CARBON-RICH GIANT PLANETS: ATMOSPHERIC CHEMISTRY, THERMAL INVERSIONS, AND FORMATION CONDITIONS. N. Madhusudhan[1], O. Mousis[2], J. Lunine[3], and T. Johnson[4], [1]Princeton University, Princeton, NJ, USA. [2]Institute UTINAM Université de Franche-Comté, CNRS/INSU, Besançon, France. [3]University of Arizona, Tucson, AZ, USA. [4]NASA Jet Propulsion Laboratory, Pasadena, CA, USA.

Introduction: Carbon-rich planets (CRPs) are the exotic new members in the repertoire of extrasolar planets. We define a CRP as a planet in which carbon is the most dominant element by number after H and He, which also means a C/O ratio $\geq$ 1. The first CRP atmosphere was discovered recently, for the hot Jupiter WASP-12b [1, 2]. Infrared photometry obtained with the Spitzer Space Telescope [3] and from the ground [4] were used in [1] to infer a C/O $\geq$ 1 in the atmosphere of WASP-12b. The observations revealed a substantial depletion of H_2O, and an overabundance of CH_4, as compared to a solar abundance chemical equilibrium model. The observations also indicated the absence of a strong dayside thermal inversion, which was surprising for the extremely irradiated atmosphere of WASP-12b based on the TiO/VO hypothesis [5]. Atmospheres of over a dozen exoplanets have now been observed [6]. WASP-12b being the first giant planet with a robust C/O constraint, the compositional diversity of exoplanets remains largely unexplored.

Theoretical studies in the recent past had anticipated the existence of CRPs. The oxygen abundance, and hence the C/O, of Jupiter is presently unknown [7]. However, based on the lower-limit on O/H measured by the Galileo probe, the hypothetical possibility of Jupiter being a CRP was studied in [8]. If Jupiter were carbon-rich it could have formed from predominantly tarry planetesimals instead of planetesimals dominated by water ice as expected based on the composition of minor bodies in the solar system [8]. Following [8], the possibility of low-mass extrasolar CRPs ($\leq$ 60 Earth masses) was studied in [9]. Such planets are characterized by atmospheres rich in hydrocarbons and deficient in oxygen-rich gases. The formation of terrestrial-mass exoplanets over a wide range of C/O ratios was studied in [10]. While metallic silicates dominate the interiors of oxygen-rich terrestrial planets, those with C/O $\geq$ 0.8 would host interiors that are dominated by carbon-rich solids such as SiC, graphite, and diamond [9,10].

The first detection of a carbon-rich planetary atmosphere [1], of WASP-12b, has opened a new class of exoplanets, with atmospheres, interiors, and formation mechanisms, manifestly different from those based on solar abundances (the solar C/O = 0.5, i.e. oxygen rich). Our focus in this study is on extrasolar giant planets that are carbon-rich: hot Jupiters, hot Neptunes, and, hydrogen-rich super-Earths. We refer to them as carbon-rich giants (CRGs) in this work.

We report a detailed study of the atmospheric chemistry and temperature structure of CRGs, their formation via core accretion, and the chemistry and apportionment of ices, rock, and volatiles in the envelopes. We first present the unique phase-space of molecular abundances in CRGs and their spectral signatures. We then address the question of whether thermal inversions can form in CRGs, given that WASP-12b does not host a strong inversion. Finally, we place our calculations in the context of the core accretion model to constrain the primordial conditions that are required in the disk for the formation of WASP-12b.

Methods: We employ numerical tools to study three aspects of carbon-rich planets: (a) Atmospheric chemistry (b) Thermal inversions, and (c) Formation.

Atmospheric chemistry. We calculate the molecular mixing ratios of the dominant species using the approach described in [11]. We compute equilibrium compositions of the species using the equilibrium chemistry code originally developed in [12], and subsequently used in several recent works, e.g. [11]. We calculate the gas phase molecular mixing ratios for 172 molecules, resulting from abundances of 23 atomic species, by minimizing the net Gibbs free energy of the system. We also consider non-equilibrium CO-CH_4 thermochemistry based on [11].

Thermal Inversions. Traditionally, TiO and VO have been proposed as potential inversion-causing absorbers in hot Jupiter atmospheres. In this work, we calculate abundances of TiO and VO in carbon-rich atmospheres, and investigate their role in thermal inversions. We derive representative temperature structures for highly irradiated atmospheres based on [5,12, and 18], and use them to estimate TiO and VO profiles under equilibrium and non-equilibrium conditions.

Formation of carbon-rich planets. Close-in giant planets are thought to have originated in the cold outer region of protoplanetary disks and migrated inwards until they stopped at closer orbital radii [13,14,15]. Here we assume that the hot Jupiter was formed via the core-accretion model. We calculate the composition of the icy planetesimals accreted by the forming planet following the approach developed in [16,17]. In this model, ices are formed during the cooling of the disk and are composed of clathrates and/or pure condensates, the relative proportion between these two types of materials being fixed by the amount of water available for clathration. Assuming that, once condensed, the ices add to the composition of planetesimals accreted by the growing planet along its migration pathway, this allows us to reproduce the volatile abundances by adjusting the mass of planetesimals that vaporized when entering the envelope.

Results and Discussion: We now present our results on the three aspects of CRGs.

Atmospheric Chemistry: CRGs probe a unique region in composition space, especially at high T. C/O ≥ 1 causes distinct changes in the molecular composition as compared to thermochemical equilibrium with solar abundances (TE_{solar}), as previously studied for hot Neptunes in [9]. Most of the oxygen is occupied by CO for $T > 1400$ K and $P < 1$bar. In this range, there is a substantial depletion in H_2O, and an overabundance of CH_4 by up to factors of 10 – 100 each compared to TE_{solar} abundances. Consequently, hot Jupiters with thermal profiles intersecting this $P – T$ range are prime candidates to search for CRGs. Cooler CRGs are less distinguishable from giant planets with solar C/O.

Thermal Inversions. Our work suggests that CRGs offer a new dimension to the theory of thermal inversions in hot Jupiter atmospheres. We find that the C/O ratio strongly affects the abundance of TiO/VO available to form thermal inversions. A C/O = 1, for example, yields TiO abundance 10-100 times lower than that obtained with TE_{solar}, as shown in Fig 1. This depletion is adequate to rule out thermal inversions even in the most highly irradiated hot Jupiters, such as WASP-12b. Therefore, the possibility of thermal inversions in hot Jupiters with lesser irradiation levels is also critically influenced by their C/O ratios.

Formation of WASP-12b. Adopting gas phase elemental abundances in the disk similar to those estimated in the star gives a C/O ratio in planetesimals and then in the envelope of WASP-12b on the order of 0.27. This value is lower than that in the star WASP-12 (about 0.44) because the condensation sequence of ices in the disk induces an important fractionation (Fig. 2) between the different elements. In these conditions, a C/O ratio of 1 in WASP-12b would require that the oxygen abundance in the disk is depleted by a factor of 0.41. We assume that only the planetesimals produced beyond the snow line materially affected the observed O and C abundances due to their vaporization when they entered the envelope of the planet.

It is commonly assumed in solar system cosmochemistry that the solar elemental abundances reflect those in the early solar nebula from which the planet formed. Explaining such a large depletion in oxygen in the material from which WASP-12b formed compared with its host star remains a significant challenge.

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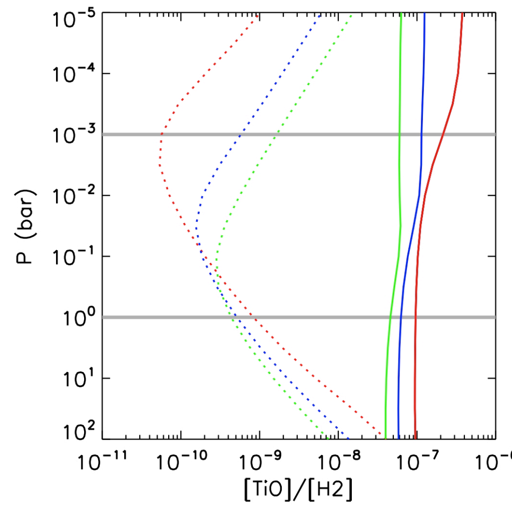

Figure 1: Mixing ratios of TiO for different C/O. The solid (dotted) curves show TiO mixing ratios, relative to H_2, for abundances with C/O = 0.5 (1.0), in chemical equilibrium. The red, blue, and green correspond to isotherms at 2650K, 3000K, and 3200 K.

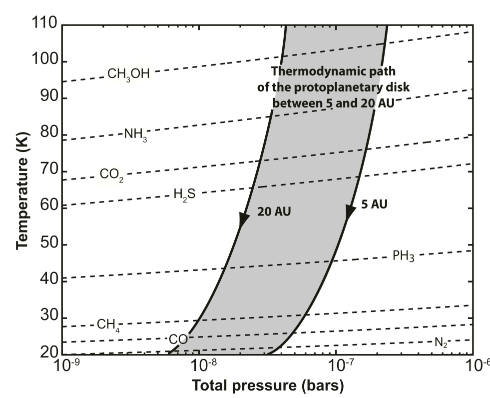

Figure 2: Equilibrium curves of ices formed in a protoplanetary disk with elemental abundances of all elements, except O, same as that of WASP-12. O is assumed to be depleted by 41% compared to the host star. In this case, water does not exist in the disk and only pure condensates form.