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EXCLUDING PRIMORDIAL BLACK HOLES AS DARK MATTER BASED ON SOLAR SYSTEM EPHEMERIS

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ABSTRACT

Current cosmological constraints allow primordial black holes (PBHs) to constitute dark matter in the mass range of 10^{18}–10^{22} g. We show that a major portion of this logarithmic window can be ruled-out based on the Solar System ephemeris, given that the external mass enclosed within 50 au from the Sun did not change by more than $\sim 5 \times 10^{-14}\ M_{\odot}\ \mathrm{yr}^{-1}$ in recent decades.

1. INTRODUCTION

Current cosmological constraints allow for the possibility that dark matter is made of primordial black holes (PBHs) in the mass range of $\sim 10^{18}$-10^{22} g (Carr & Hawking 1974; Carr & Kuhnel 2021; Green 2024; Carr & Green 2024).

Recently, Pitjeva et al. (2021) used data in the Solar System ephemeris EPM2019 to constrain the change in the mass of the Sun based on the dynamics of Solar System objects out to ~ 500 au. EPM2019 incorporates full 3D position and velocity vectors of the Sun, the Moon, the eight major planets, Pluto, the three largest asteroids (Ceres, Pallas, and Vesta) and four transneptunian objects (Eris, Haumea, Makemake, and Sedna), covering data over more than 400 yr.

Accounting for the known components of mass loss from the Sun in radiation or solar wind and the small mass gain from infall, Pitjeva et al. (2021) derived the following 3σ limits on the rate of unaccounted-for mass change,

$$-2.9 \times 10^{-14} < \frac{\delta \dot{M}}{M_\odot} < +4.6 \times 10^{-14} \text{ per yr} , \tag{1}$$

where $\delta M = (M - M_\odot)$ corresponds to any mass deficit or excess relative to the known mass budget of the Sun.

If dark matter is made of PBHs, then the temporary passage of a PBH through the inner Solar System would introduce a transient δM in the gravitational mass affecting all objects orbiting the Sun outside of the PBH-Sun separation. Here, we study the constraints set by equation (1) on the abundance of PBHs in the mass range of 10^{18}-10^{22} g. In our analysis, we ignore the possibility of a time dependent Newton's constant, because it is unlikely that such variations would compensate random δM fluctuations introduced by PBHs as they enter and exit a perihelion distance of $\sim$ 50 au over timescales of years.

2. NEW SOLAR SYSTEM CONSTRAINTS

Based on the latest Galactic data, the dark-matter near the Sun has a mass-density (Sivertsson et al. 2022; Staudt et al. 2024),

$$\rho_{\rm dm} = 7(\pm 1) \times 10^{-25} \text{ g cm}^{-3} , \tag{2}$$

a 3D velocity dispersion of $280(\pm 19)$ km s^{-1}, and a most probable speed relative to the Sun of,

$$v = 257(\pm 11) \text{ km s}^{-1} , \tag{3}$$

with a sharp truncation above 470 km s^{-1}. If PBHs of a given mass, $m = m_{20} \times 10^{20}$ g, make the dark matter, then their local number density is derived from equation (2),

$$n = \left(\frac{\rho_{\rm dm}}{m}\right) \approx 2.4 \times 10^{-5} \text{ au}^{-3} m_{20}^{-1} . \tag{4}$$

The rate by which PBHs of mass m enter a volume of radius r around the Sun is given by,

$$\Gamma = n \times \left(\pi r^2\right) \times v . \tag{5}$$

Substituting v from equation (3) and n from equation (4) yields an entry rate,

$$\Gamma = 10.2\ m_{20}^{-1} \left(\frac{r}{50\ \mathrm{au}}\right)^2\ \mathrm{yr}^{-1}\ . \quad (6)$$

For our fiducial detection volume, we consider a sphere defined by transneptunian objects around $r \sim 50$ au in the EPM2019 data which was used to derive equation (1). For generality, we also express our PBH constraints as a function of the bounding value of r.

Multiplying the PBH entry rate in equation (6) by the PBH mass m yields the rate by which the mass interior to a radius r changes as a result of the crossing of a single PBH within that radius from the Sun,

$$\dot{m} \equiv m\Gamma = 5 \times 10^{-13} \left(\frac{r}{50\ \mathrm{au}}\right)^2\ M_\odot\ \mathrm{yr}^{-1}\ , \quad (7)$$

implying that for $r \sim 50$ au a single PBH with $m_{20} > 0.1$ can violate the limits in equation (1).

The crossing time of a radius r by a PBH is given by,

$$\delta t = \left(\frac{r}{v}\right) = 0.93\ \mathrm{yr}\ \left(\frac{r}{50\ \mathrm{au}}\right)\ , \quad (8)$$

introducing a fluctuation δM on a relevant timescale to be detectable in the EMP2019 data.

At any given time, the number of PBHs within the sphere of radius r is,

$$N = n \times \left(\frac{4\pi r^3}{3}\right) = 12.6\ m_{20}^{-1}\ \left(\frac{r}{50\ \mathrm{au}}\right)^3\ . \quad (9)$$

Poisson fluctuations over a time δt in the enclosed mass of PBHs yield,

$$\delta \dot{M} = \frac{\sqrt{N} m}{\delta t} = 1.9 \times 10^{-13} m_{20}^{1/2}\ \left(\frac{r}{50\ \mathrm{au}}\right)^{1/2}\ M_\odot\ \mathrm{yr}^{-1}\ , \quad (10)$$

with a weak square-root dependence on m and r. Equation (10) holds for $N > 1$, namely $r > 22 m_{20}^{1/3}$ au.

Equations (7-10) imply that the 3σ limits in equation (1) exclude PBHs as dark matter in the previously allowed mass range of 6×10^{18} g $< m < 10^{22}$ g for $r \sim 50$ au and the entire range of 10^{18}-10^{22} g for Sedna's semimajor axis at $r \sim 500$ au . At the upper end of this mass range, a PBH with $m \sim 10^{22}$ g is expected to get within 50 au from the Sun once per decade and within ~ 8 au once per 400 years. At the lower mass end, there are ~ 210 PBHs with $m \sim 6 \times 10^{18}$ g within 50 au from the Sun at any given time. The nearest is ~ 8.4 au from the Sun at any given time, but during 400 years the nearest arrives as close as ~ 0.2 au at perihelion.

3. DISCUSSION

We have found that the dynamical constraints from the Solar System ephemeris EPM2019 exclude a substantial portion of the allowed logarithmic window for PBHs as dark matter, 10^{18}-10^{22} g, depending on the choice of the boundary radius r out to which the interior mass is not allowed to change by more than $5 \times 10^{-14}\ M_\odot\ \mathrm{yr}^{-1}$. Detailed simulations of how PBHs with a broad mass distribution across this range affect the specific details of the EMP2019 data, are required to refine these constraints.

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REFERENCES

Carr, B., & Kuhnel, F. 2021, arXiv e-prints, arXiv:2110.02821, doi: 10.48550/arXiv.2110.02821

Carr, B. J., & Green, A. M. 2024, arXiv e-prints, arXiv:2406.05736, doi: 10.48550/arXiv.2406.05736

Carr, B. J., & Hawking, S. W. 1974, MNRAS, 168, 399, doi: 10.1093/mnras/168.2.399

Green, A. M. 2024, Nuclear Physics B, 1003, 116494, doi: 10.1016/j.nuclphysb.2024.116494

Pitjeva, E. V., Pitjev, N. P., Pavlov, D. A., & Turygin, C. C. 2021, A&A, 647, A141, doi: 10.1051/0004-6361/202039893

Sivertsson, S., Read, J. I., Silverwood, H., et al. 2022, MNRAS, 511, 1977, doi: 10.1093/mnras/stac094

Staudt, P. G., Bullock, J. S., Boylan-Kolchin, M., et al. 2024, JCAP, 2024, 022, doi: 10.1088/1475-7516/2024/08/022