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P6_5 Evidence for a Diamond Layer in the Mantle of Neptune

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Abstract

This paper explores the idea of diamond formation in gas giants. We apply terrestrial experimental data to the theoretical atmospheric composition and structure of Neptune. We conclude that it is feasible that a solid layer of diamond could form in the conditions on Neptune, completely replacing a layer of liquid methane on the planet. This is not in line with current theories but does have some supporting evidence from the scientific community. Further observational data is required to confirm either theory.

Introduction

According to an article in *Nature* [1] it is possible for diamonds to spontaneously form on gas giants such as Neptune. A study by Benedetti et al. has shown that under high temperatures and pressures methane (CH_4) will spontaneously break down to produce diamond crystals. Benedetti et al. describe a diamond anvil cell with axial length $40\mu m$ and radius $300\mu m$ which was heated by lasers to temperatures of $2000K - 3000K$ and put under pressures of $10GPa - 50GPa$ for durations of $1000s$ [2]. In this experiment small precipitated crystals were formed with diameters of up to $0.2mm$ which were confirmed to be solid diamonds using Raman and X-Ray spectroscopy. This paper will discuss the implications of this finding on the internal structure of Neptune.

Theory

The conditions generated in this experiment are similar to those found on Neptune between radii of $97,000km$ and $129,000km$, calculated from the isothermal barometric law for gas planets $P = P_0\exp(\frac{-h}{H})$ [3] where h is the height at which the pressure is P, H is the scale height of the atmosphere, $19.7km$, [4] and P_0 is the pressure at the planet's core, $7000GPa$, [5]. The total mass of gas, M, in this layer was evaluated by integrating the density of the gas ρ as a function of pressure (from the ideal gas law [6]) between these two radii:

$$M = \int_{97,000}^{129,000} \rho 4\pi r^2 dr = \int_{97,000}^{129,000} \frac{P\bar{M}}{RT} 4\pi r^2 dr = \frac{4\pi P_0 \bar{M}}{RT} \int_{97,000}^{129,000} \exp(-r/H) r^2 dr, \tag{1}$$

where $\bar{M}$ is the average molecular mass of the gas [7], taken to be $1.69AMU$, $R = 8.31JK^{-1}mol^{-1}$ is the molar gas constant, and T is the temperature of the gas, which in this layer is approximately $3000K$ [7]. This, combined with the fraction of CH_4 in the atmosphere, 2% [5], gave a total mass of methane, M_{CH_4}, of $1.16 \times 10^{19}kg$.

In order to determine the reaction rate in the diamond anvil cell we assumed the total amount of diamond formed was a single cylindrical crystal of diameter $0.2mm$ and axial length $40\mu m$ [2]. We then assume a linear relationship between reaction rate $\frac{dN}{dt}$ and CH_4 concentration N, as in constant conditions the only factor affecting how much CH_4 reacts is the amount of CH_4 present. We then integrated this to give:

$$N = N_0 \exp(-kt) \tag{2}$$

where N_0 is the initial concentration of CH_4 and k is a reaction constant, which we found to be $k = 6 \times 10^{-6}s^{-1}$, which we assume will be the same on Neptune as the conditions are similar.

We then used this value and assumed firstly vertical convection currents that were unimportant on time scales similar to those we were evaluating, and then vertical convection currents that were of importance, and acted to replenish the methane in this layer. For the situation in which the currents were not important, and as such the methane is not replenished, we have an equation for the mass of diamond M_d formed in a time t of

$$M_d = \frac{12}{16} M_{\mathrm{CH_4}} \times (1 - \exp(-kt)) \tag{3}$$

where the factor of $\frac{12}{16}$ comes from the difference in molecular mass of CH_4 and carbon.

Results

For $t > 10 days$ M_d approaches $\frac{12}{16} M_{\mathrm{CH_4}}$, which implies that after only one year the vast majority of methane in this layer would have been converted into diamond. For completeness we also evaluated the situation in which the methane is continuously replenished from other layers in the atmosphere, i.e. the convection currents are significant. This yields a constant diamond production rate, which we calculated as $4.14 \times 10^{16} kgyr^{-1}$ from the mass produced in the described diamond cell experiment, and the length of time of the experiment.

Discussion

The non-replenishing case in which the reacting layer becomes solid diamond is in contradiction with current theories about the composition of Neptune, which assume this layer is CH_4 ice [8], however a solid diamond composition in agreement with our own was proposed by Ross [1]. For the replenishing case the constant reaction rate implies that over the lifetime of Neptune, almost the entire mass of CH_4 on the planet would have been converted to diamond multiple times, which is obviously not the case. It would appear then that the scientific community does not fully understand the composition of Neptune and the reactions that occur within its atmosphere. Without detailed *in situ* measurements of its structure it would be hard to say which theory most accurately describes the atmospheric chemistry of Neptune.

References

[1] M. Ross, Nature. **292**, 435-436 (1981).
[2] L. R. Benedetti et al., Science. **286**, 100-102 (1999).
[3] J. Nichols *"Jovian Planets and Moons"*, PA:opt2603. University of Leicester, UK (2011).
[4] `http://nssdc.gsfc.nasa.gov/planetary/factsheet/neptunefact.html` accessed 23/10/2013.
[5] W. B. Hubbard, Science. **275**, 1279-1280 (1997).
[6] Tipler and Mosca (2008), *"Physics with Modern Physics for Scientists and Engineers"*. 6th edition (570), W. H. Freeman and Company.
[7] `http://www.solarviews.com/eng/neptune.htm` accessed 23/10/2013.
[8] S. Atreya et al., Geophys Res Ab. **8** (2006).