ATMOSPHERE, INTERIOR, AND EVOLUTION OF THE METAL-RICH TRANSITING PLANET HD 149026B. J. J. Fortney, M. S. Marley, R. S. Freedman, *NASA Ames Research Center (jfortney@arc.nasa.gov)*, D. Saumon, *Los Alamos National Laboratory*, K. Lodders, *Department of Earth and Planetary Sciences, Washington University*.

Searches for extrasolar giant planets (EGPs) over the past ten years have yielded a bizarre menagerie of planets, many of which are in orbits with periods of only a few days. These "hot Jupiters," or "Pegasi planets," which orbit within ∼0.1 AU of their parent stars, form a class of astrophysical objects that is still yielding surprises. The latest, and perhaps most unanticipated, is HD 149026b, a planet in a 2.87 day orbit around a metal-rich G0 IV parent star [1]. The most striking feature of planet HD 149026b is its small radius of only $0.725 \pm 0.05\ R_{\rm J}$, given its mass of $0.36 \pm 0.03\ M_{\rm J}$ (114 $M_\oplus$). For comparison, Saturn has a mass of 0.30 $M_{\rm J}$ (95 $M_\oplus$), is about 2.5 Gyr older than HD 149026b and receives 140,000 times less stellar flux, and yet has a mean radius of 0.81 $R_{\rm J}$. The transiting planet most similar in mass to HD 149026b, OGLE-Tr-111b, has a mass of 0.53 $M_{\rm J}$ and a radius of ∼1 $R_{\rm J}$ [2]. Evolution models of Pegasi planets have shown that lower-mass giant planets should be preferentially influenced by irradiation, leading to larger radii [3], but HD 149026b is decidedly small. The small radius of HD 149026b implies that it has significantly more heavy elements in its interior than does Saturn. Indeed, Sato et al. have estimated a core mass near 70 $M_\oplus$, or 60% of the planet's mass!

Here we investigate atmosphere models for the planet and show how under certain circumstances the atmosphere features a hot stratosphere driven by absorption of stellar flux by TiO and VO at mbar pressures. We provide model planet-to-star flux density ratios in *Spitzer* IRAC and MIPS bandpasses that will allow for a determination of the character of the planet's atmosphere. We also investigate the evolutionary history of HD 149026b with the help of a new grid of model atmospheres computed specifically for this planet. This atmosphere grid, applied to a planetary evolution code, with high-pressure equations of state of H/He mixtures, rock and ice, allow us to place constraints on the abundances of heavy elements in HD 149026b, and to begin to understand its current structure.

We have computed atmospheric *P–T* profiles for three metallicities: [M/H]=0, 0.5, and 1. These profiles are shown in Fig. 1. The solar metallicity model allows a comparison with published models of other planets, the [M/H]=0.5 is close to the metallicity of the star HD 149026, and [M/H]=1 represents an enrichment of ~ 3 times over the star's value, which is typical of the atmospheres of Jupiter and Saturn. These atmosphere models assume 1) reradiation of the absorbed stellar flux over 4π steradians, 2) cloud opacity where applicable, and 3) an intrinsic temperature (the $T_{\rm eff}$ the planet would have in isolation) of 100 K, which is realistic, based on our thermal evolution models. As the metallicity is increased, the atmosphere becomes warmer as a larger fraction of incident radiation ($\geq$90%) is absorbed. Profiles that cross the $CaTiO_3$ condensation curve at high pressures form a $CaTiO_3$ cloud at that pressure, leaving no free TiO in the upper atmosphere. Due to mixing in the atmosphere, all gaseous TiO in the upper atmosphere would eventually mix down to this condensation point, where the $CaTiO_3$ cloud remains confined, due to the gravitation field. This process, known as a "cold trap," is responsible for the extremely low water abundance in the Earth's stratosphere. However, profiles that do not cross this condensation curve do have free gaseous TiO everywhere in the atmosphere. Absorption of stellar flux by TiO leads to a hot stratosphere for some of the models, which leads to *qualitatively different spectra*. This effect was pointed out for irradiated planetary atmospheres by Hubeny et al. [4], and we obtain similar results. We have also computed planet-to-star flux density ratios in various *Spitzer* bandpasses. Due to the combination of the planet's small radius and the large luminosity of the parent star, these ratios are typically ∼1/4 to 1/2 of those for TrES-1, which means detection may be difficult.

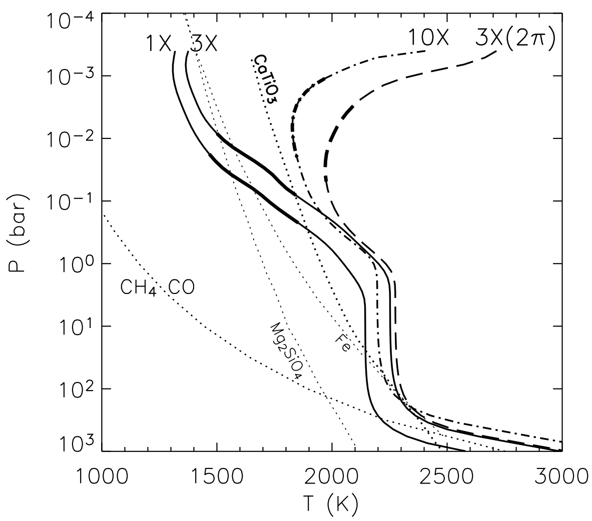

Figure 1: Atmospheric *P–T* profiles for [M/H]=0, 0.5 and 1 (1X, 3X, and 10X, respectively). In the models with [M/H]=0 and 0.5, the opacity of TiO and VO has been removed at pressures less than 10 bar, but the opacity of clouds of forsterite and iron is included. The [M/H]=1 and "3X(2π)" models may not cross the $CaTiO_3$ condensation curve, depending on the exact value of $T_{\rm int}$ so TiO has been retained in the upper atmosphere. The "3X(2π)" model assumes that the absorbed stellar flux can only be reradiated on the planet's day side. The thick part of each profile shows the extent of the brightness temperatures for each model in the 3 to 30 μm wavelength range. Also shown is the curve where the abundances of CH_4 and CO are equal, for solar composition.

We now turn to structure and evolution models of the planet's interior. We assume that the core is made either entirely of rock or ice. At the estimated age of 2 Gyr for HD

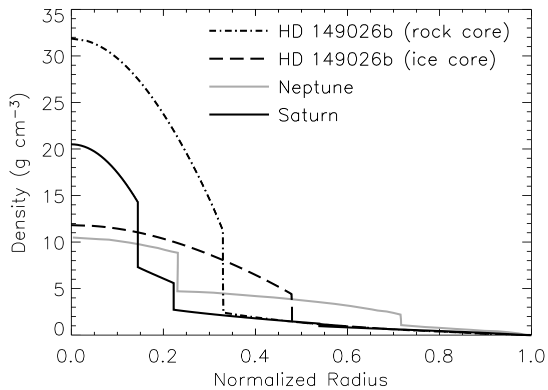

Figure 2: Interior density profiles of two possible models for HD 149026b compared with Neptune and Saturn. The two profiles of HD 149026b assume that [M/H]=0.5 in the H/He envelope and a core made entirely of either ice or rock.

149026 [1], we find that a core mass of 65.5 $M_\oplus$ of rocks or of 77$M_\oplus$ of ices is consistent with the currently derived planetary radius. Including $\sim$2 $M_\oplus$ of heavy elements in the envelope (Z=0.045), we derive a total mass of heavy elements for each model of 68 and 79 $M_\oplus$. As a check on these results, we also investigated the contraction of HD 149026b with alternative "rock" and "ice" EOSs, which are given in Hubbard and Marley [5]. We find very similar total heavy element masses of 66 and 78 $M_\oplus$, respectively. The evolution models show that the interior of HD 149026b has cooled significantly, which is not surprising given the relatively small percentage of its mass contributed by H/He. We find that values of $T_{\rm int}$ from 80-105 K are realistic for the current intrinsic heat flux of the planet.

Figure 2 shows the interior density distribution as a function of normalized radius for our two interior models compared to models of Saturn [6] and Neptune [7]. The Saturn and Neptune models both have two-layer cores of rock overlayed by ice. The interior structure of HD 149026b may be a hybrid of the ice giants and gas giants. Uranus and Neptune are $\sim$90% heavy elements, while Saturn is $\sim$25% and Jupiter $\lesssim$10% [8]. Although HD 149026b is more massive than Saturn, it has a bulk percentage of heavy elements (60-70%) more similar to that of the solar system's ice giants.

Guillot and Gladman [9] point out that for Pegasi planets in general, the orbital velocity of $\sim$150 km/s is much larger than the planet's escape velocity of $\sim$50 km/s, meaning the planet will be inefficient at removing planetesimals near its orbit at very young ages. Thus, Pegasi planets may accumulate more heavy elements than has been previously appreciated [10]. HD 149026b may be towards the high-accumulation end of a continuum for Pegasi planets, possibly due to the high metallicity in the stellar system it occupies. This leads us to consider the bulk content of heavy elements of the other transiting planets. HD 209458b is the only known transiting planet with a large radius that is difficult to model. This has suggested to many that this *one* planet harbors an additional energy source that slows it contraction [11, 12]. The discovery of HD 149026b suggests another possibility. It is conceivable that all Pegasi planets would be affected by an additional energy source (yet to be identified), resulting in large radii, but that it is partly compensated by a relatively large bulk metal content, thanks to favorable conditions for planetesimal accretion. In this perspective, HD 209458b and HD 149026b would represent extremes of the metallicity range of Pegasi planets, with relatively low metallicity for HD 209458b (large radius) and a very high metallicity for HD 149026b (small radius). Given Jupiter and Saturn's large bulk inventory of heavy elements (as much as 6 times and 14 times solar, respectively [8]) and the fact that most calculations on the radii of transiting planets have assumed metallicities lower than that of Jupiter [10, 13, 14], this scenario is quite plausible. In tentative support of this picture, Fortney et al. [15] found that the match to the Charbonneau et al. [16] *Spitzer* photometry for the transiting planet TrES-1 improved as the metallicity of the model atmosphere was increased.

We will also discuss how uncertainties in the EOS of hydrogen affect calculations of model planet radii. For example, "harder" EOSs can lead to radii of HD 209458b that are $\sim$5% larger than previously calculated, in better agreement with observations. However, it still appears unlikely that the 1σ radius error bar can be reached without an additional energy source.

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