THE EFFECT OF METALLICITY ON THE ATMOSPHERIC COMPOSITION OF GJ 436b. M. R. Richardson[1], J. I. Moses[2], M. R. Line[3], T. S. Barman[4], C. Visscher[5], and J. J. Fortney[6], [1]Rice University, Houston, TX, USA; [2]Space Science Institute, Boulder, CO, USA; [3]California Institute of Technology, Pasadena, CA, USA; [4]Lowell Observatory, Flagstaff, AZ; [5]Southwest Research Institute, Boulder, CO, USA; [6]Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA, USA; (mrr4 @rice.edu; jmoses @spacescience.org).

Introduction: The discovery of GJ 436b in 2004 by the radial velocity method [1], followed by the 2007 discovery of its transit [2], made this intriguing object the first Neptune-sized extrasolar planet ever identified. The planet was dubbed a "hot Neptune" due to its perceived similarities to our solar system's eighth planet and to its close proximity to its M-dwarf host star — GJ 436b has a mass of ~1.4M_{Nep}, a radius of ~1.065R_{Nep}, a semimajor axis of ~0.03 AU, and an effective temperature of ~700-800 K [2-5]. Recent ground-based and *Kepler* observations indicate that GJ 436b is not unique: Neptune-sized planets are common within the known population of extrasolar planets and planetary candidates [6-8].

Observational data from GJ 436b have revealed many puzzles with respect to the planet's atmospheric composition. Transit observations have been controversial, both in terms of the wavelength-dependent transit absorption depths and the resulting implications with respect to constituent abundances [9-13]. Eclipse observations, on the other hand, indicate that the planet's atmospheric composition is inconsistent with chemical-equilibrium predictions for a solar-like, H_2-dominated atmosphere [4,14-16], despite the fact that the planet's mass-radius relationship and interior models suggest that GJ 436b must contain a H/He atmospheric component of ~0.1-20% by mass [17-19]. The main problem is that water and methane are expected to be the dominant carriers of oxygen and carbon in the planet, but *Spitzer* photometric data (especially the large 3.6-to-4.5-μm flux ratio and 8-μm flux) suggest that CH_4 is at most a minor constituent (i.e., at the ~ppm level) in the atmosphere of GJ 436b, that the H_2O abundance is unexpectedly low, and that the CO abundance is unexpectedly high [4,14].

Stevenson et al. [4] and Madhusudhan and Seager [14] suggest that disequilibrium processes like transport-induced quenching and photochemistry can increase the CO abundance on GJ 436b relative to CH_4, thus reconciling the models and observations. However, Line et al. [20] demonstrate that disequilibrium processes cannot remove methane as the dominant carbon constituent on GJ 436b. How then can the puzzling eclipse observations for GJ 436b be understood?

We suggest that a very high metallicity atmosphere for GJ 436b might help resolve the apparent discrepancy between models and observations. The "photosphere," where the atmosphere becomes optically thick to incoming and outgoing radiation, moves to lower pressures as the metallicity is increased, shifting the temperature-pressure profile into a more CO-dominated regime on GJ 436b ([21]; see also Fig. 1). For sufficiently high metallicities (e.g., ~2000x solar) in combination with low eddy diffusion coefficients, the CH_4 mole fraction can remain below ppm levels on GJ 436b. At such high metallicities, hydrogen is roughly as abundant as oxygen and carbon, and molecules like CO and CO_2 can become thermodynamically favored over molecules like CH_4 and H_2O that contain several H atoms. The interior models for GJ 436b [17-19] seem to allow such extreme metallicities, and high metallicities for Neptune-sized ice giants are reasonable theoretically [23]. In fact, Neptune itself is observed to have a carbon-to-hydrogen ratio 40-70x solar [24] and is estimated to have an oxygen-to-hydrogen ratio as much as 440x solar [25].

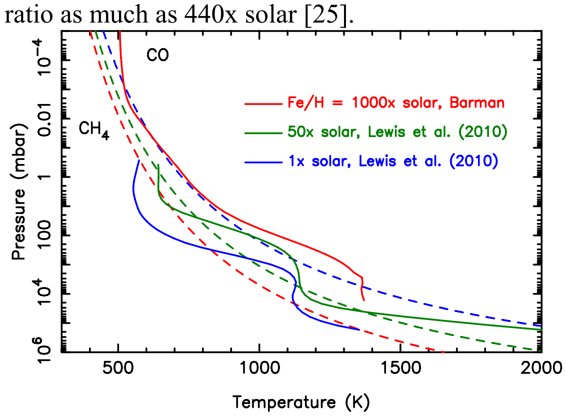

FIG. 1. Theoretical temperature-pressure profiles for GJ 436b at various metallicities: The 1x solar (blue solid lines) and 50x solar (green) show the dayside-average atmospheric temperatures from the GCMs of Lewis et al. [21]; the 1000x solar (red) shows a 1-D, efficient-heat-redistribution model from radiative calculations based on Barman et al. [22]. The dashed lines represent the chemical boundaries where CH_4 and CO have equal abundances: CH_4 dominates to the bottom left, and CO to the upper right. Note that this boundary shifts downward with increasing metallicity, whereas the *T-P* profile shifts upward with increasing metallicity. The 1x solar *T-P* model profile lies solidly within the CH_4-dominated regime, whereas the 1000x solar profile lies within the CO-dominated regime.

We explore the effects of metallicity on the predicted composition of GJ 436b and other generic "hot Neptunes" using a state-of-the-art thermochemical and photochemical kinetics and transport model [26-28]. Observational consequences are discussed.

Model: The 1-D KINETICS model of Allen et al. [29] is used to solve the continuity equations for ~90 atmospheric species via ~1800 forward and reverse chemical-reaction pairs. Only species containing the elements H, He, C, N, and O are considered in the model, which is described in detail in Moses et al. [28]. Current changes to the model include the addition of O_3 (and related reactions) and updates to our UV photodissociation cross-sections and quantum yields for several species based on the Mainz database (http://www.atmosphere.mpg.de/enid/2295) and compilations such as Atkinson et al. [30]. Eddy diffusion coefficients K_{zz} are free parameters in the model.

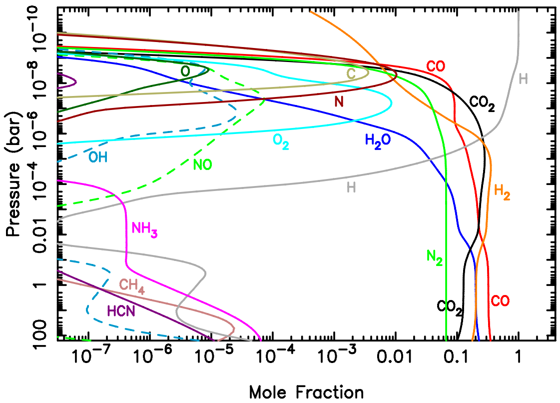

FIG. 2. Mole fraction profiles for several species (as labeled) in our 2000x solar metallicity disequilibrium model.

Results: We find that our 1x solar metallicity results are similar to those of Line et al. [20]: water and methane are the dominant heavy constituents, with mole fractions approaching ~10^{-3}. Photochemistry and quenching strongly increase the abundances of CO, HCN, C_2H_2, C_2H_6, and CO_2 in the stratosphere. However, we find that these species do not have column abundances large enough to influence spectra significantly, so that absorption by H_2O and CH_4 dominates the infrared spectrum. The resulting spectra compare very poorly to the *Spitzer* data [4], due largely to excess absorption in the 3.6 and 8 μm bands [14].

The situation changes dramatically for the 2000x solar case (Fig. 2), as CO and CO_2 become major equilibrium constituents. Transport-induced quenching strongly depletes the abundance of CH_4 and slightly increases the abundance of H_2O and CO; photochemistry increases the upper atmospheric abundances of atomic H, N, C, O, and molecular O_2 and NO. Methane is no longer abundant enough to affect the infrared spectrum, which is dominated by H_2O in the 3.6, 5.8, 8, and 24 μm channels, by CO and CO_2 in the 4.5-μm channel, and by CO_2 in the 16-μm channel. As Fig. 3 shows, the predicted eclipse spectrum from this model does a better job of fitting the 3.6-to-4.5 μm flux ratio and the overall fluxes at 5.8 and 8 μm (total goodness of fit to all data is $\xi^2 = 2.7$), but the large CO_2 abundance results in excess absorption at 16 μm.

Conclusions: A very high metallicity (> 1000x solar) atmosphere is so far the only way we have found to make CH_4 be deficient under the expected thermal conditions for GJ 436b. Models with such high metallicities are no longer truly H_2-dominated, but have CO and CO_2 abundances similar to that of H_2. We have no analog for this type of planet in our own solar system, but with increasing metallicity, the atmospheric composition is expected to become more Venus-like. A Neptune-sized planet can become metal-rich through efficient icy-planetesimal accretion and inefficient gas accretion, and/or through efficient hydrogen escape after the planet migrates and parks near the host star.

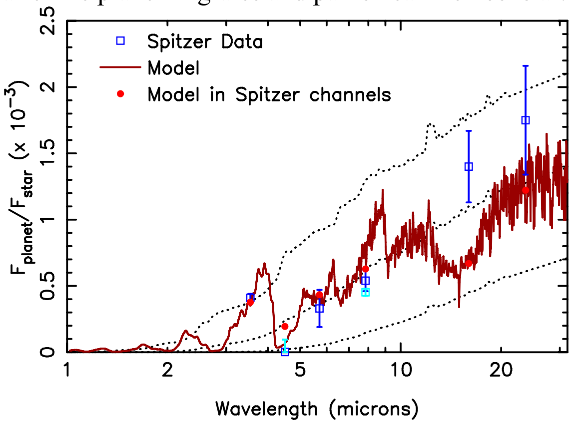

FIG. 3. Eclipse spectra predicted from our disequilibrium model assuming 2000x-solar metallicity (dark red), in comparison with the *Spitzer* photometric data from Stevenson et al. [4] (dark blue; recent updates in cyan). The red circles represent the model fluxes convolved over the *Spitzer* bandpasses. The dotted black lines represent blackbodies of 500 K (lower), 800 K (middle), and 1100 K (upper), divided by a 3350-K PHOENIX stellar model.

The large CO_2 abundance in our 2000x solar metallicity model is inconsistent with the observed flux in the 16-μm *Spitzer* channel [4], making it unclear whether a high-metallicity model is viable for GJ 436b. Even if such a model cannot explain this particular exoplanet, such exotic, high-metallicity, Neptune-sized objects may exist in the transiting planet population, and we might expect in the near future to observe a continuum of compositions ranging from H_2-rich, Neptune-like planets to H_2-poor, Super-Venus-like planets, and various compositions in between.

References: [1] Butler, R.P. et al. (2004) *ApJ*, *617*, 580. [2] Gillon, M. et al. (2007) *A&A, 472*, L13. [3] Deming, D. et al. (2007) *ApJ*, *667*, L199; [4] Stevenson, K.B. et al. (2010), *Nature*, *464*, 1161. [5] von Braun, K. et al. (2012), *ApJ*, *753*, 171. [6] Howard, A.W. et al. (2010), *Science*, *330*, 653. [7] Borucki, W.J. et al. (2011), *ApJ*, *736*, 19. [8] Batalha, N.M. et al. (2012), arXiv:1202.5852. [9] Pont, F. et al. (2009), *MNRAS*, *393*, L6. [10] Beaulieu, J.-P. et al. (2011), *ApJ*, *731*, 16. [11] Shabram, M. et al. (2011), *ApJ*, *727*, 65. [12] Gibson, N.P. et al. (2011), *MNRAS*, *411*, 2199. [13] Knutson, H.A. et al. (2011), *ApJ*, *735*, 27. [14] Madhusudhan, N. & Seager, S. (2011), *ApJ*, *729*, 41. [15] Spiegel, D.S. et al. (2010), *ApJ*, *709*, 149. [16] Lodders, K. & Fegley, B., Jr. (2002), *Icarus*, *155*, 393. [17] Figueira, P. et al. (2009), *A&A*, *493*, 671. [18] Rogers, L.A. & Seager, S. (2010), *ApJ*, *712*, 974. [19] Nettelmann, N. et al. (2010), *A&A*, *523*, A26. [20] Line, M.R. et al. (2011), ApJ, 738, 32. [21] Lewis, N.K. et al. (2010), [22] Barman, T.S. et al. (2005), ApJ, 632, 1132. [23] Fortney, J.J. et al. (2012), DPS meeting #44, #103.05. [24] Karkoschka, E. & Tomasko, M.G. (2010) *Icarus*, *205*, 674. [25] Lodders, K. & Fegley, B. Jr. (1994) *Icarus*, *112*, 368. [26] Visscher, C. et al. (2010), *Icarus*, *209*, 602. [27] Moses et al. (2010), *Faraday Disc*., *147*, 103. [28] Moses et al. (2011), *ApJ*, *737*, 15. [29] Allen et al. (1981) *JGR*, *86*, 3617. [30] Atkinson, R. et al. (2004) *Atmos. Chem. Phys.* 4, 1461.