THE HUNT FOR PLANET NINE: ATMOSPHERE, SPECTRA, EVOLUTION, AND DETECTABILITY

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ABSTRACT

We investigate the physical characteristics of the solar system’s proposed Planet Nine using modeling tools with a heritage of studying Uranus and Neptune. For a range of plausible masses and interior structures, we find upper limits on the intrinsic $T_{\text{eff}}$, from $\sim$35 to 50 K for masses of 5–20 $M_{\oplus}$, and we also explore lower $T_{\text{eff}}$ values. Possible planetary radii could readily span from 2.7 to 6 $R_{\oplus}$, depending on the mass fraction of any H/He envelope. Given its cold atmospheric temperatures, the planet encounters significant methane condensation, which dramatically alters the atmosphere away from simple Neptune-like expectations. We find that the atmosphere is strongly depleted in molecular absorption at visible wavelengths, suggesting a Rayleigh scattering atmosphere with a high geometric albedo approaching 0.75. We highlight two diagnostics for the atmosphere’s temperature structure: (1) the value of the methane mixing ratio above the methane cloud and (2) the wavelength at which cloud scattering can be seen, which yields the cloud-top pressure. Surface reflection may be seen if the atmosphere is thin. Due to collision-induced opacity of H$_2$ in the infrared, the planet would be extremely blue instead of red in the shortest wavelength WISE colors if methane is depleted and would, in some cases, exist on the verge of detectability by WISE. For a range of models, thermal fluxes from $\sim$3 to 5 $\mu$m are $\sim$20 orders of magnitude larger than blackbody expectations. We report a search of the AllWISE Source Catalog for Planet Nine, but find no detection.

Key words: Kuiper belt: general – planets and satellites: atmospheres – planets and satellites: detection – planets and satellites: physical evolution

1. INTRODUCTION

Trujillo & Sheppard (2014) found that the orbits of long-period Kuiper Belt objects with semi-major axes beyond 150 au cluster in their arguments of perihelion. That clustering, and also the clustering of these objects in physical space, led Batygin & Brown (2016) to suggest that dynamical perturbations arising from a relatively small giant planet of perhaps 10 $M_{\oplus}$ (see also Trujillo & Sheppard, 2014), on an eccentric orbit with a semimajor axis distance of perhaps a sim $\sim$700 au, can explain this clustering.

The formation, evolution, and detectability of this possible “Planet Nine” has been the target of intense study (Bromley & Kenyon 2016; Brown & Batygin 2016; Cowan et al. 2016; de la Fuente Marcos & de la Fuente Marcos 2016; Fienga et al. 2016; Ginzburg et al. 2016; Holman & Payne 2016; Kenyon & Bromley 2016; Li & Adams 2016; Linder & Mordasini 2016; Malhotra et al. 2016; Mustill et al. 2016). To date, studies that include discussions of the atmosphere, emission, or cooling history of the planet focus on Planet Nine as a blackbody. This is certainly a valid starting point, especially as nothing is yet known about this possible object. Yet a straightforward but more detailed look at the planet yields a better understanding of the planet’s atmosphere, evolution, and spectra that cannot come from simple analysis. For instance, the spectra of the solar system’s giant planets differ strongly from blackbodies.

Planet Nine, if it exists, may have a mass between that of Earth and Uranus. Exoplanets in this mass range are extremely common (Borucki et al. 2011). Should Planet Nine be detected, the characterization of the planet would either confirm or refute studies such as the one we present here and could serve as a proxy for the physical and atmospheric properties of the as-yet largely unstudied worlds that are among the most common outcomes of the planetary formation process.

In this Letter, we first investigate the cooling history of Planet Nine over a wide range of possible masses from 5 to 50 $M_{\oplus}$. Here, we assume a planet that has at least some H/He atmosphere, in analogy with Uranus and Neptune as well as the thousands of sub-Neptune exoplanets that suggest a non-negligible H/He envelope (Lopez & Fortney 2014). We draw connections between the cooling history of Planet Nine and our incomplete understanding of the thermal evolution of Uranus and Neptune. With fluxes from the planet’s interior and from the Sun then reasonably well-bounded, we can begin to estimate the atmospheric temperature structure. We assess the condensation of methane, atmospheric opacity sources, and the spectrum of the planet from optical to thermal infrared wavelengths, focusing on novel and at times counter-intuitive behavior at very low temperatures ($\sim$30–40 K). Finally, we apply these findings to a revised assessment of the detectability of Planet Nine and report on a new search of the WISE catalog.

2. THERMAL EVOLUTION

2.1. Method

To estimate the possible radius and intrinsic luminosity of Planet Nine, we ran Neptune-like thermal evolution models in which we varied several structure parameters around those appropriate for Neptune. These models are somewhat similar to
those of Linder & Mordasini (2016), although we make different choices about particular compositions to investigate. Here, we assume planet masses between 5 and 50 $M_⊕$ ($M_{\text{Neptune}} = 17.15 \ M_⊕$) and two compositionally different layers consisting of a H/He envelope atop a core that is either ice-rich (2:1 ice:rock) or ice-poor (1:4 ice:rock). We varied the core mass fraction within 0.1–0.3 for the most massive models, representing a sub-Saturn mass giant, 0.30–0.84 for a 15 $M_⊕$ series of models, and 0.6–0.9 for the least massive models of 5–8 $M_⊕$, representing a sub-Neptune. For reference, constraints from Neptune suggest ∼0.76–0.9 ice/rock by mass (Helled et al. 2011; Nettelmann et al. 2013) and detailed modeling suggests an ice-enriched H/He envelope atop very ice/rock rich deep interior (Hubbard et al. 1995; Nettelmann et al. 2011; Nettelmann et al. 2013). Like Nettelmann et al. (2013), we represent the warm fluid ices in the interior by the water equation of state (EOS) H2O-REOS.1, H/He the updated H/He-REOS.3 tables of Becker et al. (2014) and for the rock EOS Hubbard & Marley (1989).

We followed the thermal evolution of Planet Nine at 1000 au, corresponding to a zero-albedo equilibrium temperature of 9 K. We explored a range of incident fluxes, but found that it yielded little impact on the thermal evolution. For the upper boundary condition, the radiative atmosphere, we applied an analytic description (Guillot et al. 1995) of to the non-gray Graboske et al. (1975) model atmosphere grid, which relates the 1 bar temperature (and hence the specific entropy of the interior adiabat) and surface gravity to the $T_{\text{eff}}$. For the constant of proportionality between the 1 bar temperature and the $T_{\text{eff}}$, we use $K = 1.50$ based on Neptune. We assume a hot start initial condition (e.g., Marley et al. 2007) and then adiabatic cooling thereafter. At all points in the evolutionary history, we track the evolution of the intrinsic luminosity and radius. See Nettelmann et al. (2013) for further modeling details.

2.2. Results

Our modeling results for Planet Nine are summarized in Table 1. We recover the strong influence of the assumed H/He mass fraction on the resulting radius, as it is well known from mass–radius relations for warm exoplanets (e.g., Fortney et al. 2007; Lopez & Fortney 2014). In particular, the radius of Planet Nine may reach from 2.7 to 4.4 $R_⊕$ if its mass is within 5–8 $M_⊕$, or from 3.6 to 6.7 $R_⊕$ if 15–20 $M_⊕$ (Neptune: 3.9 $R_⊕$), and further to 6.4–8.3 $R_⊕$ if 35–50 $M_⊕$. Intrinsic temperatures range from the Uranian upper limit of $T_{\text{int}} \sim 40K$ if $M \leq 12 \ M_⊕$ to sub-Saturn like values of $T_{\text{int}} \sim 60 \ K$ for $M = 50 \ M_⊕$. As expected, we find $T_{\text{int}}$ to rise with planet mass, but, surprisingly, to decrease with H/He content. The latter behavior results from the larger energy that can be radiated away from a larger surface area, and from the low internal temperatures along the H/He adiabats at ∼1 Mbar pressures.

On the whole, we find excellent agreement with the findings of Linder & Mordasini (2016). We agree that the planet’s luminosity is likely strongly dominated by intrinsic flux, rather than re-radiated solar energy. Specifically, they suggest a $T_{\text{eff}}$ of 47 K for a 10 $M_⊕$ planet model with a 1:1 ice:rock core and 1.4 $M_⊕$ envelope, which suggests an agreement within a few Kelvin for our cooling models, based on our Table 1.

These results should be taken with significant caution. While adiabatic cooling models can reproduce the current intrinsic flux from Neptune, they significantly overestimate the flux from within Uranus, which has been an outstanding problem for decades (Hubbard et al. 1995, Fortney & Nettelmann 2010). Therefore, these $T_{\text{int}}$ and $T_{\text{eff}}$ values should be taken as upper limits. Below, when modeling the atmosphere, we examine $T_{\text{int}}$ values down to 20 K, lower than that predicted by our evolutionary calculations.

3. ATMOSPHERE AND SPECTRA

With these upper limits on the flux from the planet’s interior, we can begin to assess the state of the planet’s atmosphere. To model the pressure–temperature ($P$–$T$) profile, chemical abundances, and spectrum of the planet we use a model atmosphere code with a long heritage, including Titan (McKay et al. 1989), Uranus (Marley & McKay 1999), and also a wide array of brown dwarfs (Marley et al. 1996; Morley et al. 2014) and exoplanets (Fortney et al. 2008; Marley et al. 2012). The predicted chemical equilibrium abundances follow the methods of Visscher et al. (2010).

For the initial exploration of this paper, we choose five values for the intrinsic flux, $T_{\text{int}}$, of 20, 30, 40, 50, and 60 K. There are also some additional modeling choices and constraints, which have caveats. At these cold temperatures, methane (CH4) condenses out and leaves the gas phase. In our normal modeling efforts of relatively warmer objects (e.g., water condensation into clouds in cool brown dwarfs), we calculate the vapor pressure of water above any cloud to self-consistently determine the gaseous water mixing ratio at any $P$–$T$ point (e.g., Morley et al. 2014). Given the large uncertainties for this possible planet, here we take a simpler path. We choose an opacity grid calculated at solar metallicity, but deplete these opacities by various factors to simulate the loss of methane. We

| Planet Mass | Core Mass | H/He Environ. Mass | I/R Ratio | Planet Radius | $T_{\text{eff}}$ | $T_{\text{int}}$ |
|-------------|-----------|--------------------|----------|---------------|----------------|---------------|
| $M_⊕$      | $M_⊕$     | $M_⊕$              | $M_⊕$   | $M_⊕$         | (K)            | (K)           |
| 5           | 3         | 2                  | 2:1      | 4.12          | 36.7           | 51.6          |
| 5           | 4.5       | 0.5                | 2:1      | 2.94          | 42.2           | 54.6          |
| 5           | 4.5       | 0.5                | 1:4      | 2.71          | 38.9           | 48.1          |
| 5           | 3         | 2                  | 2:1      | 4.44          | 39.5           | 55.4          |
| 8           | 7         | 1                  | 2:1      | 3.44          | 46.2           | 59.7          |
| 8           | 7         | 1                  | 1:4      | 3.17          | 42.6           | 52.5          |
| 5           | 5         | 2                  | 2:1      | 5.09          | 40.3           | 53.0          |
| 8           | 7         | 1                  | 2:1      | 3.46          | 48.3           | 60.9          |
| 10          | 9         | 1                  | 1:4      | 3.16          | 45.1           | 54.3          |
| 12          | 5         | 7                  | 2:1      | 5.57          | 41.4           | 57.1          |
| 12          | 10        | 2                  | 1:4      | 3.93          | 46.1           | 58.2          |
| 12          | 10        | 2                  | 2:1      | 3.64          | 44.6           | 52.3          |
| 15          | 5         | 10                 | 2:1      | 6.16          | 43.2           | 62.4          |
| 15          | 13        | 2                  | 1:4      | 3.92          | 48.7           | 60.0          |
| 15          | 13        | 2                  | 2:1      | 3.63          | 46.8           | 55.6          |
| 20          | 5         | 15                 | 2:1      | 6.74          | 46.2           | 63.1          |
| 20          | 15        | 5                  | 2:1      | 4.72          | 50.6           | 63.7          |
| 20          | 15        | 5                  | 1:4      | 4.48          | 50.2           | 62.0          |
| 35          | 5         | 30                 | 2:1      | 7.76          | 53.5           | 73.5          |
| 35          | 15        | 20                 | 2:1      | 6.60          | 57.5           | 76.2          |
| 35          | 15        | 20                 | 1:4      | 6.44          | 57.1           | 74.8          |
| 50          | 5         | 45                 | 2:1      | 8.33          | 59.5           | 81.0          |
| 50          | 15        | 35                 | 2:1      | 7.50          | 63.3           | 84.3          |
| 50          | 15        | 35                 | 1:4      | 7.37          | 62.8           | 83.0          |

Note. Results of thermal evolution models for planets at 4.5 Gyr.
also use an opacity database that is only complete above 75 K for most molecules (and 100 K for H₂) (Freedman et al. 2014), such that the details of the calculated spectra should be taken with some caution. However, our main findings below are insensitive to these caveats.

At a fiducial distance of 622 au (motivated by Fienga et al. 2016), we present atmospheric P–T profiles in Figure 1(a). The most important conclusion from these models is that for a wide range of parameter space, the planet is cold enough that most gaseous methane has condensed out of the planet’s atmosphere, leaving behind a nearly pure H/He atmosphere above a methane cloud that could exist in a location between a few tenths of a bar to hundreds of bars. The vapor pressure (and hence mole fraction) of methane above the cloud is independent of metallicity and is directly tied to the atmospheric temperature structure, such that a determination of

the methane mole fraction would serve as a “thermometer” of the visible atmosphere.

The spectra of these cold atmospheres with and without methane opacity are shown in Figure 1(b) for a $T_{\text{int}} = 40$ K model, representing the expected upper limit of the flux from a 10 $M_\oplus$ model. The optical spectrum is nearly feature-free, except for H₂ CIA opacity at 0.8 μm and possibly methane, if present. The profiles differ by a factor of $10^5$ in the methane abundance, which is allowed given the wide-range potential P–T profiles. In the mid-infrared, H₂ CIA and methane are the dominant absorbers, and the presence or absence of methane dramatically alters the spectra. In particular, the thermal fluxes from ~3 to 5 μm are enhanced by around 20 orders of magnitude compared with blackbody expectations. All absorption features in the red model spectrum are due to H₂ CIA. In addition, the loss of methane opacity shifts a prominent flux maximum from 4+ μm to ~3–3.5 μm, which dramatically alters the flux ratio in the two shortest WISE and Spitzer bands. Tabulated thermal infrared magnitudes are given in Table 2.

Our previously mentioned uncertain opacities at low temperature lead to some qualifications on our conclusions. A strong enhancement of flux from 3 to 5 μm is robust. The large H₂ CIA opacities at tens of microns, with a pronounced minimum at 3–4 μm, is a generic outcome at any temperature (e.g., Sharp & Burrows 2007, Figure 15), which forces flux into these opacities windows, as is well understood in brown dwarf and giant planet atmospheres. However, quantitatively, the shape of the emitted spectra certainly do depend on specifics of the absorption coefficients. An addition, we do not include the effects of the hypothesized, and potentially optically thick (at least at short wavelengths) CH₄ cloud, given the large uncertainties on its location and optical properties. This could depress the 3–5 μm flux compared to the cloud-free case, which emerges from deep, hotter atmospheric layers. Even with potentially dramatic flux enhancements, given the faintness of the planet in the mid-infrared, we expect that in the near future a detection in the optical is the most likely and we next turn to what information may be gleaned from an optical spectrum.

4. OPTICAL CHARACTERIZATION

Because any atmosphere of Planet Nine will be cold and may be relatively “clean” compared with solar system analogs, the reflection spectrum may well have some counter-intuitive characteristics which we discuss below. In Figure 2 we present a notional geometric albedo spectrum of a planet such as modeled here to help motivate early characterization efforts.

The geometric albedo of an infinitely deep Rayleigh scattering albedo is 0.75 at all wavelengths. (See Marley et al. 1999 for a discussion of the various forms of albedo and limiting cases.) Thus the scattered light spectrum from a deep, mostly H₂–He atmosphere would primarily be a mirror of that of the Sun. At UV wavelengths, however, Raman scattering by H₂ becomes important (e.g., Marley et al. 1999; Oklopcič et al. 2016) and will depress the geometric albedo (to as low as ~0.6). But at longer wavelengths where the Rayleigh cross-section is high and Raman less important, $\sigma_{\text{Ray}} \approx \sigma_0 \lambda^{-4}$ (where $\sigma_0 = 8.14 \times 10^{-17}$ with $\lambda$ in nm), is large and the photochemical hazes that darken the UV and blue spectra of solar system giants will likely be sparse or absent (owing to the faint UV flux and the paucity of methane). If there is, however, a bright CH₄ cloud deck, then we would expect the geometric albedo to transition from the pure Rayleigh value in the blue to
Table 2

| $T_{\text{eff}}$ (K) | CH$_4$ Abund. | $u$ | $g$ | $r$ | $i$ | $z$ | Y | VR | Y | J | H | K | L' | M' | W1 | W2 | W3 | W4 |
|---------------------|----------------|-----|-----|-----|-----|-----|----|-----|----|----|----|----|----|-----|-----|-----|-----|-----|
| 20                  | 10$^{-3}$      | 22.3| 22.0| 21.4| 22.4| 22.1| 23.0| 21.5| 23.4| 24.4| 23.9| 31.0| 29.4| 29.9| 27.6| 29.3| 35.5| 26.4|
| 20                  | 10$^{-3}$      | 22.3| 22.0| 21.3| 22.3| 21.3| 21.9| 21.5| 22.4| 23.9| 23.4| 30.9| 28.1| 29.9| 27.1| 27.9| 36.4| 29.6|
| 20                  | 10$^{-6}$      | 22.3| 22.0| 21.3| 22.3| 21.2| 21.8| 21.5| 22.3| 23.8| 23.4| 30.9| 27.1| 29.9| 26.0| 29.3| 36.3| 29.6|
| 30                  | 10$^{-3}$      | 22.3| 22.0| 21.4| 22.4| 22.2| 23.0| 21.5| 23.3| 24.3| 24.0| 30.8| 29.5| 29.7| 27.4| 29.0| 31.9| 19.8|
| 30                  | 10$^{-3}$      | 22.3| 22.0| 21.3| 22.2| 21.3| 21.8| 21.4| 22.3| 23.8| 23.5| 30.7| 27.9| 29.7| 26.9| 28.9| 31.9| 19.8|
| 30                  | 10$^{-6}$      | 22.3| 22.0| 21.4| 22.4| 22.2| 23.0| 21.5| 23.3| 24.3| 24.0| 30.8| 29.5| 29.7| 27.4| 29.0| 31.9| 19.8|
| 40                  | 10$^{-3}$      | 22.3| 22.0| 21.4| 22.4| 22.2| 21.8| 21.4| 22.2| 23.7| 23.5| 30.7| 26.4| 29.7| 25.6| 28.9| 31.9| 19.8|
| 40                  | 10$^{-3}$      | 22.3| 22.0| 21.4| 22.3| 22.2| 21.8| 21.4| 22.2| 23.7| 23.5| 30.7| 26.4| 29.7| 25.6| 28.9| 31.9| 19.8|
| 50                  | 10$^{-3}$      | 22.3| 22.0| 21.4| 22.3| 22.3| 21.8| 21.4| 22.3| 23.8| 23.6| 30.6| 20.5| 23.9| 20.5| 22.8| 25.4| 14.2|
| 50                  | 10$^{-3}$      | 22.3| 22.0| 21.4| 22.3| 22.3| 21.8| 21.4| 22.3| 23.8| 23.6| 30.6| 20.5| 23.9| 20.5| 22.8| 25.4| 14.2|
| 60                  | 10$^{-3}$      | 22.3| 22.0| 21.4| 22.3| 22.3| 21.8| 21.4| 22.3| 23.8| 23.6| 30.6| 20.5| 23.9| 20.5| 22.8| 25.4| 14.2|

Note. Apparent magnitudes at 622 au (see Fienga et al. 2016), using the described cloud-free atmosphere models and the radius of Neptune. The first seven filters are for DECam ($u$ to VR), the next five or MKO filters, while the last four are for WISE (W1 to W4). $L'$ band and redder are dominated by thermal emission, which is dominated by intrinsic flux and therefore does not depend on the orbital separation, while shorter wavelength bands are dominated by solar reflection. Therefore, these thermal versus reflected magnitudes will change as a function of orbital distance in different ways.
be a strong function of temperature (and hence, depth) in the atmosphere (Figure 1(a)). This could necessitate the detection multiple bands of CH$_4$ into the near-IR. These bands would be of different inherent strengths, which would become optically thick at different atmospheric depths, yielding a full picture of the CH$_4$ mixing ratio with depth.

If there is a solid surface, then at some wavelength, $\lambda_s$, the scattered light albedo will be dominated by the properties of the surface. For Mie scattering particles the extinction cross-section drops precipitously for wavelengths greater than about 10 times the mean particle radius. Thus, for a cloud consisting of submicron particles, near-infrared flux may penetrate both the cloud and the scattering gas, assuming the surface pressure is not too great. The windows through which the deep atmosphere of Venus and the surface of Titan are glimpsed through haze and gas are examples of this effect. The wavelength of such a break at which the surface becomes detectable, if observed, provides a measure of the surface pressure $\lambda_s \propto P_s^{1/4}$.

5. DETECTABILITY

With its expected eccentricity of order $e = 0.6$ and a posited semimajor axis of order $a = 700$ au, Planet Nine’s reflected light visual magnitude would vary by a factor of $((1 + e)/(1 - e))^2 = 256$ over the course of its orbit. As a consequence, its detectability is strongly influenced by its current radial distance from the Sun, which, as a function of true anomaly, $\nu$, is given by

$$ r_{pg} = \frac{a(1 - e^2)}{(1 + e \cos \nu)}. $$

(2)

Planet Nine’s $V$-band magnitude, therefore, is

$$ V_{pg} = 7.8 + 5 \log_{10} \left[ \left( \frac{R_{pg}}{R_{Nep}} \right)^2 \left( \frac{A_{pg}}{A_{Nep}} \right) \left( \frac{r_{pg}}{29 \text{ au}} \right)^4 \right], $$

(3)

where $V_N = 7.8$ is Neptune’s visual magnitude at opposition, and Neptune’s geometric albedo is taken as $A_{Nep} = 0.41$.

As a concrete illustration, consider the fiducial 10 $M_{Jup}$ Planet Nine candidate proposed by Batygin & Brown (2016) in conjunction with the orbital location obtained by Fienga et al. (2016) that provides the maximum reduction of the Cassini residuals. These assumptions lead to orbital elements: $a = 700$ au, $e = 0.6$, $i = 30^\circ$, $\omega = 150^\circ$, $\Omega = 113^\circ$, and $\nu = 118^\circ$, where $i$ is the inclination to the ecliptic, $\omega$ is the argument of perihelion, and $\Omega$ is the longitude of the planet’s ascending node. These elements correspond to a sky position of R.A. ~2 hr, decl. ~$-20^\circ$ in the constellation Cetus and imply a current distance $r_{pg} = 622$ au. In addition, if we adopt a Neptune-like envelope mass fraction of $f_{env} = M_{env}/M_{Jup} = 0.1$, our structural model suggests $R_{pg} = 3.46 R_{Jup}$. Drawing on the results of Section 4, we adopt a geometric albedo $A_{pg} = 0.75$, which generates a current visual magnitude $V = 21.6$. In the event that it has these parameters, Planet Nine would be detectable in the optical by the ongoing Dark Energy Survey, which is sensitive in the relevant sky location to $r < 23.8$ (Brown & Batygin 2016).

If considered as a 40 K blackbody radiator, Planet Nine’s thermal spectrum peaks at $\lambda \sim 70$ $\mu$m, rendering its detection difficult, but potentially possible, with present-day space-based instrumentation and survey coverage.

Ginzburg et al. (2016) adopt a primarily analytic approach to infer the current planetary surface temperature from the mass and composition of the planet. Using a two-component model for the core-envelope structure of the planet, they show that some of the mass-composition parameter space (assuming a blackbody spectrum) is accessible to the NASA WISE Mission’s W4 (22 $\mu$m) bandpass, and find that for a bulk composition with $f_{env} = M_{env}/M_{pl} = 0.1$ and $R_{pl} = 1.2 R_{Nep}$. Planet Nine is potentially detectable by WISE at an $r_{pg} \sim 700$ au distance.

The models delineated in Table 2 indicate that Planet Nine might be much brighter in the W1 (3.4 $\mu$m) WISE band than its effective temperature would otherwise suggest. Our extremal case, with $T_{eff} = 50$ K and $10^{-6}$ CH$_4$ abundance, predicts $W1 = 16.1$, which exceeds the WISE All-Sky $5\sigma$ sensitivity limit of $W1 = 16.5$ (Wright et al. 2010) for static object flux measurements obtained by co-adding individual source frame images. For W1 and W2, these limits were substantially improved (for stationary sources) through the incorporation of post-cryo NEOWISE observations as well as by data processing improvements (Mainzer et al. 2011). On the other hand, an object that moves significantly between epochs would contribute all of its flux to a given cataloged point source during a single epoch. For example, if P9 with intrinsic $W1 = 16.11$ were to contribute to half of the frames in a co-added two-epoch image, its reported $W1$ would be ~0.75 mag fainter than its true $W1$.

At the nominal Fienga et al. (2016) location of R.A. ~2 hr, decl. ~$-20^\circ$, Planet Nine’s total apparent parallax shift would be of an order of $\pi = 663^\circ$, and its yearly positional shift on the sky arising from its orbital motion would be of order $\sigma \sim 60^\circ$ yr$^{-1}$. These displacements combine to yield a maximum sky motion of $\delta \lesssim 6^\circ$ day$^{-1}$. Given WISE’s Sun-synchronous geocentric orbit and Planet Nine’s current nominal angular parameters ($i = 30^\circ$, $\Omega = 113^\circ$, and $\nu = 118^\circ$), its expected angular sky motion at the epochs of observation would be $\pi \sim 0^\circ12$ hr$^{-1}$, or $\Delta \pi \sim 2^\circ3$ over the 4/5th day observing sequence that is expected at Planet Nine’s current ecliptic latitude. This estimate for $\Delta \pi$ is smaller than WISE’s W1 FWHM resolution of 6$/''$. As a consequence, any WISE detection of Planet Nine in the AllWISE point source catalog would register as a series of several fully separated W1-detected (and possibly W2-detected) objects lying within a roughly one square arc minute region of the sky. These separate appearances of Planet Nine, in turn, will each be drawn from roughly twelve single-exposure images taken during a ~4/5 day period covered by overlapping scans; for further details see Wright et al. (2010).

We filtered the AllWISE Source Catalog for objects with $0 < \text{R.A.} < 4$ hr and $-30^\circ < \text{decl.} < 0^\circ$, having $W1 > 16$, $W2 > 17$ (or null), $W3 > 20$ (or null), and $W4 > 10$ (or null). This screen produced a single match: J005009.06-315732.2 (J005), which has $W1 = 16.972$ and $W2 = 17.032$, and which was observed by WISE on five individual image frames. The WISE catalog reports that J005’s W1 timestamps span a single two-day period from HJD 2455542.53 through 2455546.16. Based on the foregoing discussion, a single-source detection built up over four days is at best marginally consistent with

\[ \text{http://wise2.ipac.caltech.edu/docs/release/allwise/express/sec1_5.html} \]
Planet Nine’s expected sky movement. Furthermore, the J005 object is not paired with any sources having similar photometry in the near vicinity and at separate epochs. Moreover, J005’s W2 single-frame detection epochs range over a six-month span from HJD 2455365.12 to HJD 2455546.16, implying that it is a transiently detected, yet nonetheless stationary object or noise source. J005 can, therefore, confidently be rejected from consideration as a Planet Nine candidate. While we believe it is exceedingly unlikely that Planet Nine can be located in the AllWISE Source Catalog, it is unlikely, yet nonetheless possible, that it makes an appearance in the AllWISE Reject Table. We are currently sifting this 428, 787, 253-line database for candidates.

6. CONCLUSIONS

We modeled several aspects of the thermal evolution and atmospheric structure and spectra of the possible Planet Nine. Like others, we find a planetary $T_{\text{eff}}$ of perhaps $35-50$ K, depending on mass, but we caution that these are upper limits. The atmosphere could well be in a temperature range of significant condensation of methane. The loss of this important "giant planet" opacity source can dramatically alter both the reflection and emission spectra away from expectations based on Uranus and Neptune, with the notable effect of causing Planet Nine to appear “blue” rather than “red” in the WISE bands.

Our models suggest that the reflection spectrum, due to a mix of Rayleigh scattered sunlight, cloud scattering, and absorption due to $\text{H}_2$ and $\text{CH}_4$ opacity could provide rich diagnostics of the temperature structure, possible cloud location, and even surface pressure of the atmosphere. Let the hunt continue.

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