Primordial Black Holes, Hawking Radiation and the Early Universe

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The 511 keV gamma emission from the galactic core may originate from a high concentration ($\sim 10^{22}$) of primordial black holes (PBHs) in the core each of whose Hawking radiation includes $\sim 10^{21}$ positrons per second. The PBHs we consider are taken as near the lightest with longevity greater than the age of the universe (mass $\sim 10^{12}$ kg; Schwarzschild radius ~ 1 fm). These PBHs contribute only a small fraction of cold dark matter, $\Omega_{PBH} \sim 10^{-8}$. This speculative hypothesis, if confirmed implies the simultaneous discovery of Hawking radiation and an early universe phase transition.

The slices of the cosmological energy pie have been clarified recently. Only about 4% comes from the familiar baryons. The other 96% is mysterious: some 25% is dark matter (hereafter DM) and the remaining 71% is dark energy. Neither of these two large slices is understood.

Here we investigate the hypothesis that a small fraction of cold dark matter (CDM) is made up of primordial black holes (PBHs). In particular, we investigate the possibility that the 511 KeV gamma rays from the vicinity of Sagittarius A* may originate from Hawking radiation[1]; the detection of Hawking radiation within the Solar System is frustrated by the number (as we shall estimate below) of PBHs therein.

We should first define the meaning of PBH. The Hawking temperature of a Black Hole is given by

$$T_H = \frac{M_{Planck}^2}{8\pi M} \sim 4 \times 10^{-10} \left(\frac{M_{Planck}}{M} \right) kg \tag{1}$$

and, using $1kg \sim 10^{27}eV$, $1^oK \sim 10^{-4}eV$ this is

$$T_H \sim 10^{31}K \left(\frac{M_{Planck}}{M} \right) \tag{2}$$

so to make $T_H \sim 2.7K$, the temperature of the Cosmic Background Radiation (CMB), one needs $M \sim 3 \times 10^{30} M_{Planck} \sim 3 \times 10^{22}kg \sim (1\%)M_{\oplus}$, or about one per cent of the mass of the Earth, $M_{\oplus} \sim 4 \times 10^{24}kg$. Let us denote this PBH mass by M_{rad} since it is the maximum mass PBH which will radiate with a temperature higher than that of the CMB.

Heavier black holes will generally accrete matter and grow but these are also possible PBHs. In the galactic halo the maximum mass compatible with the behavior observed [2, 3] we shall take to be $M_{max} \sim 10^6 M_{\odot} \sim 10^{36}kg$.

The lifetime[4] of a PBH is proportional to M^3. For $T_H > 100GeV$ it is approximately

$$\tau(M) \sim 100\tau_{Planck} \left(\frac{M}{M_{Planck}} \right)^3 \tag{3}$$

Taking $\tau_{Planck} \sim 10^{-43}sec$ we find $\tau(M_{min}) \sim t_O \sim 10^{18}sec$, the age of the Universe, for $M_{min} \sim 5 \times 10^{11}kg$. This is therefore the minimal mass PBH which could have survived since the Big Bang.

Thus the allowed range of masses of PBHs in existence today spans 24 order of magnitude from $M_{max} \sim 10^{36}$ kg down to $M_{min} \sim 10^{12}$ kg. We shall assume a phase transition in the early universe which produces PBHs centered around $M_{PBH} = 10^{12}$ kg.

Black hole sizes are characterized by the Schwarzschild radius $r = 2GM$. It is of order 10^7 km for M_{max} and $10^{-13}cm = 1fm$ for M_{min}. The minimal PBH is a formidable object with the mass of Mount Everest and the size of a proton; its density is some 53 orders of magnitude times that of water, and its Hawking temperature is a hundred billion (10^{11}) degrees Kelvin, or ~ 10 MeV. Such $(PBH)_{min}$ are the most interesting cases since they may make their presence known by an explosive final evaporation. Detection of Hawking radiation is most likely if all PBHs have mass M_{min}, so we shall emphasize this unjustified (but interesting) assumption.

Let us make a preliminary discussion of the CDM. A convenient volume is $V = (mly)^3$, roughly the volume of the Solar System where mly is a milli-lightyear $\sim 10^{15}cm$. The total DM mass in the visible Universe is $\sim 10^{80}GeV \sim 10^{53}kg$ in a total volume $\sim 10^{39}(mly)^3$ so the average DM density is $\sim 10^{14}kg/(mly)^3$. Since the DM is concentrated in clusters with an overdensity of about a hundred, the local DM density is closer to $10^{16}kg/(mly)^3$ or $10^4(PBH)_{min}/(mly)^3$.

We would need to estimate the mass distribution of PBHs, but let us continue with the most optimistic scenario. Consider the core of the Milky Way, which subtends an angle of several degrees at a distance about 10^4ly and so the core volume is $\sim (10^3ly)^3 = 10^{18}(mly)^3$ or $\sim 10^{18}$ times the volume of the Solar System. The galactic core thus contains some 10^{34} kg of DM which corresponds to $\sim 10^{22}M_{min}$. This corresponds to only a small fraction of the CDM, $\Omega_{CDM} \sim 10^{-8}$.

Given that the local density of CDM is $\sim 10^{16}kg/(mly)^3$, detection of Hawking radiation within the Solar System is quickly seen to be impracticable since our $\Omega_{PBH} \sim 10^{-8}$ suggests the number of PBHs in the Solar System is vanishingly small (a number $\sim 10^{-4}$!) even for the minimal mass of a PBH, becoming even smaller if larger M_{PBH} are considered: unfortunately, confirmation of Hawking radiation within the *mly* scale of the Solar System looks impossible even in this most optimistic scenario. Therefore, we must look further afield, at least $\sim 10^7$ times further, to the distance ($\sim 10kpc$) of the galactic core where the situation is much more hopeful.

Given our hypothesis that $\Omega_{PBH} \sim 10^{-8}$ in the form of PBHs, we have seen that there can be up to $\sim 10^{22}(PBH)_{min}$ in the core of the Milky Way. We now investigate whether this is a plausible source of the 511 KeV gamma rays detected therefrom, see the recent measurements reported in [5, 6] and the earlier data cited therein.

The mass decay rate of a PBH is given by (see *e.g.* [7, 8])

$$\frac{dM}{dt} = -5 \times 10^{25} (M \quad \text{in} \quad \text{grams})^{-2} g/s \tag{4}$$

so for $M = 10^{15}$ g the rate of mass loss is 5×10^{21} g/s, which using 1 g $\sim 10^{24}$ eV and the fact that some 22% of the radiation[7] is in the form of positrons suggests some 10^{21} positrons per second per PBH.

Thus the total number of annihilations in the core per second is estimated as $\sim 10^{22+21} = 10^{43}$, very consistent [9] with the observational number [5, 6] which is 1.3×10^{43} per second.

This then provides an attractive alternative to the ideas [11, 12, 13] of dark matter annihilation or [14] gamma-ray bursters as an explanation of the 511 KeV gamma rays.

Let us consider the implications of PBHs with mass $\sim 10^{12}$ kg. In order for them to form there must have been density perturbations of mass of order the particle horizon $M_H(t)$ mass at their time of formation, where $M_H(t) \approx \frac{c^3 t}{G} \approx 10^{15} \left(\frac{t}{10^{-23}\text{ s}}\right) g$. At the Planck time $\sim 10^{-43}$ s one finds $M_H(t) \approx 10^{-5}$ g. When $M_H(t) \approx 10^{12}$ kg we have $t \sim 10^{-20}$ s, the horizon size was ~ 1 fm, and the energy scale was $\sim 10^8$ GeV. This provides information on the state of the Universe at this early epoch. In fact, to generate the density perturbations the Universe would need to have been going through a phase transition at this time. An earlier phase transition would have generated less massive PBHs which would have already evaporated by now. A later phase transition would have generated more massive PBHs with T_H below the level needed to evaporate positrons. So, given the evidence for positrons from the 511 KeV gamma ray data, and assuming the positrons come from PBHs, we are lead to the inevitable conclusion that there must have been a phase transition in the early Universe at approximately $\sim 10^8$ GeV. Furthermore, there could have been very little inflation since this phase transition, otherwise the PBHs would have been inflated away. The $\sim 10^8$ GeV energy scale in near the geometric mean of the electroweak scale and the grand unification or string scale, and has appeared in many contexts in particle physics model building, ranging from axion physics (which has been suggested as a dark matter candidate) to the scale of supersymmetry breaking. PBHs at mass $\sim 10^{12}$ kg is solid evidence for a phase transition at the $\sim 10^8$ GeV energy scale.

To confirm that the the 511 keV gamma rays are coming from PBHs further tests are required. For example, along with the positrons, there are electrons and a black body spectrum of direct gamma rays. If these spectra could be discovered, then the PBH scenario would be on solid ground and simultaneously imply the discovery of Hawking radiation and an early universe phase transition.

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[1] S.W. Hawking, Commun. Math. Phys. **43,** 199-220 (1975).
[2] G. Xu and J. Ostriker, Ap. J. **437,** 184 (1994).
[3] N. Afshordi, P. McDonald and D.N. Spergel, Ap. J. **594,** L71 (2003).
[4] R. Daghigh and J. Kapusta, Phys. Rev. **D65,** 064028 (2002).
[5] J. Knodsleder, *et al.* `astro-ph/0309442`.
[6] P. Jean, *et al.* `astro-ph/0309484`.

[7] B. J. Carr, "Primordial black holes as a probe of cosmology and high energy physics," Lect. Notes Phys. **631**, 301 (2003). `astro-ph/0310838`.

[8] B. J. Carr and J. H. MacGibbon, "Cosmic Rays from Primordial Black Holes and Constraints on the Early Universe," Phys. Rept. **307**, 141 (1998).

[9] This general idea seems to have been suggested, among a variety of possible sources, by the discoverers[10] of the 511 keV line.

[10] M. Leventhal, C.J. MacCallum and P.D. Stang, Astrophys. J. Letters, **225,** L11 (1978); see also P.N. Okele and M.J. Rees, Astron. Astrophys. **81,** 263 (1980).

[11] C. Boehm, D. Hooper, J. Silk, M. Casse and J. Paul, Phys. Rev. Lett. **92,** 101303 (2004). `astro-ph/0309686`.

[12] D. Hooper, J. E. Taylor and J. Silk, Phys. Rev. D **69**, 103509 (2004). `hep-ph/0312076`

[13] D. Hooper and J. Silk, `hep-ph/0409104`.

[14] E. Parizot, M. Casse, R. Lehoucq and J. Paul, "GRBs and the 511 keV emission of the Galactic bulge," `astro-ph/0411656`.