Spectral Lags of Gamma-Ray Bursts from Primordial Black Hole (PBH) Evaporations

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Abstract. Primordial Black Holes (PBHs), which may have been created in the early Universe, are predicted to be detectable by their Hawking radiation. PBHs with an initial mass of \(\sim 5 \times 10^{14} \text{g}\) should be expiring today with a burst of high energy particles. Evaporating PBHs in the solar neighborhood are candidate Gamma-Ray Bursts (GRBs) progenitors. We propose spectral lag, which is the temporal delay between the high energy photon pulse and the low energy photon pulse, as a possible method to detect PBH evaporation events with the Fermi Gamma-ray Space Telescope Observatory.

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INTRODUCTION

In the present era black holes with mass less than a few solar masses are not expected to be created by any known process. Early in the Universe, however, primordial black holes (PBHs) could have been created with masses ranging from the Planck mass \(10^{-5} \text{g}\) to as large as \(10^{5} \text{M}_\odot\), or larger. PBH formation scenarios include the collapse of overdense regions due to primordial inhomogeneities, especially those generated by inflation, a softening of the equation of state, or bubble collisions at cosmological phase transitions, and the collapse of oscillating cosmic string loops or domain walls. (For a recent review see [1]).

Hawking discovered that, due to thermodynamical requirements and quantum-gravitational effects, all black holes continually radiate particles thermally [2, 3]. The Hawking temperature \(T\) is inversely proportional to the black hole mass \(M\). Thus, as the black hole radiates its temperature increases. It can be shown that PBHs with an initial mass of \(\sim 5.0 \times 10^{14} \text{g}\) should be expiring today in a burst of high energy particles [4]. In this context evaporating PBHs in the solar neighborhood are candidate Gamma-Ray Bursts (GRBs) progenitors.

HAWKING RADIATION

According to quantum theory, virtual particles are continuously created and destroyed in the vacuum. Heuristically, one way to interpret the Hawking radiation process invokes the strong gravitational field gradient near the event horizon of the black hole. This field gradient can separate particle-antiparticle pairs. In some cases, one particle falls with apparent negative energy into the black hole, while the remaining one has sufficient positive energy to escape to infinity. As a result, some particles can come out of the vacuum as real particles by obtaining energy from the black hole.

Black holes will predominantly radiate particles whose de Broglie wavelength \(\lambda\) is roughly of the order of the Schwarzschild radius of the black hole \(R_s \equiv 2GM/c^2\) and so the energy of radiated particles can be estimated as follows [5]

\[ E = \frac{\hbar c}{\lambda} \sim kT = \frac{\hbar c^3}{8\pi GM}. \]  \hspace{1cm} (1)
From the thermodynamic Stefan-Boltzmann relation, the Hawking luminosity can be estimated by the area of the black hole horizon times the radiation intensity (with $a$ proportional to the number of degrees of freedom of the radiated particles) as follows:

$$ L \equiv - \frac{dM}{dt} c^2 \approx (4\pi R^2)(aT^4) \propto \frac{1}{M^2}.$$  

Thus, the time remaining until the black hole expires by radiating away its mass is roughly given by

$$ t \approx M^3. $$

The estimated black hole temperature, luminosity and time to expire are summarized below

$$ T \approx 10 \left( \frac{10^{15} g}{M} \right) \text{MeV}; \quad L \approx 10^{20} \left( \frac{10^{15} g}{M} \right)^2 \text{erg s}^{-1}; \quad t \sim 10^{10} \left( \frac{M}{10^{15} g} \right)^3 \text{yr}. $$

The latter two relations are modified by the contributions of various particle species producing Hawking radiation and subsequent decay processes [6].

**PHOTON SPECTRA FROM PBHS**

A black hole should directly emit those particles which appear non-composite compared to the wavelength of the radiated energy (or equivalently the black hole size) at a given temperature. When the temperature of the PBH exceeds the Quantum Chromodynamics (QCD) confinement scale (250-300 MeV), quarks and gluons will be emitted [7]. These particles should fragment and hadronize, analogous to the jets seen in accelerators, as they stream away from the black hole [4]. The jets will decay on astrophysical timescales into photons, neutrinos, electrons, positrons, protons and anti-protons. The particle spectra of direct as well as decay products are shown in Fig 1 for a $T = 100$ GeV black hole. Most of the photon flux seen at astrophysical distances are jet decay products.

The average energy of the photons ($E_\gamma$) emitted by the PBH scales, for black hole temperatures $T \sim 0.3 - 100$ GeV, as [7]

$$ E_\gamma \approx 3 \times 10^{-1} \left( \frac{T}{\text{GeV}} \right)^{0.5} \text{GeV} $$

Hence, most of the photons emitted by $T < 1$ TeV PBHs are in the Fermi Large Area Telescope (LAT) energy range ($20 \text{ MeV} < E < 300 \text{ GeV}$). The emitted flux of photons ($\dot{N}_\gamma$) scales for $T \sim 0.3 - 100$ GeV as [7]

$$ \dot{N}_\gamma \approx 2 \times 10^{24} \left( \frac{T}{\text{GeV}} \right)^{1.6} \text{s}^{-1}. $$

The time ($t$) left until the PBH completes its evaporation is calculated in Table 1 for a range of black holes temperatures using the method of reference [6].

A PBH burst should produce $n$ photons in a detector of effective area $A_{\text{eff}}$ and angular resolution $\Omega$ if it is closer than

$$ d \approx 0.03 n^{-0.5} \left( \frac{A_{\text{eff}}}{\text{m}^2} \right)^{0.5} \left( \frac{T}{\text{TeV}} \right)^{-0.7} \text{pc} $$

and be detectable above the extragalactic gamma ray background at energy $E$ if it is closer than

$$ d \approx 0.04 \left( \frac{\Omega}{\text{sr}} \right)^{-0.5} \left( \frac{E}{\text{GeV}} \right)^{0.7} \left( \frac{T}{\text{TeV}} \right)^{0.8} \text{pc}. $$

If PBHs are clustered in our galaxy with local density enhancement factor $f_{\text{local}}$ then the number presently expiring (i.e. PBH evaporation rate $R$) is given by [8]

$$ R \leq 10^{-7} f_{\text{local}} \text{pc}^{-3} \text{yr}^{-1}. $$

A typical estimate for Galactic (halo) $f_{\text{local}}$ is $\sim 10^6$ or larger [8]. Thus, such bursts may be observable with the LAT. Conversely, non-detection of PBHs by the LAT may lead to tighter bounds on the PBH distribution.
FIGURE 1. Instantaneous emission from a 100 GeV black hole [7].

TABLE 1. Temperatures of the PBH according to various high energy models when its remaining lifetime until total evaporation is 1 hour, 1 min, 30 sec, 1 sec, 30 ms and 10 ms, using the method of [6].

| Model     | 1 Hour  | 1 min   | 30 sec  | 10 sec  | 1 sec   | 30 ms   | 10 ms   |
|-----------|---------|---------|---------|---------|---------|---------|---------|
| Standard Model | 294 GeV | 1.15 TeV | 1.45 TeV | 2.09 TeV | 4.51 TeV | 14.5 TeV | 20.9 TeV |
| Higgs     | 250 GeV | 0.98 TeV | 1.24 TeV | 1.8 TeV  | 3.8 TeV  | 12.0 TeV | 18.0 TeV |
| SUSY      | 206 GeV | 0.81 TeV | 1.0 TeV  | 1.5 TeV  | 3.2 TeV  | 10.0 TeV | 15.0 TeV |

DISCUSSION

With the launch of the Fermi Gamma-ray Space Telescope observatory on June 11, 2008, we have a new opportunity to examine the high energy band pass which is suited to detect PBH evaporation events. The discovery of a PBH would provide a unique probe of many areas of physics including the early Universe, gravitational collapse mechanisms, dark matter, and quantum gravity. Positive PBH burst detection should also elucidate extensions of the Standard Model, e.g. the existence of Higgs boson or Supersymmetry.

One approach to identify a PBH evaporation event directly is to look at the spectrum spanning from MeV to GeV energy scales. However, getting enough photons from these fast transient events to make a spectrum can be difficult. In contrast, spectral lag measurements merely require a light curve in two energy bands and does not need many counts. Therefore we can measure the spectral lag even for weak events that last for very short time scales. Hence measuring spectral lag is a possible method to identify PBHs. Qualitative analysis of the spectral lag of PBHs shows positive to negative evolution with increasing energy. Work is in progress to calculate quantitative values for the PBH spectral lags, including the low energy inner bremsstrahlung contribution [9].

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