

# Extrasolar Carbon Planets

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## ABSTRACT

We suggest that some extrasolar planets  $\lesssim 60 M_{\oplus}$  will form substantially from silicon carbide and other carbon compounds. Pulsar planets and low-mass white dwarf planets are especially good candidate members of this new class of planets, but these objects could also conceivably form around stars like the Sun. This planet-formation pathway requires only a factor of two local enhancement of the protoplanetary disk's C/O ratio above solar, a condition that pileups of carbonaceous grains may create in ordinary protoplanetary disks. Hot, Neptune-mass carbon planets should show a significant paucity of water vapor in their spectra compared to hot planets with solar abundances. Cooler, less massive carbon planets may show hydrocarbon-rich spectra and tar-covered surfaces. The high sublimation temperatures of diamond, SiC, and other carbon compounds could protect these planets from carbon depletion at high temperatures.

*Subject headings:* astrobiology — planets and satellites, individual (Mercury, Jupiter) — planetary systems: formation — pulsars, individual (PSR 1257+12) — white dwarfs

## 1. INTRODUCTION

The recent discoveries of Neptune-mass extrasolar planets by the radial velocity method (Santos et al. 2004; McArthur et al. 2004; Butler et al. 2004) and the rapid development

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of new technologies to study the compositions of low-mass extrasolar planets (see, e.g., the review by Kuchner & Spergel 2003) have compelled several authors to consider planets with chemistries unlike those found in the solar system (Stevenson 2004) such as water planets (Kuchner 2003; Leger et al. 2004). Here we describe a new possibility: extrasolar planets in which carbon is the most abundant component by number—carbon planets.

Recently, Lodders (2004) argued that the *Galileo*-measured abundances of CH<sub>4</sub> and H<sub>2</sub>O in Jupiter’s atmosphere imply that O is depleted by a factor of 4 and C is enriched by 1.7 relative to solar abundances, giving C/O = 1.8. She suggested that the planetary embryo that grew into Jupiter may have formed where the nebula was locally carbon-rich, and that Jupiter’s embryo was a carbon planet. This suggestion inspired our research; if Jupiter could have formed from a carbon-rich embryo, we would expect that carbon-rich embryos should be relatively common and occasionally observable as carbon planets. Although Lodders (2004) did not provide the only possible interpretation of the *Galileo* data, it seems reasonable that the solar nebula and other planetary systems could have formed large carbon-rich bodies. This Letter discusses formation scenarios for carbon planets (Section 2), their likely compositions (Section 3), and their possible appearances (Section 4).

## 2. FORMATION OF CARBON PLANETS

### 2.1. Condensation

If solar composition gas at  $10^{-4}$  bars is cooled slowly from high temperatures, several major building blocks of the solar system condense out one by one. First metal oxides and iron-peak elements condense at  $\sim 1500$  K, then silicates condense at 1200–1400 K, water at  $\sim 180$  K, and eventually, ammonia and methane at lower temperatures (e.g., Lodders 2003). This equilibrium condensation sequence apparently describes the gross compositions of the inner solar system planets: Fe and Ni cores surrounded by silicate mantles, topped by more complicated veneers containing water and more volatile compounds. Lewis (1974) connected these two trends, suggesting that the locations of the planets determined their compositions; the solar system terrestrial planets formed in hot regions of the solar nebula from high-temperature condensates while the planets with larger semi-major axes formed in cooler regions of the solar nebula from lower-temperature condensates. Some lower temperature condensates spread around the planetary system via small bodies late in the process of planet formation, coating planetary surfaces with volatiles. Although the details of this picture have evolved—chemical processing is thought to be quenched in the outer solar system, planets are now known to migrate, etc.—the equilibrium condensation sequence survives as a standard reference point for understanding the compositions of the solar system planets.

In gas with C/O ratio  $> 0.98$ , the condensation sequence changes dramatically (Larimer 1975). In carbon-rich gas, the highest temperature condensates ( $T \approx 1200\text{--}1600$  K) are carbon-rich compounds: graphite, carbides, nitrides, and sulfides. Since the sun has C/O ratio 0.5 (Asplund et al. 2005), carbon-rich condensation sequences are not ordinarily associated with planet formation, though they have been investigated at length in the context of the formation of silicon carbide (SiC) grains in meteorites (e.g., Lodders & Fegley 1995) and also in the context of outflows from evolved stars (e.g., Lodders & Fegley 1997, 1999).

Low-mass planets formed via these carbon-rich condensation sequences would be carbon planets, initially composed largely of the high-temperature condensates formed in carbon-rich gas, like graphite and silicon carbide.

## 2.2. Formation Scenarios

Some protoplanetary disks may spawn many carbon planets simply because they are especially rich in carbon overall, and planet formation proceeds by a carbon-rich condensation sequence. The planets around the pulsar PSR 1257+12 (Wolszczan & Frail 1992) might have been formed in a carbon-rich nebula created by the disruption of either a carbon-rich star or of a white dwarf (Tutukov 1991; Podsiadlowski et al. 1991; Phinney & Hansen 1993); perhaps these pulsar planets are carbon planets. These mechanisms may also operate around white dwarfs (Livio et al. 1992). In general, C/O ratios in stars and H II regions increase with metallicity and towards the galactic center (e.g., Esteban et al. 2005), as reflected in galactic chemical evolution models (e.g., Gavilán et al. 2005); planets detected by microlensing may stand a better-than-average chance of being carbon planets because they are closer to the galactic center than the Sun. Stars that host extrasolar planets are on average enhanced in metals, including carbon, and often show 10–15% enhancements in C/O ratio compared to the sun (Gonzalez et al. 2001).

The formation of carbon planets in our own solar nebula is also consistent with our current understanding of planet formation. Lodders (2004) suggested that the orbital radius in the solar nebula corresponding to a temperature of 350 K should be called the “tar line” by analogy to the snow line (the orbital radius where water ice sublimates), and that a high concentration of carbon should accumulate there as carbon diffuses outward from interior to that radius and as carbon-rich grains spiral inwards toward that radius. Condensation lines like the tar line described by Lodders (2004) now seem less important for accumulating material than they used to, since new calculations of the Prandtl numbers in turbulent disks imply that outward chemical diffusion is likely too slow to play a major role (Carballido et al. 2005). However, the inward spiral of solid grains probably can substantially influence

disk carbon chemistry. Youdin & Chiang (2004) showed that over  $10^5$  years, gas drag can augment the concentration of solid grains in the central 2 AU of a protoplanetary disk by factors of 10–100; this concentration of solids can trigger gravitational instability of the solid layer in a quiescent disk (Goldreich & Ward 1974). In such high concentrations, the material imported by the grains dominates the total C/O ratio in the disk. Observations of PAH features in Herbig Ae stars provide strong evidence for the presence of carbon-rich grains in these disks. If the grains in protoplanetary disks have C/O ratios even slightly greater than 1, as some models of the spectra of Herbig Ae stars suggest (Habart et al. 2004), the particle-pileup mechanism of Youdin & Chiang (2004) naturally leads to the formation of carbon planets where the particles pile up.

A mechanism that could prevent this particle pileup process from forming carbon-planets would be one that spreads condensates outward from the hot center of the disk near the star faster than gas drag can bring in the carbon-rich particles. For example, some kinds of turbulence can conceivably spread silicate grains around in a protoplanetary disk faster than the carbon-rich grains pile up, as could X-winds (Shu et al. 2001). However, the time-scale for gas drag is reasonably short, and turbulent mixing is not likely to be efficient throughout the disk, and the solid mass processed by winds is uncertain and likely highly variable from system to system. It is conceivable that these processes that spread nebular solids were effective at spreading solar composition equilibrium condensates throughout the inner  $\sim 2$  AU of the solar system, but that outside this region relatively carbon-rich bodies formed.

### 2.3. Carbonaceous Chondrites and Fischer-Trope-Type Reactions

Besides possibly Jupiter, carbonaceous chondrites demonstrate the presence of planet-forming processes operating far from the chemical equilibrium condensation sequence for solar-composition gas (see the review by Krot et al. 2000). Carbonaceous chondrites are found with up to  $\sim 6\%$  carbon (Grady et al. 2002) in the form of long-chain carbonaceous compounds and smaller amounts of silicon carbide, graphite, and even diamond. This mass fraction of carbon greatly surpasses that of the Earth, which is only  $10^{-5}$ – $10^{-4}$  carbon by mass (Lodders & Fegley 1998). It is likely that the more carbon-rich meteorites are oxidized on impact and never recovered. In standard equilibrium condensation sequence for solar-composition gas, carbon in the solar nebula remains entirely in the gas phase as CO at high temperatures and CH<sub>4</sub> at low temperatures except where temperature drops below  $\sim 78$  K (Lewis 1972). At  $\sim 78$  K, CH<sub>4</sub> becomes trapped in water ice as a clathrate hydrate. In this picture, we should expect carbon to be found only as methane, mostly on the outermost planets or in small quantities on the surfaces of inner planets, and always in combination with

large quantities of water from the ice that trapped the methane. Yet the parent bodies of the carbonaceous chondrites are likely C-type asteroids that formed at much higher nebular temperatures than 78 K.

Krot et al. (2000) reviewed some of the sources of solid carbon in carbonaceous chondrite formation, describing three potentially important processes:

*Local C/O Enhancement:* Some regions of the solar nebula may have had C/O ratios  $> 0.98$ , yielding the high-temperature carbon-rich condensates described above.

*Direct Incorporation of ISM Carbon:* The presence of pre-solar materials, including diamonds (e.g., Huss & Lewis 1995), in meteorites demonstrates that some of the carbonaceous material from the molecular cloud out of which the protoplanetary nebula formed was preserved in the solar nebula and directly incorporated into protoplanetary material. Up to half of all carbon in the interstellar medium exists as organic solids (Ehrenfreund & Charnley 2000), including amorphous carbon, coal, soot, quenched-carbonaceous condensates, diamonds and other compounds. Larger carbon-bearing molecules such as polycyclic aromatic hydrocarbons (PAHs), fullerenes, and long-chain carbon compounds are present in ISM gas and incorporated into ISM dust grains (Ehrenfreund & Charnley 2000).

*Fischer-Trope-type reactions (FTTs):* Nebular grains may undergo surface-mediated Fischer-Trope-type reactions, in which transition metals promote the conversion of nebular CO and H<sub>2</sub> into hydrocarbons at relatively high temperatures.

Besides the accumulation of imported carbon-rich ISM grains, FTTs may also contribute to the formation of carbon planets. Laboratory evidence suggests that grain surfaces poisoned with FTT reaction products also mediate FTTs; this cyclic process can conceivably convert as much as half of the disk’s gaseous carbon to solid organics (J. Nuth 2004, private communication) at temperatures of  $\sim 500$  K where FTTs are most efficient (Llorca & Casanova 1998; Kress & Thielens 2001).

### 3. COMPOSITION AND SURVIVAL OF CARBON PLANETS

Our picture of the composition of carbon planets stems from the equilibrium condensation sequence for C/O enriched nebular gas; this analogy could be expected to extend to a wide variety of planetary structures and compositions. But now let us be more specific, and hereafter refer to a planet as a carbon planet only if carbon is its most abundant component by number. This definition excludes Jupiter-mass planets with carbon-rich cores (Lodders

2004) and marginally excludes the extremely CO-rich gas giants that might be found around pulsars or massive white dwarfs (Livio et al. 1992). These CO-rich gas giants could form in accretion disks created from the disruption of a C-O white dwarf, disks that contain hundreds of Jupiter masses of carbon and oxygen and scarcely any hydrogen. They would probably contain roughly equal parts carbon and oxygen.

Carbon planets, by our definition, are likely to be less massive planets without massive gas envelopes to dilute the carbon content. Such low-mass planets could form like terrestrial planets, as carbon-rich embryos that were too small to acquire a gaseous envelope and evolve to a gas giant planet. The masses of such failed embryos can range up to  $\sim 60 M_{\oplus}$  (Rafikov 2004). Alternatively, carbon planets could form as gas-giant planets that migrate inward and lose their gaseous envelopes. Gas envelope loss close to the parent star could occur either by hydrodynamic escape associated with stellar UV and extremely high exospheric temperatures (e.g., Lecavelier des Etangs et al. 2004) or by Roche-lobe overflow, a mechanism that may help park migrating planets at small orbital periods (Trilling et al. 1998; Gu et al. 2003; McArthur et al. 2004).

Now we can return to the carbon-rich equilibrium condensation picture. This picture probably describes the gross internal structure of carbon planets. FTTs and direct incorporation of ISM carbon can also help provide solid carbon enrichment, but the high temperatures of planet accretion should process planetary interiors to near chemical equilibrium after these non-equilibrium mechanisms would operate. In this equilibrium picture, carbon planets should be composed of SiC, graphite and a lesser amount of other minerals that form in a reducing environment (see Fegley & Cameron 1987; Cameron et al. 1988), with cores made of iron and iron-peak elements and surface layers of graphite and delivered volatiles.

Carbon condensation is strikingly different from the oxygen-rich condensation sequence because of the availability of graphite as a high-temperature condensate; there is no analogous high temperature condensate of pure oxygen. In a typical condensation sequence for carbon enriched gas (Lodders & Fegley 1997), CO forms, using up all of the oxygen, and then carbon left over from CO formation (called “condensable carbon”) condenses as SiC or TiC using up about half of the Si (e.g., Lodders & Fegley 1997). Most of the carbon left over after SiC and TiC formation condenses as graphite; the higher the C/O ratio, the more graphite forms. Pure carbon can dissolve in metals and in the planet’s carbide mantle, but since graphite is less dense than SiC ( $2 \text{ g cm}^{-3}$  compared to  $3.2 \text{ g cm}^{-3}$ ), we might expect a pure carbon layer to form on top of the SiC in a completely differentiated planet.

Using this basic picture of planetary composition dictated by carbon-rich condensation, Fegley & Cameron (1987) and Cameron et al. (1988) discussed carbon planets in terms of what Mercury would have been like if it formed in a carbon-rich environment. In their

discussion, graphite would be the predominant form of carbon by mass, yielding a planet of lower density than silicate or iron planets. They discuss the changes in planetary composition as a function of C/O ratio, including the specific presence and absence of minerals found in enstatite chondrites, the formation of  $\text{Fe}_3\text{C}$  and  $\text{FeSi}$  alloys instead of pure Fe, and the presence of SiC and other unusual minerals like CaS, TiN and AlN.

A possible concern about the existence of carbon planets is that they could be threatened by collisional devolatilization. However, although carbon is usually considered a volatile in the solar system this concern about carbon planets is likely unwarranted. On carbon planets, large amounts of carbon can be locked into refractory compounds, as oxygen is on Earth. For example, SiC is a sturdy ceramic used for lining the cylinders of motorcycle engines; it remains solid until temperatures of  $\sim 2800$  K at pressures of 35 bars (Tairov & Tsvetkov 1988). Although graphite should emerge as a surface layer in a differentiated carbon planet, a few km into the planet’s interior at a pressure of  $\sim 10^5$  bars, pure carbon in a cool carbon planet should turn to diamond. Diamond remains solid up to temperatures of at least 4000 K under a thin atmosphere (Grumbach & Martin 1996). If the pure carbon in a carbon planet does not completely partition into the core or mantle, the resulting diamond shell could protect the planet from strong stellar radiation even as close 0.03 AU from a solar-type star, where other volatiles would easily be stripped.

#### 4. APPEARANCE OF EXTRASOLAR CARBON PLANETS

Since all we can see of a planet is its surface and atmosphere, it is difficult to confidently ascertain the bulk composition of a planet—this holds true even for planets in our own solar system. However, under some circumstances, carbon planets may contain distinguishing spectral features that we can recognize from far away. The low densities expected for carbon planets, between those of water planets (Kuchner 2003; Leger et al. 2004) and silicate planets, may provide one more clue to their presence.

We will discuss the potentially recognizable properties of carbon planets in two rough size ranges that we will refer to as “Earth mass” and “Neptune mass”. By Earth-mass planets ( $\lesssim 10 M_\oplus$ ) we mean those with thin secondary atmospheres like the terrestrial planets in the solar system. These planets have too low a mass to retain the primary hydrogen atmospheres they acquire hydrostatically from their protoplanetary disks. By Neptune-mass planets, we mean  $\sim 10\text{--}60 M_\oplus$  planets that retained thick primary atmospheres like those of Uranus and Neptune, planets whose rocky surfaces are too deep to see at any wavelength.

### 4.1. Neptune-Mass Carbon Planets

Neptune-mass carbon planets can have atmospheres massive enough not to be dominated by volatiles delivered by late impacts of comets and asteroids; their atmospheres are probably mostly H, like the atmospheres of Uranus and Neptune. However, since the atmospheres of these Neptune-mass carbon planets would have formed in contact with a large reservoir of carbon they likely have large C/O ratios. Pollution by late carbon-rich impactors could conceivably generate a high atmospheric C/O ratio on a planet that is not a carbon planet, so finding a planet with a carbon-rich atmosphere does not guarantee that the planet is a carbon planet. But we can begin to understand the appearance of a Neptune-mass carbon planet by investigating a Neptune-mass planet with a large atmospheric C/O ratio.

We explored the equilibrium chemistry of a Neptune-mass planet’s atmosphere using a Gibbs free energy minimization chemical equilibrium calculation (Seager 1999; Seager et al. 2000). We modeled atmospheres with the H and He fractional abundances like those of Neptune’s atmosphere ( $\text{H}_2 = 80\%$ ,  $\text{He} = 19\%$ ). We considered two cases: an atmosphere with metals in the same relative abundances as found in the solar photosphere, (e.g.,  $\text{C/O} = 0.5$ ) and an atmosphere similar to the first but with  $\text{C/O} = 1.01$ .

Figure 1 summarizes the equilibrium chemistry for CO,  $\text{CH}_4$ , and  $\text{H}_2\text{O}$  as a function of temperature and pressure for these two cases. In the blue regions,  $\text{H}_2\text{O}$  is abundant, at  $\geq 0.1 \times$  the CO number density. In the red regions,  $\text{H}_2\text{O}$  is relatively scarce. A series of dotted lines in each panel indicate contours of the  $\text{H}_2\text{O}$  concentration at  $\text{H}_2\text{O}/\text{CO} = 1, 0.1, \dots, 10^{-8}$ . At high temperatures, CO is the dominant carbon-bearing molecule, and at low temperatures  $\text{CH}_4$  is the dominant carbon-bearing molecule; thick dashed lines indicate the temperatures and pressures where CO and  $\text{CH}_4$  have equal abundances.

Cold planets will have temperature-pressure profiles residing largely in the left side of Figure 1, where  $\text{H}_2$ ,  $\text{CH}_4$  and  $\text{H}_2\text{O}$  dominate in both the  $\text{C/O}=0.5$  case and the  $\text{C/O}=1.01$  case. So cold Neptune-mass planets will have similar dominant spectral absorption features whether they have  $\text{C/O} = 0.5$  or  $\text{C/O} = 1.01$ . Planets with C/O ratios even greater than 1.01 will have a similar chemical equilibrium profile to those with  $\text{C/O} = 1.01$ , though planet atmospheres richer in carbon will have lower  $\text{H}_2\text{O}/\text{CO}$  ratios, higher  $\text{CH}_4/\text{H}_2\text{O}$  ratios and a  $\text{CH}_4$ -dominated region at slightly higher temperatures. The cold Neptune-mass carbon planets, therefore, will be difficult to recognize as carbon planets because their spectra should be very similar to other planets with solar-system abundances; though they may be carbon enriched, their spectra should be dominated by  $\text{CH}_4$  and  $\text{H}_2\text{O}$ . The limited spectroscopic capabilities expected for extrasolar planet observations may make identification of such cold carbon planets impossible.

Hot Neptune-mass carbon planets, on the other hand, will have temperature-pressure profiles stretching into the right side of Figure 1, where, as Figure 1 shows, the atmospheric chemistry is a strong function of C/O ratio. These planets will have a low atmospheric abundance of H<sub>2</sub>O, the molecule that normally dominates the spectra of hot planets. In atmospheres of hot planets with C/O < 1, H<sub>2</sub>, H<sub>2</sub>O and CO molecules dominate the chemistry. For hot planets with C/O > 1, H<sub>2</sub> is still the most abundant atmospheric molecule, but CO is the main O-bearing molecule and H<sub>2</sub>O is scarce.

Figure 2 shows the significant differences between the spectrum of a hot Neptune-mass planet with C/O = 0.5 and the spectrum of a hot Neptune-mass carbon planet with C/O = 1.01. We computed the spectra with a 1D radiative transfer code described in Seager et al. (2005). We computed the temperature-pressure profile using a 1D radiative-transfer/radiative equilibrium/hydrostatic equilibrium code (Seager et al. 2000, 2005) for a cloud-free planet with Neptune’s mass and radius and C/O=0.5 located 0.04 AU from a G8V star. This temperature-pressure profile appears in Figure 1 as a solid curve in each plot. Although atmospheres of different compositions should have somewhat different temperature-pressure profiles because of their different interactions with stellar radiation, for this exploratory calculation we made the approximation of using the same profile for both synthetic spectra.

Besides water abundance, a second likely major difference between hot carbon planets and hot solar-system-abundance planets is the grain chemistry. The solar-system abundance planets are likely to have Fe clouds and silicate clouds, whereas the carbon planets are likely to have Fe clouds, SiC clouds, and graphite clouds. Graphite clouds can be dark—much darker than silicate clouds. Graphite clouds tend to deplete carbon until the gas C/O ratio is near 1 (Lodders & Fegley 1997); this possibility is why we assumed a C/O ratio only slightly greater than 1 in our carbon-rich models. In a carbon-rich atmosphere containing hydrogen and some iron grains or other suitable catalyst, atmospheric FTTs can potentially slowly convert CO into methane. These details will need to be incorporated into a more sophisticated carbon-rich model atmosphere.

The reducing atmospheres of cold Neptune-mass carbon planets should also allow for photochemical hydrocarbon synthesis, as the atmospheres of solar system giant planets do (e.g., Strobel 1983; Gladstone et al. 1996). For example, the atmospheres of all the giant planets in the solar system contain ethane (C<sub>2</sub>H<sub>6</sub>) and acetylene (C<sub>2</sub>H<sub>2</sub>) identifiable via infrared bands at 3.3–3.4 μm and 11.6–12.4 μm (ethane) and 2.9–3.2 μm and 13.7 μm (acetylene) (Rothman et al. 1992).

## 4.2. Earth-Mass Carbon Planets

Carbon planets with little or no atmosphere may be even harder to recognize spectroscopically than the cold Neptune-mass carbon planets. Such low-mass carbon planets could have undergone dramatic atmospheric evolution and therefore will have a wide variety of appearances, comparable to the variety of silicate planets seen in the solar system (i.e., Earth, Venus and Mars).

Earth-mass carbon planets would probably not have atmospheric  $\text{CO}_2$ , the dominant atmospheric molecule on Mars and Venus. The surface layers of terrestrial planets, including their atmospheres, are shaped by the delivery of low-temperature condensates that were not processed to chemical equilibrium. A variety of delivery agents may be important (e.g., Kuchner et al. 2004), but we can take a comet as an example. A comet contains both graphite and silicates and metal oxides in its core, materials that would combust if heated, releasing CO. When a comet arrives at a terrestrial planet, it meets an oxygen-rich environment where water and silicates can survive while the delivered carbon is easily oxidized. When a comet arrives at a carbon planet, it meets a reducing environment, and a carbon-rich surface to stir up and chemically interact with. Here delivered carbon can survive, while the water is easily converted to CO, H<sub>2</sub>, and hydrocarbons, and the silicates are easily converted to carbides. So the hallmark of a terrestrial-mass carbon planet's atmosphere might be the absence of oxygen-rich gases like  $\text{CO}_2$ ,  $\text{O}_2$ ,  $\text{O}_3$ , etc., and the dominance of CO, or, on a cold carbon planet,  $\text{CH}_4$ .

Some Earth-mass carbon planets in short-period orbits may have lost most or all of their atmospheres from atmospheric escape, revealing their solid surfaces. Such planets would be stable near their host stars, protected by graphite, diamond, or silicon carbide shells. We would expect carbon planets with no atmosphere to be dark, with relatively featureless spectra at visible wavelengths like the graphite-rich rock of carbonaceous chondrites, since an admixture of a few percent of small carbon grains in a rock that would otherwise be light-colored readily damps spectral features from other minerals (Clark 1983).

Cold low-mass carbon planets could also foster the long-term survival of photochemically-synthesized long-chain carbonaceous compounds that would be burned to CO in more oxidizing atmospheres. These compounds can rain onto the planet's surface, creating tar oceans like those proposed for Titan (Hunten 1992; Lunine 1993). So a carbon planet that has lost its atmosphere could conceivably retain a coating of long-chain carbon compounds, i.e., tar.

## 5. SUMMARY AND DISCUSSION

A logical companion to the picture championed by Lewis (1972) and others for planet formation via the equilibrium condensation sequence for solar composition gas is planet formation via equilibrium condensation of carbon-rich gas. A mere factor of 2 increase in the C/O ratio beyond solar leads to a different new suite of carbon-rich high temperature condensates. We briefly explored some planet-formation scenarios that would lead down this path and discussed their likely products, carbon planets composed largely of SiC, graphite, and lesser amounts of other carbides and minerals that form in a reduced environment. These planets would also likely contain metal cores and possibly contain graphite or diamond layers.

We also discussed the observational signatures of carbon planets. The CO-dominated spectra of hot Neptune-mass carbon planets should distinguish them from the H<sub>2</sub>O-dominated spectra of hot Neptune-mass planets with solar-composition atmospheres (Figure 2). Cold carbon planets of all sizes could have stable long-chain hydrocarbons in their atmospheres and on their surfaces that would be destroyed in a more oxidizing environment. Diamond or graphite shells can protect carbon planets from devolatilization by heat and ionizing radiation as close as a few stellar radii from a solar-type star.

Planets around pulsars and white dwarfs are good candidates for carbon planets; they could have formed in a carbon-rich nebulae created by the disruptions of carbon-rich stars or white dwarfs. Carbon planets should be more common around more metal-rich stars and stars near the Galactic center such as microlensing targets. Given the slow increase in Galactic C/O ratio with time, there may even come a day when the C/O ratio of nearby star forming regions is so high that all new planets formed in the solar neighborhood are carbon planets. Our current picture of planet formation is also consistent with carbon planets forming in protoplanetary disks like the solar nebula; particle pileups (Youdin & Chiang 2004) of carbon-rich grains from the ISM can create the needed carbon-rich environment.

Carbon planets may soon regularly turn up in transit studies and in searches for extra-solar Earth analogs. The possibility of low-mass carbon-planets suggests that a key element of characterizing planets with the Terrestrial Planet Finder (TPF) missions should be determining whether their atmospheres are oxidizing or reducing. It is tempting to rely on the presence of CO<sub>2</sub> as a hallmark of terrestrial planets; but if low-mass carbon planets are common, many small planets may not share this feature.

What other possible kinds of planets are there? The planet zoo now contains silicate planets (e.g., Earth and Mars), hydrogen and helium planets (e.g., Jupiter and Saturn), water planets (which perhaps we might think of as oxygen planets), iron planets (Stevenson 2004), and carbon planets. A glance at a table of solar abundances suggests that next we

might consider helium, neon, and nitrogen planets. Neon seem disadvantaged as planet-building material because of its chemical inertness. However, some AGB stars could have envelopes greatly enriched in nitrogen (Dominy 1984), possibly suggesting a mechanism for forming nitrogen-enriched planets.

Could there be life on a carbon planet? Life on Earth appears to owe its existence to the presence of carbon and water and other volatile compounds delivered late in the planet-formation process in trace quantities. It is reasonable to think that the chemical microcosm required to support life could likewise be delivered to the surface of a terrestrial-mass carbon planet. One thing seems likely—if a carbon planet hosted intelligent creatures, they would not go to war over such a common trifle as carbonaceous fuels.

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## REFERENCES

- Asplund, M., Grevesse, N., Sauval, A. J., Allende Prieto, C., Blomme, R. 2005, *A&A*, 431, 693
- Butler, R. P. et al. 2004, (astro-ph/0408587)
- Cameron, A. G. W., Benz, W., Fegley, B. J., & Slattery, W. L. 1988, in *The strange density of Mercury - Theoretical consideration*, Mercury, University of Arizona Press, p.692
- Carballido, A., Stone, J. M. & Pringle, J. E. 2005, to appear in *MNRAS*
- Clark, R. N., 1983, *J. Geophys. Res.* 88, 10635
- Des Marais, D. J., 2002, *Astrobiology*, 2, 153
- Domini, J. F. 1984, *ApJS*, 55, 27
- Ehrenfreund, P. & Charnley, S. B. 2000, *ARA&A*, 38, 427
- Esteban, C., Garcia-Rojas, J., Peimbert, M., Peimbert, A., Ruiz, M. T., Rodriguez, M., & Carigi, L. 2004, *ApJ*, 618, L95
- Fegley, B. & Cameron, A. G. W, 1987, *E&PSL*, 82, 207

- Gavilán, M., Buell, J. F., & Mollá, M. 2005, *A&A*, 432, 861
- Gladstone, G. R., Allen, M. & Yung, Y. L. 1996, *Icarus*, 119, 1
- Goldreich, P. M. & Ward, W. R. 1974, *ApJ*, 183, 1051
- Gonzalez, G., Laws, C., Tyagi, S., & Reddy, B. E. 2001, *ApJ*, 121, 432
- Grady, M. M., Verchovsky, A. B., Franchi, I. A, Wright, I. P. & Pillinger, C. T. 2002, *Meteor. & Planet. Sci.*, 37, 713
- Grumbach, M. P. & Martin, R. M. 1996, *Phys. Rev. B*, 54, 15730
- Gu, P.-G., Lin, D. N. C., & Bodenheimer, P. H. 2003, *ApJ*, 588, 509
- Habart, E., Natta, A., Krgel, E. 2004, *A&A*, 427, 179
- Hunten, D. M. 1992, in *Proceedings Symposium on Titan*, Eur. Space Agency Spec. Publ., SP-338, 37
- Huss, G. R. & Lewis, R. S. 1995, *Geochim. Cosmochim. Acta*, 59, 115
- Kress, M. E. & Tielens, A. G. G. M. 2001, *M&PS*, 36, 75
- Krot, A. N., Fegley, B., Jr., Lodders, K., Palme, H. 2000, *Protostars and Planets IV*, eds Mannings, V., Boss, A. P., & Russell, S. S. (Tucson: University of Arizona Press), 1019
- Kuchner, M. J. 2003, *ApJ*, 596, 105
- Kuchner, M. J. & Spergel, D. N. 2003, in *ASP Conf. Ser. 294, Scientific Frontiers in Research on Extrasolar Planets*, ed. D. Deming & S. Seager (San Francisco:ASP), (astro-ph/0305522)
- Kuchner, M. J., Youdin, A. & Bate, M. 2004, in preparation.
- Larimer, J. W. 1975, *Geochim. Cosmochim. Acta*, 39, 389
- Lecavelier des Etangs, A., Vidal-Madjar, A., McConnell, J. C. & Hébrard, G. 2004, *A&A*, 418, L1
- Leger et al. 2004, *Icarus*, 169, 499
- Lewis, J. S. 1972, *Icarus*, 16, 241

- Lewis, J. S. 1974, *Science*, 186, 440
- Livio, M., Pringle, J. E., & Saffer, R. A. 1992, *MNRAS*, 257, 15p
- Llorca J. & Casanova, I 1998, *M&PS*, 33, 243
- Lodders, K. 2003, *ApJ*, 591, 1220
- Lodders, K. 2004, *ApJ*, 611, 587
- Lodders, K. & Fegley, Jr., B. 1995, *Meteoritics*, 30, 661
- Lodders, K. & Fegley, Jr., B. 1997, in *Astrophysics Implications of the Laboratory Study of Presolar Materials*, edited by T. J. Bernatowicz & E. K. Zinner.
- Lodders, K. & Fegley, Jr., B. 1998, *The Planetary Scientist's Companion*, Oxford University Press, New York, p. 83
- Lodders, K. & Fegley, Jr., B. 1999, *Asymptotic Giant Branch Stars*, I.A.U. Symposium 191, 279
- Lunine, J. I. 1993, *Rev. Geophys.*, 31, 131
- McArthur, B., et al. 2004, (astro-ph/0408585)
- Phinney, E. S. & Hansen, B. M. S. 1993, *Planets Around Pulsars*, ASP Conference Series, J. A. Phillips, J. E. Thorsett & S. R. Kulkarni eds., Vol. 36, 371
- Podsiadlowski, P., Pringle, J. E. & Rees, M. J. 1991, *Nature*, 352, 783
- Rafikov, R. 2004, submitted to *ApJ*, (astro-ph/0405507)
- Rothman, L. S., et al. 1992, *J. Quant. Spectrosc. Radiat. Transfer* 48, 469
- Santos, N. C. et al. 2004, *A&A*, in press, (astro-ph/0408471)
- Seager, S. 1999, Ph.D. Thesis, Harvard University
- Seager, S., Richardson, L. J., Hansen, B. M. S., Menou, K., Cho, J. Y-K. & Deming, D. 2005, submitted to *ApJ*
- Seager, S., Whitney, B. A. & Sasselov, D. D. 2000, *ApJ*, 540, 504
- Shu, F. H., Shang, H., Gounelle, M., Glassgold, A. E. & Lee, T. 2001, *ApJ*, 548, 1029
- Stevenson, D. 2004, *Physics Today*, April, p. 43

Strobel, D. F. 1983, *Int. Rev. Phys. Chem.*, 3, 145

Tairov, Yu. M. & Tsvetkov, V. F. 1988, in *Handbook on Electrotechnical Materials* Eds. Koritskii, Yu.V., V.V. Pasynkov, B.M. Tareev, Vol.3, Sec.19, “Semiconductor Compounds AIV BIV”, *Energomashizdat, Leningrad*, p. 446

Trilling, D. E. et al. 1998, *ApJ*, 500, 428

Tutukov, A. V. 1991, *Soviet Astr.* 35, 415

Wolszczan, A. & Frail, D. A. 1992, *Nature*, 355, 145

Youdin, A. N. & Chiang, E. I. 2004, *ApJ*, 601, 1109

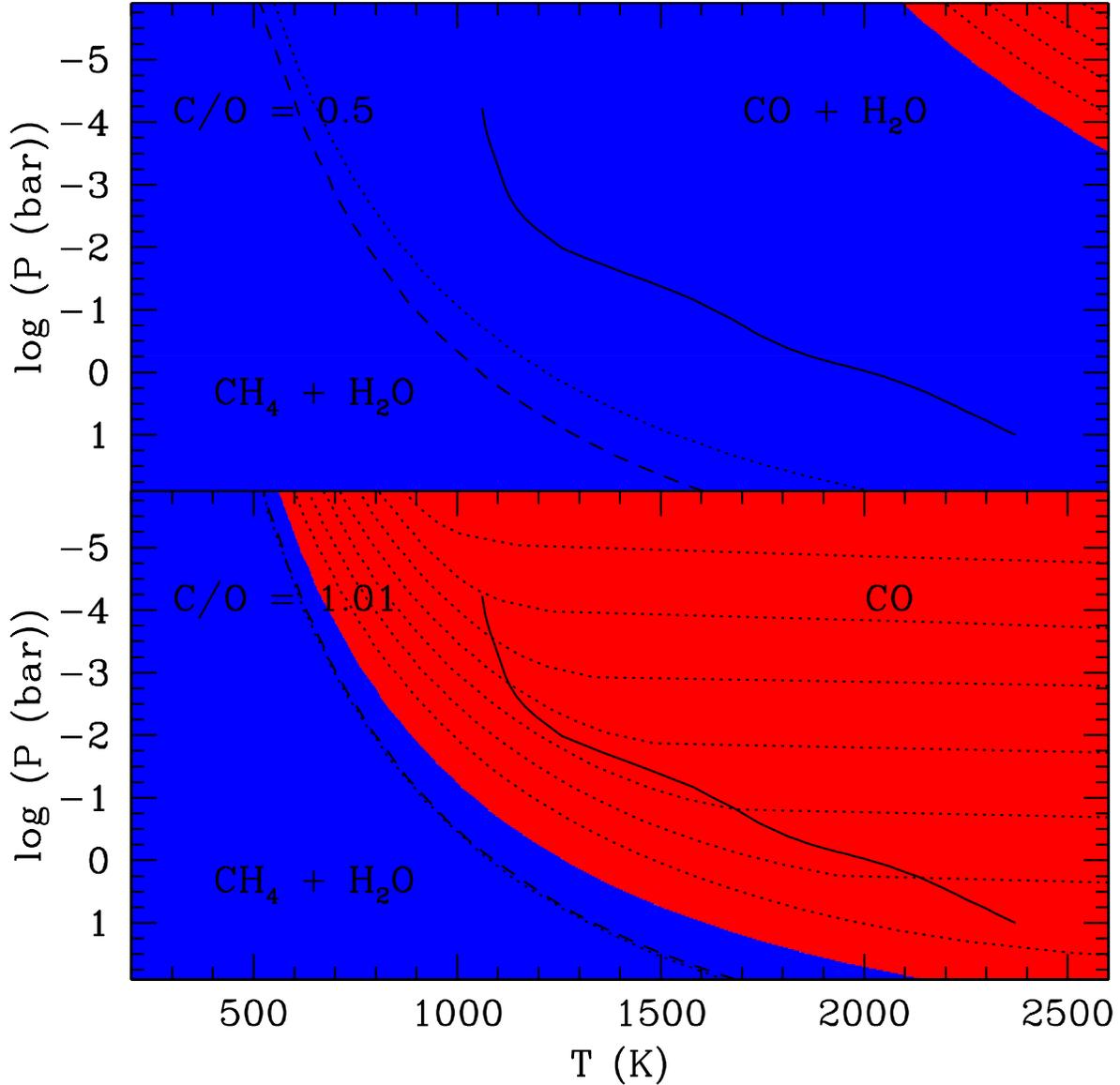


Fig. 1.— Summary of the  $CO$ ,  $CH_4$ , and  $H_2O$  concentrations at chemical equilibrium in a Neptune-mass planet atmosphere with  $C/O \approx 0.5$  (upper panel) and  $C/O \approx 1.01$  (lower panel). The blue regions shows where  $H_2O/CO > 0.1$ ; red regions are drier. Dotted lines, from left to right, show where  $H_2O/CO=1, 0.1, \dots, 10^{-8}$ . Heavy dashed curves show where  $CO$  and  $CH_4$  gases have equal abundance;  $CO$  is the dominant carbon-bearing molecule at high temperatures and  $CH_4$  is the dominant carbon-bearing molecule at low temperatures. In the lower panel the dashed curve and leftmost dotted curve overlap. The solid black line shows a possible temperature-pressure profile of a  $T_{eff} = 1500 \text{ K}$  hot Neptune planet.

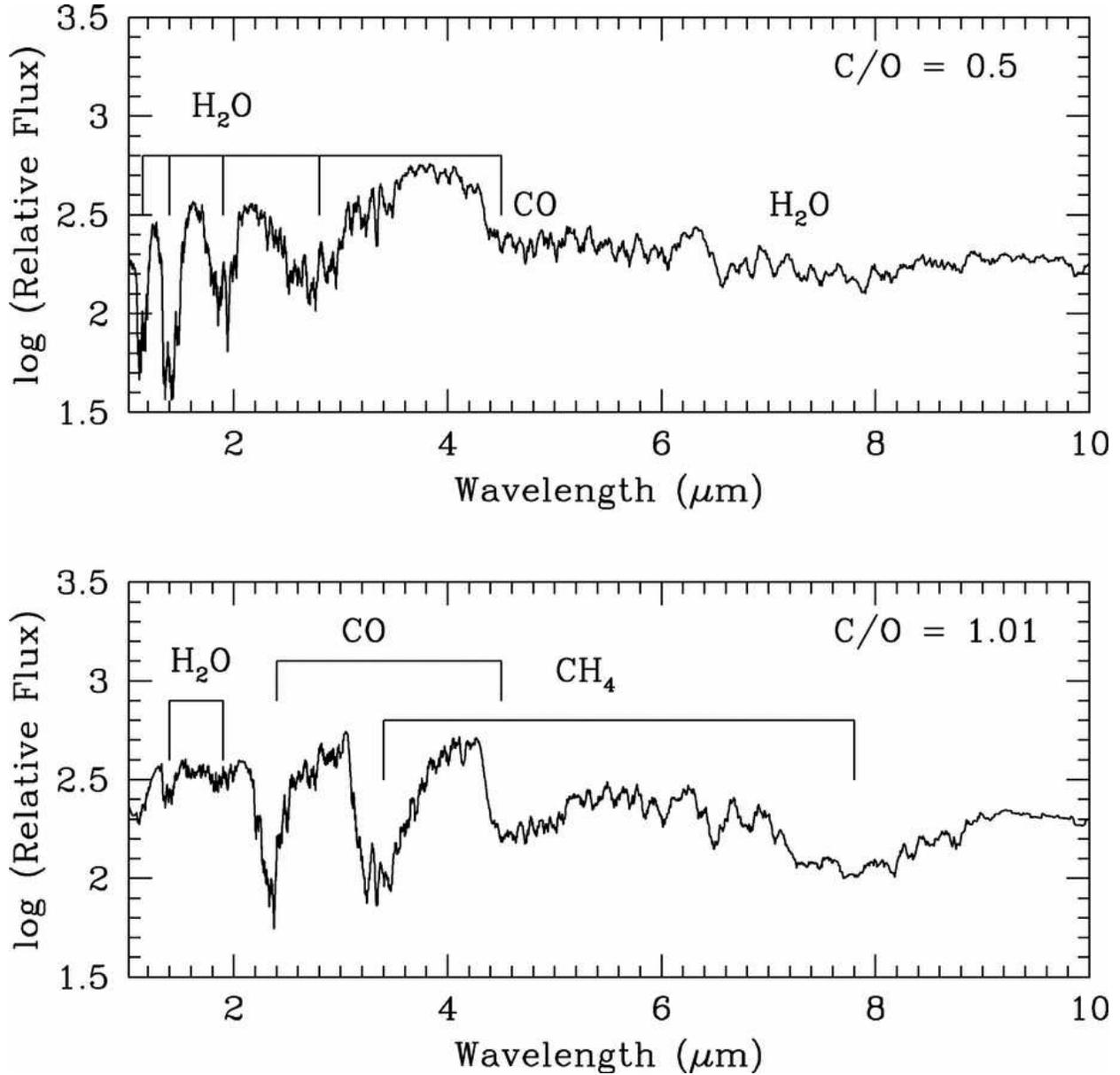


Fig. 2.— Model thermal emission spectra for a hot Neptune-mass planet. Upper panel: a C/O = 0.5 hot Neptune-mass planet atmosphere is dominated by H<sub>2</sub>O spectral features with some weak CO absorption features. Lower panel: a C/O = 1.01 hot Neptune carbon planet atmosphere has very little H<sub>2</sub>O; instead CO and CH<sub>4</sub> absorption features dominate the spectrum.