

SENSITIVITY OF THE FERMI DETECTORS TO GAMMA-RAY BURSTS FROM EVAPORATING PRIMORDIAL BLACK HOLES (PBHS)

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Primordial Black Holes (PBHs), which may have been created in the early Universe, are predicted to be detectable by their Hawking radiation. The Fermi Gamma-ray Space Telescope observatory offers increased sensitivity to the gamma-ray bursts produced by PBHs with an initial mass of $\sim 5 \times 10^{14}$ g expiring today. PBHs are candidate progenitors of unidentified Gamma-Ray Bursts (GRBs) that lack X-ray afterglow. We propose spectral lag, which is the temporal delay between the high and low energy pulses, as an efficient method to identify PBH evaporation events with the Fermi Large Area Telescope (LAT).

Keywords: Gamma-Ray Bursts; Primordial Black Holes; Spectral Lag.

1. Introduction

The formation of Primordial Black Holes (PBHs) has been postulated in many theories of the early Universe (for a recent review see Ref. 1). Black holes of mass M_{bh} continually emit Hawking radiation² with a temperature of $T_{\text{bh}} = 1.06 \text{ GeV} / (M_{\text{bh}}/10^{13} \text{ g})$ in the form of all available fundamental particle species. The emitted particles decay quickly on astrophysical timescales into γ , $\nu_{e,\mu,\tau}$, $\bar{\nu}_{e,\mu,\tau}$, p , \bar{p} , e^+ and e^- . PBHs with an initial mass³ of $M_* \sim 5 \times 10^{14} \text{ g}$ should be expiring today with a burst of high energy particles including gamma-rays. The current upper limit on the number expiring today per volume per unit time is⁴

$$R \lesssim 10^{-7} \eta_{\text{local}} \text{ pc}^{-3} \text{ yr}^{-1} \quad (1)$$

where η_{local} is the density enhancement of PBHs in the local region. Typically η_{local} is $\sim 10^6$ (for clustering in the Galactic halo) or larger. Such PBH bursts may be detectable by the Fermi Gamma-ray Space Telescope observatory's Large Area Telescope (LAT). Conversely, non-detection by the LAT may lead to tighter bounds on the PBH distribution.

2. PBH burst as seen by Ideal Detector

In the standard model³, the total number of photons emitted per second by a $T_{\text{bh}} \sim 0.3 - 100$ GeV black hole scales as⁵

$$\dot{N}_{\text{bh}\gamma} \simeq 1.4 \times 10^{29} \left(\frac{T_{\text{bh}}}{\text{TeV}} \right)^{1.6} \text{ s}^{-1}. \quad (2)$$

The number of photons per second per unit area reaching the Earth from a PBH bursting at a distance d from the Earth is

$$F_{\text{bh}} = \frac{\dot{N}_{\text{bh}\gamma}}{4\pi d^2}. \quad (3)$$

Let us assume an ideal detector of effective area A_{eff} which can detect every photon that falls on it. (If the detector is non-ideal then the efficiency can be incorporated into the value of A_{eff} .) **If the detector requires X photons over time t to distinguish an incoming event as a burst, then to detect a burst we require $F_{\text{bh}} A_{\text{eff}} t \geq X$.** That is the PBH must be closer than

$$d_{\text{D}} \simeq \frac{2.6 \times 10^{-2}}{\sqrt{X}} \left(\frac{T_{\text{bh}}}{\text{TeV}} \right)^{0.8} \left(\frac{A_{\text{eff}}}{\text{m}^2} \right)^{1/2} \left(\frac{t}{\text{min}} \right)^{1/2} \text{ pc}. \quad (4)$$

What T_{bh} maximizes the chance of detection? The remaining lifetime⁶ of a PBH of temperature T_{bh} is $\tau_{\text{evap}} \simeq 7.4 \times 10^3 / (T_{\text{bh}}/\text{TeV})^3 f$ s where $f(T_{\text{bh}})$ weights the number of emitted species. (The remaining lifetime of a 300 GeV, 1 TeV, or 5 TeV black hole is 1 hour, 1 minute, or 1 second, respectively.) Taking $t = \tau_{\text{evap}}$, a PBH will be detected by the ideal detector if it is closer than

$$d_{\text{D}} \simeq \frac{0.03}{\sqrt{X}} \left(\frac{T_{\text{bh}}}{\text{TeV}} \right)^{-0.7} \left(\frac{A_{\text{eff}}}{\text{m}^2} \right)^{1/2} \text{ pc}. \quad (5)$$

Thus the detectability is maximized for the lowest T_{bh} black hole visible above the background and/or by using the longest detector exposure time. For a detector of angular resolution Ω to resolve the PBH above the gamma-ray background F_{γ} , we also require that $F_{\text{bh}} A_{\text{eff}} \geq F_{\gamma} \Omega A_{\text{eff}}$. The PBH will be resolved above the observed (EGRET) extragalactic background⁷

$$\frac{dF_{\gamma}}{dE} \simeq 1.4 \times 10^{-6} \left(\frac{E}{\text{GeV}} \right)^{-2.1} \text{ cm}^{-2} \text{ GeV}^{-1} \text{ s}^{-1} \text{ sr}^{-1} \quad (6)$$

at energy E by the ideal detector if the PBH is closer than

$$d_{\text{R}} \simeq 0.03 \left(\frac{\Omega}{\text{sr}} \right)^{-1/2} \left(\frac{E}{\text{GeV}} \right)^{0.55} \left(\frac{T_{\text{bh}}}{\text{TeV}} \right)^{0.8} \text{ pc} \quad (7)$$

and E is less than the average energy⁵ of the PBH photons $\bar{E}_{\gamma} \approx 10 (T_{\text{bh}}/\text{TeV})^{0.5}$ GeV. The isotropic diffuse gamma-ray background, which is an upper limit on the extragalactic background, recently measured⁸ by the LAT at mid-Galactic latitudes is consistent with the earlier EGRET measurements Eq. (6), although the extragalactic component may⁹ be weaker by up to a factor of 2.

For a given detector, the scanned volume of space is then $V_{\text{bh}} = (\omega_A/\text{sr}) d_S^3/3$ where ω_A is the detector acceptance angle (field of view) and $d_S = \min(d_D, d_R)$. Extensive air shower arrays characteristically have $A_{\text{eff}} \gtrsim 10^4 \text{ m}^2$, large ω_A and small Ω but very high threshold energy (typically $\gtrsim 10 \text{ TeV}$) and hence are background-limited, while atmospheric Cerenkov detectors¹⁰ characteristically have $A_{\text{eff}} \gtrsim 200 \text{ m}^2$ and small Ω but high threshold energy (typically $\gtrsim 100 \text{ GeV}$ although the Whipple SGARFACE system¹¹ has a threshold of 100 MeV) and very small ω_A ($\lesssim 10^{-2} \text{ sr}$). In contrast, the Fermi LAT has¹² a smaller $A_{\text{eff}} \sim 0.8 \text{ m}^2$ but large $\omega_A \sim 2.4 \text{ sr}$, finer source position angular resolution ($0.3 - 2'$), low energy thresholds (down to 20 MeV), good time resolution and is essentially background-free with respect to burst sensitivity. **Additionally, most of the photons emitted by expiring $T_{\text{bh}} \lesssim 1 \text{ TeV}$ PBHs are in the LAT energy range (20 MeV - 300 GeV).**

3. Conclusions

The Fermi LAT offers greater sensitivity to local PBH bursts than ground-based detectors. We have proposed¹³ spectral lag measurements (the temporal delay between high and low energy pulses) of the incoming light curve in two different energy bands as a method to identify PBH bursts. A PBH burst arriving at the detector will exhibit positive to negative evolution with increasing energy because the black hole temperature and \overline{E}_γ increase over time as the black hole loses mass. Because spectral lag measurements require counts in only two energy bands, and not the full spectrum, spectral lag can be measured even for weak events that last for very short time scales. Work is in progress to calculate quantitative values for the PBH spectral lags for the characteristics of the Fermi LAT.

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