Detecting Planet 9 via Hawking radiation

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Abstract

Concordant evidence points towards the existence of a ninth planet in the Solar System at more than 400 AU from the Sun. In particular, trans-Neptunian object orbits are perturbed by the presence of a putative gravitational source. Since this planet has not yet been observationally found with conventional telescope research, it has been argued that it could be a dark compact object, namely a black hole of probably primordial origin. Within this assumption, we discuss the possibility of detecting Planet 9 via a sub-relativistic spacecraft fly-by and the measure of its Hawking radiation in the radio band. We also present some perspectives related to the study of such a Hawking radiation laboratory in the Solar System.

1 Introduction

Perturbations of orbits of known objects in the Solar System have led astronomers to search for gravitational sources from which they originate, under the form of unknown planets. After the discovery of Neptune in 1846, no more planets were found beyond dwarf planets such as Pluto or Eris. However concordant evidences have recently appeared in direction of what has been a proofless obsession for many astronomers: the existence of Planet 9, which may become an object under even more intense scrutiny. The apparent clustering of trans-Neptunian objects (TNOs) orbits in the Kuiper belt suggests the presence of a massive body of a mass $M \sim 5 - 10 \, \text{M}_\oplus$ orbiting between 300 and 1000 AU \cite{1,2}. Even though the statistics of clustered TNOs is not sufficient enough to robustly exclude coincidental observations, the probability of accidental correlations is $\lesssim 1\%$ \cite{3}. The parameters of this hypothetical Planet 9 are further constrained by ephemeride measurements such as those of Cassini \cite{4,5}.

In spite of telescope searches, no new object has been found in the sky to be Planet 9. Ref. \cite{6} thus suggests that Planet 9 may be a compact dark object, invisible to telescopes – namely, a Black Hole (BH). A BH with such a light mass certainly points towards a non-stellar origin because of the Chandrasekhar limit; this BH could be one of the putative primordial BHs (PBHs) that are under intense scrutiny since they could represent some or all of dark matter (DM) (for a recent review on PBH formation mechanisms and constraints, see e.g. \cite{7} and references therein). PBH abundance is severely constrained for about 50 orders of magnitude in mass, but there still exists an open parameter space for them to represent all DM in the sub-lunar mass range, or part of it in various other mass windows. The fraction of dark matter under the form of PBHs is expected to be $f \sim 0.1 - 0.01$ in the Planet 9 mass region. PBHs are believed to have formed after inflation from primordial density inhomogeneities that collapsed when the overdensity was above some threshold. No confirmed PBH has been observed yet, but OGLE has recently found PBH candidates in microlensing events \cite{8} whose masses would correspond to the mass of Planet 9. Thus, it is plausible to consider that if a population of terrestrial mass PBHs exists, one of them could have been captured by the Sun gravity and could be orbiting beyond Neptune, providing an explanation for the "invisible" body responsible for the gravitational anomalies of TNOs.

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Successively, two experiments have been proposed to detect Planet 9 if it were a BH (hereafter called P9). Both are based on ideas similar to the Breakthrough Starshot proposal\(^3\) in which it is proposed to send a fleet of very small spacecrafts \(m \sim g–kg\) at sub-relativistic speeds \(v \sim 0.001c\) in different directions of the sky to reach nearby stars in order to study their planetary systems and achieve the most distant explorations ever \([9]\). Their advantage is that such light and fast spacecrafts would reach the orbit of an eventual P9 in a few years. By sending many of those across the sky towards the hypothetical location of P9 orbit, one gets a chance that one of them experiences a fly-by of P9. The first proposal is to measure the time delay in the line of sight trajectory of a given spacecraft (hereafter called SC0 for spacecraft 0, the discoverer), induced by the presence of a nearby massive body \([10]\). This would necessitate an on-board precision clock to measure a \(\sim 10^{-5}\) s time delay over a one year trajectory. The second proposal is to measure the transverse inclination of the trajectory of SC0 induced by the presence of P9 \([11]\). This alleviates the on-board clock problem but necessitates a \(\sim 10^{-9}\) rad angular displacement measurement, which could be doable with VLBI for example. However, in Ref. \([12]\) the authors examined the environment in which SC0 would travel to reach the orbit of P9 and concluded that the interstellar medium turbulence – drag and magnetic fields – would make the precise gravitation-perturbed trajectory measurements cited above impossible to achieve due to noise signals from unknown medium local properties.

There also exists a completely different approach to P9 detection proposed in \([13]\), based on the fact that icy objects of the Oort cloud would get disrupted by the P9 gravitational field and the accretion of such material could cause flares detectable by the LSST survey\(^4\) \([14]\). A few of such events could occur per year, making them detectable. In addition, it would prove the BH nature of P9, and solve the trajectory difficulties of the sub-relativistic spacecrafts described in \([12]\).

Here we suggest a new proposal, based on the fact that P9, if it is indeed a BH, will emit Hawking radiation \([15]\). When classical general relativity is mixed up with quantum mechanics effects, the fluctuations of the vacuum at the horizon of a BH give rise to a net emission of particles at spatial infinity, causing the BH to slowly evaporate away. Thus even if P9 is not visible from the Earth (not being a reflective planet but a BH), it would still emit a small amount of radiation. This was already considered in the original paper about the BH nature of P9 \([6]\) but the authors concluded that the amount of Hawking radiation was too small to be detectable from Earth, which is true. What we consider here is the detection of this very Hawking radiation by the flying-by SC0, in the vicinity of P9, as described in the next section. This would be of particular importance since, even if rather well theoretically motivated, Hawking radiation has not yet been observed, because the power received on Earth is much too small for conventional BHs, such as stellar ones like Cygnus X-1 \([16,18]\) or supermassive ones like Sagitarius A* \([19,20]\). Hawking radiation by smaller BHs results in constraints on their abundance but not in detection signals, see e.g. the recent work on BBN \([17,21]\), CMB \([21,22]\), gamma rays \([23,24]\), electrons-positrons annihilation or detection \([27,30]\), neutrinos \([30,31]\), local PBH burst rate \([32,34]\), dark matter production \([35,36]\) and even primordial gravitational waves \([37,38]\). Nevertheless the precise spectrum of Hawking radiation may contain information on the quantum structure of BH horizons. Therefore directly observing the BH Hawking radiation would be of great importance, and a PBH in our Solar System would represent the best laboratory to study it.

2 Hawking radiation light curves

2.1 Setup

The setup of the experiment would be the following. SC0 passes by P9 at speed \(v\) and with impact parameter \(b\). We define \(t = 0\) to be the time of minimal approach. When SC0 approaches P9, the radiation flux will increase, reach maximum at \(t = 0\) and then decrease. Since we consider sub-relativistic velocities, Doppler effect is negligible. The spatial displacements considered in \([10,12]\) have however to be taken into account as an uncertainty on the precise trajectory of the ship. We neglect them for the moment and consider an ideal straight line trajectory for SC0.

P9 has a super-terrestrial mass \(M_{P9} \sim 5–10 M_\oplus\), thus its peak electromagnetic emission frequency

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lies around the GHz radio band. We do not have any indication of P9 dimensionless spin $a^*$; as a PBH it is expected to have a negligible spin but it has been shown that transient matter-domination era at the end of inflation can produce high-spin PBHs that can conserve their spin until today despite Hawking evaporation \[39\]. We show in Fig. 1 the power emission as a function of frequency for different P9 masses and spins such as

$$\frac{d\mathcal{P}(M, a^*)}{d\nu} = E \frac{d^2 N}{dt d\nu},$$

where $\frac{d^2 N}{dt d\nu}$ is the number of photons emitted by Hawking radiation per units of time and frequency. We clearly see that the low-mass high-spin setup is favoured by detection because it implies more energetic and abundant emission.

Let us consider that the solar sail of the Breakthrough Starshot-like spacecrafts considered here is used as a radio antenna in the GHz band, with a surface area of $S \sim m^2$ \[9\]. The power received by the ship, if the sail is considered perpendicular to its trajectory, is then of the form

$$\mathcal{P}(t) = \eta \frac{S(t)}{4 \pi r(t)^2} \int_0^{+\infty} E \frac{d^2 N}{dt dE} \, dE,$$

where the energy integral covers the radio GHz band, $r(t)$ is the distance between SC0 and P9 and $S(t)$ is the area of the sail projected in the direction of P9. Here $\frac{d^2 N}{dt dE}$ is the number of photons emitted per units of time and energy. The emission rates of particles by evaporating BHs are computed using the public code BlackHawk \[40\]. The efficiency coefficient $\eta$ corresponding to the absorption of the sail is considered in Eq. (2) for completeness, but since we do not make any assumption on the material or technology, we do not have an estimation of it; in any case it has to be maximized. Finally we assume the sail to be perpendicular to the direction of motion for simplicity, but we note that there probably exists more optimized geometries to maximize the power received during a fly-by while keeping a sufficient acceleration via laser propulsion.

![Figure 1: Total power emission of photons by P9 as a function of frequency for different values of the P9 parameters $M = \{5, 10\} M_\odot$ and $a^* = \{0, 0.99\}$.

\[\text{Figure 1: Total power emission of photons by P9 as a function of frequency for different values of the P9 parameters}}\]
2.2 Ideal straight line trajectory

We geometrically compute \( S(t) \) and \( r(t) \) by defining \( \alpha \) as the angle between SC0 velocity \( \vec{v} \) and position \( \vec{r} \) relative to the origin at P9, and consider that the (one dimensional) sides of an area \( A \) have lengths of the order \( \sqrt{A} \). We obtain

\[
\cos(\alpha) = \frac{\sqrt{S(t)}}{\sqrt{S}} \iff S(t) = \cos(\alpha)^2 S, \tag{3}
\]

and

\[
\tan(\alpha) = \frac{b - \sqrt{S}}{|r^*(t)|}. \tag{4}
\]

Thus the projected area is

\[
S(t) = \cos\left[ \arctan\left( \frac{b - \sqrt{S}}{|r^*(t)|}\right) \right]^2 S, \tag{5}
\]

where \( r^*(t) = vt \) is the distance to minimal approach in the straight trajectory approximation and \( r(t) = \sqrt{r^*(t)^2 + b^2} \). We see that even if the distance is minimal at \( (t = 0, r^*(t) = 0, r(t) = b) \), the projection of the flux on the sail is zero at this point. Thus we expect a peak feature in the time-dependent radio signal with a discontinuity at \( t = 0 \).

2.3 Perturbed trajectory

If the kinetic energy carried by SC0 becomes comparable to the gravitational potential energy of P9, we can expect a gravitational perturbation of the trajectory, i.e. for

\[
E_{\text{kin}} \sim E_{\text{pot}} \iff \frac{1}{2} m v^2 \sim \frac{G M m}{r} \iff r \sim \frac{2 G M}{v^2}. \tag{6}
\]

Considering the speed and mass at stake here, it occurs when \( b \lesssim 100 \text{ km} \). The trajectory will be deviated as given in [11, 12] because of the time build-up of small shifts, but this will occur at timescales much larger than this fly-by detection time. However if the impact parameter becomes very small the full trajectory needs to be taken into account to predict the form of the signal. This can be done by taking again the geometrical definitions given in the previous section and redefining an effective instantaneous (at time \( t \)) impact parameter \( \tilde{b}(t) \) and effective instantaneous distance to the minimal approach point \( \tilde{r}^*(t) \), which could be seen as the geometric quantities obtained in case SC0 were to continue in a straight line from time \( t \). Thus the \( \tilde{\alpha}(t) \) angle is the angle between the instantaneous velocity and position vectors

\[
\cos(\tilde{\alpha}) = \frac{\vec{v} \cdot \vec{r}}{vr}, \tag{7}
\]

and the perturbed quantities to be considered in the area projection formula in Eq. (5) are

\[
\tilde{b} = r \sin(\tilde{\alpha}) , \quad \tilde{r}^* = r \cos(\tilde{\alpha}). \tag{8}
\]

2.4 Results

The expressions (2) and (5) (with ideal or perturbed geometrical quantities) allow us to compute the light curve received by SC0 as it passes by P9. A test result is shown in Fig. 2. The main aspect of this test signal is that it is symmetrical, making the detection easier with respect to the background. Doppler effect would make it asymmetrical but due to the sub-relativistic speed it has negligible effects in our analysis. One can extract the parameters from the signal by using the following approximation, which is valid far from the minimal approach position \( vt \gg b \)

\[
P(t) = \frac{S(t)}{4 \pi r(t)^2} \int_0^{+\infty} E d^2 N dtdE 
\]

\[
\equiv \frac{S(t)}{4 \pi r(t)^2} \mathcal{P}_0 
\]

\[
\approx \mathcal{P}_0 S \left( \frac{1}{4\pi} \frac{1}{(vt)^2} \left( 1 - 2 \left( \frac{b}{vt} \right)^2 \right) \right), \tag{9}
\]
Figure 2: Example of a light curve for a speed $v = 0.001c$, impact parameter $b = 10^3$ m, sail area $S = 1$ m$^2$, and P9 parameters $M = 5M_\oplus$ and $a^* = 0$ (solid line). The approximation of Eq. (9) leads to the dashed line.

Table 1: Parameters of the P9 and SC0 setups used in Fig. 3

| setup | $M$ | $a^*$ | $b$ | $S$ |
|-------|-----|-------|-----|-----|
| setup 1 | $5M_\oplus$ | 0.99 | $10^5$ m | $100$ m$^2$ |
| setup 2 | $5M_\oplus$ | 0 | $10^6$ m | $10$ m$^2$ |
| setup 3 | $10M_\oplus$ | 0 | 1 AU | 1 m$^2$ |

as can be seen in Fig. 2. This approximation is valid in the straight line trajectory approximation, which is a good approximation as we will see below. In Fig. 3 we show the light curves for different setups as summarized in Table 1. According to Eq. (9) one has to draw the detection signal with a rescaled time

$$t_0 = \left(\frac{3 \times 10^4 \text{ m}}{b}\right) s,$$

in order to display all signals of Fig. 3 in the same plot. This is only in the favourable setup 1 that one gets an order of magnitude for the radio signal that is comparable with the currently most precise (Earth-based) detection tools. For example, the project Breakthrough Listen aims at detecting GHz signals from nearby stars to search for artificial signals as hints of advanced civilizations. Ref. [41] claims a minimal flux detection of $7.14 \times 10^{-26}$ W·m$^{-2}$ using the Green Bank Telescope – a 100 meters diameter collecting antenna [42]. We do not expect the signal extraction from ambient noise to be any more difficult in P9 neighbourhood than on Earth. In Fig. 3 we show also the results with the exact trajectory calculations taking into account the gravitational well of P9. We see that for the considered setups the effect is very small.

P9 mass $M$ affects the energy of emission and thus its power. The resulting signal is proportional to the inverse of the mass squared (temperature squared). The degeneracy in mass is small for P9, hence we expect a $O(10)$ factor at best when going from higher masses to lower masses as permitted by current constraints. P9 spin $a^*$ affects the emission rate and the power received, and we know that the signal can be enhanced by a factor of $O(100)$ for photons when the spin is near extremal [24, 43].

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The signal reception is proportional to the sail area $S$, so multiplying the area by $\mathcal{O}(10)$ gives an amplification factor of $\mathcal{O}(100)$. The impact parameter $b$ fixes the minimum distance $r(t)$ that can be achieved, so the peak result is inversely proportional to $b^2$. The impact parameter on the other hand is a highly random parameter, which depends on the density of spacecrafts launched in the direction of the orbit of P9.

2.5 Other perspectives

Finally, we point out that our proposal of Hawking radiation detection during a fly-by can be viewed as a complementary mean of detection of P9, would it be a BH. Indeed, optimizations of proposals presented in [10, 11], while taking into account the trajectory shifts estimated in [12], or proposal [13], may lead to a drastic reduction in the possible sky localization of P9 along its already constrained orbit. Therefore, with a more precise determination of its localization and if P9 still appears as a BH, it will be of utmost importance to send a mission orbiting P9, or at least to try to achieve the closest possible fly-by for a radio mission as described in this work. Hawking radiation would be the only direct measurement of the presence of P9, gravitational perturbations being only indirect evidence. The in situ measure of radio emission will give access to the form and properties of the BH horizon, thus giving exciting prospects for BH and fundamental physics. In case of satellization of a spacecraft around P9, Fig. 4 shows the radio flux $F$ as a function of the orbit radius $r$, defined as

$$F = \frac{1}{4\pi r^2} \int_0^{+\infty} E \frac{d^2N}{dt dE} dE.$$  

Another direct probe of the presence of such a heavy BH via Hawking radiation is the emission of gravitational waves (GWs). In a semi-classical view of gravity, GWs are dual to massless spin 2 particles named gravitons. If the graviton is indeed a fundamental particle, it can be expected to be emitted by Hawking radiation. It has already been conjectured that graviton emission by PBH evaporation in the primordial universe could constitute a stochastic background carrying information on the first seconds after the Big Bang [37, 38, 44–46]. The detection of this high-frequency background remains a technical challenge. The amount of GWs emitted by present day BHs is again usually considered.
too low to be detectable from Earth. If one were to put spacecrafts in orbit around P9, search for such gravitational waves would be of utmost importance to probe the existence and properties of the gravitons, constituting a portal to quantum gravity. In Fig. 5 we show the density of GHz GWs that such a satellite would receive as a function of its orbit radius

$$\Omega_{GW} = \frac{1}{c \rho_c} \left( \frac{H_0}{100 \text{ km} \cdot \text{s}^{-1} \cdot \text{Mpc}^{-1}} \right)^2 \frac{1}{4 \pi r^2} \int_0^{+\infty} E \frac{d^2 N}{dt dE} dE,$$

(12)

where $c$ is the speed of light, $\rho_c \approx 8.523 \times 10^{-30} \text{ g} \cdot \text{cm}^{-3}$ is the critical density and $H_0 = h \times (100 \text{ km} \cdot \text{s}^{-1} \cdot \text{Mpc}^{-1})$ with $h \approx 0.67$ the reduced Hubble constant [47]. Since it would constitute a constant signal, extraction from the noise may be easy. We see from Fig. 5 that a high P9 spin can increase the amplitude of GWs by 4 orders of magnitude [43, 46].

3 Conclusion

In this exploratory work we have proposed a new way to probe the presence of a hypothetical Planet 9 in the outer Solar System if it were actually a black hole, by using a Breakthrough Starshot-like fleet of nano-spacecrafts. Considering the difficulties of measuring tiny longitudinal or transverse displacements that P9 would induce on a spacecraft during a pass-by, mostly related to the fact that trajectory perturbations arising from the interstellar medium would be of the same order, we propose to measure in situ the Hawking radiation emitted by P9 in the form of GHz radio photons. This method has two main advantages, first it is not affected by the trajectory noise because it only relies on classical on-board electromagnetic detection, second it would be a unique occasion to measure and thus prove the existence of Hawking radiation, a long-standing prediction of black hole thermodynamics. The principal difficulty is to measure a very faint signal in the radio GHz band, with an amplitude inversely proportional to the square of the impact parameter $b$, therefore requiring either great luck or a multitude of spacecrafts in order to reach a fly-by of P9 at $\sim 100 \text{ km}$ distance, or the use of an extremely precise radio detection technology. Nevertheless, if P9 were indirectly localized using for example spacecraft trajectory measurements or LSST flares, an orbital mission would be of great importance to study the properties of black holes and Hawking radiation.
Figure 5: GWs density as a function of orbit radius for different P9 masses $M = \{5, 10\} M_\oplus$ and spins $a^* = \{0, 0.99\}$.

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