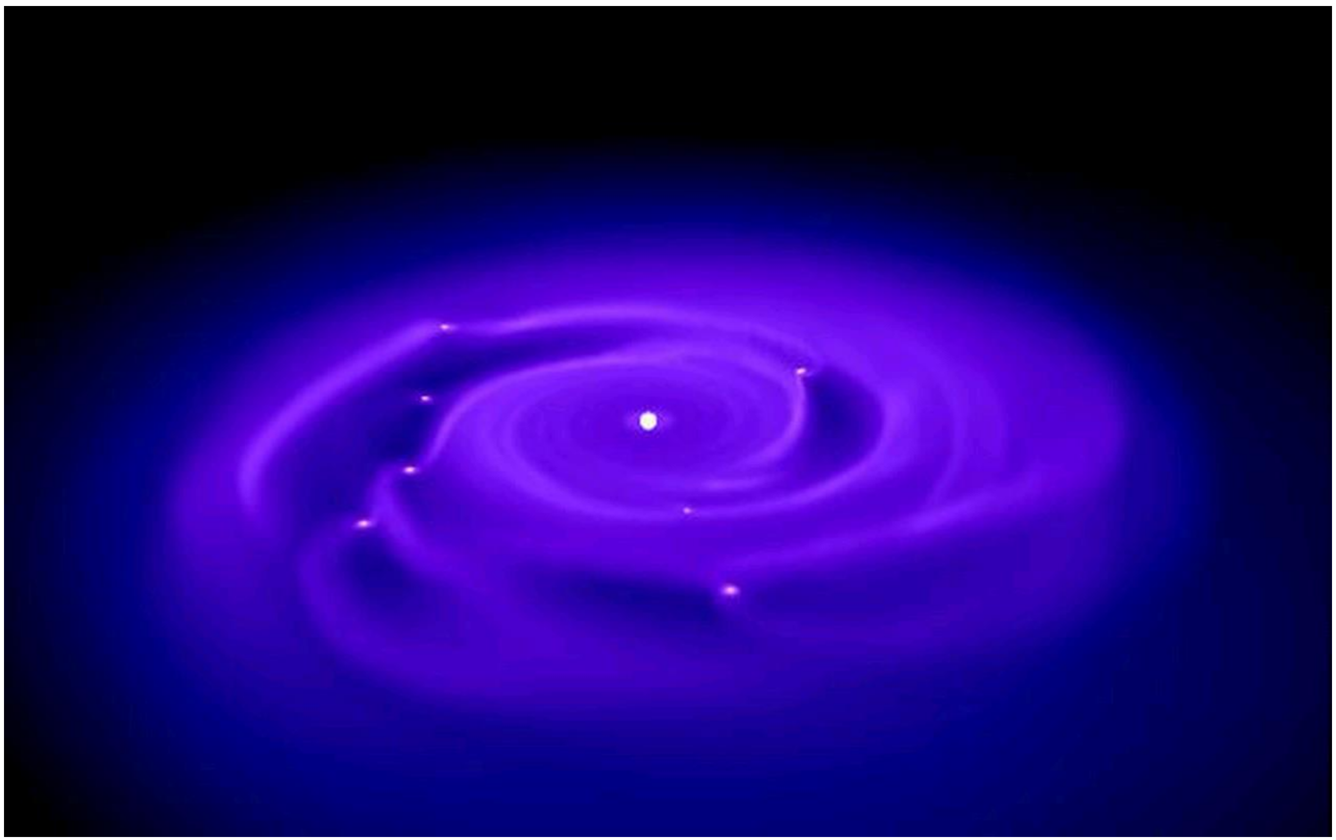
- our results suggest a water enrichment consistent with other heavy elements (relative to solar)
- rules out formation mechanisms which require large amounts of water (e.g. clathrate hydrates)



heavy element enrichments on Jupiter; Visscher et al 2010 (in press)

Jupiter's Water Abundance

- core accretion model: rock or rock/ice core initially forms
- continued accretion until it is massive enough to capture nebular gas (mostly H)
- how are heavy elements delivered? ice? clathrate hydrates? carbon-rich matter?



Planetary formation in a protoplanetary disk