An Improved Gamma-ray Limit on the Density of Primordial Black Holes

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Abstract

Gamma-rays are, with antiprotons, a very efficient way to derive upper limits on the density of evaporating black holes. They have been successfully used in the last decades to severely constrain the amount of Primordial Black Holes (PBHs) in our Universe. This article suggests a little refinement, based on the expected background, to improve this limit by a factor of three. The resulting value is : $\Omega_{PBH} < 3.3 \times 10^{-9}$.

Small black holes could have formed in the early Universe if the density contrast was high enough (typically $\delta > 0.3 - 0.7$, depending on models). Since it was discovered by Hawking [1] that they should evaporate with a black-body like spectrum of temperature $T = \hbar c^3/(8\pi kGM)$, the emitted cosmic rays have been considered as the natural way, if any, to detect them. Those with initial masses smaller than $M_* \approx 5 \times 10^{14}$ g should have finished their evaporation by now whereas those with masses greater than a few times M_* do emit nothing but extremely low energy massless fields. The emission spectrum for particles of energy Q per unit of time t is, for each degree of freedom, given by :

$$\frac{\mathrm{d}^2N}{\mathrm{d}Q\mathrm{d}t} = \frac{\Gamma_s}{h\left(\exp\left(\frac{Q}{h\kappa/4\pi^2 c}\right) - (-1)^{2s}\right)} \tag{1}$$

where κ is the surface gravity, s is the spin of the emitted species and Γ_s is the absorption probability proportional to M^2Q^2 in the high energy limit (contributions of angular velocity and electric potential have been neglected since the black hole discharges and finishes its rotation much faster than it evaporates). PBHs have been investigated for many different purposes, including tests for quantum gravity [2] that are especially active nowadays.

As was shown by MacGibbon and Webber [3], when the black hole temperature is greater than the quantum chromodynamics confinement scale Λ_{QCD}, quark and gluon jets are emitted instead of composite hadrons. This should be

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taken into account when computing the cosmic-ray flux expected from their evaporation. Among all the emitted particles, two species are especially interesting : gamma-rays around 100 MeV because the Universe is very transparent to those wavelengths and because the flux from PBHs becomes softer ($\propto E^{-3}$ instead of $\propto E^{-1}$) above this energy, and antiprotons around 0.1-1 GeV [4] because the natural background due to spallation of protons and helium nuclei on the interstellar medium is very small and fairly well known. This article aims at taking into account the contribution from blazars as well as from normal galaxies in the gamma-ray background to reduce the available window for PBHs.

Computing the contributions both from the direct electromagnetic emission and from the major component resulting from the decay of neutral pions, the gamma-ray spectrum from a given distribution of PBHs can be compared with measurements.

The flux on Earth can be written as:

$$\begin{aligned} \frac{d^2\Phi}{dEdt} &= \frac{1}{2}\int_{t_{form}}^{t_0}\left(\frac{R(t)}{R_{form}}\right)e^{-\tau(t,E)}\int_{M_*(t)}^{\infty}\frac{d^2\phi}{dEdt}(M(t,M_i),E' \\ &= E\frac{R_0}{R})\frac{d^2n}{dM_idV}dM_icdt \end{aligned}$$

where t_{form} is the formation time, t_0 is the age of the Universe, τ is the optical depth, $R(t)$ is the scale factor of the Universe at time t, ϕ is the individual gamma spectrum from a PBH and d^2n/dM_idV is the initial mass spectrum. When compared with the observations, this translates (in units of critical density) into [5] : $\Omega_{PBH}(M_*) < 1.0\times10^{-8}$, bettering substantially previous estimates [6].

This limit can be improved when taking into account the "guaranteed" gamma-ray background. Computing the contribution from unresolved blazars and the emission from normal galaxies, Pavlidou & Fields [7] have estimated the minimum amount of extragalactic gamma-rays which should be expected. The first one was computed using the Stecker-Salamon model and the second one is assumed to be proportional to the massive star formation rate (which is itself proportional to the supernovae explosion rate) as it is due to cosmic-ray interactions with diffuse gas. This background at 100 MeV is estimated at $\Phi_{TH} = 5.45\times10^{-14}$ cm^{-3}GeV^{-1}. Using the Carr & MacGibbon estimation at the same energy [5] $\Phi_{PBH} = 7.5\times10^{-6}\Omega_{PBH}$ cm^{-3}GeV^{-1}, a new limit can be obtained by requiring that $\Phi_{PBH}+\Phi_{TH} < \Phi_{EGRET}$ where Φ_{EGRET} is the measured flux [8]. To evaluate this later in a very conservative way, both the normalisation and the spectral index were chosen (within the error bars) in this paper at the value leading to the highest 100 MeV flux : $\Phi_{EGRET} < 7.94\times10^{-14}$ cm^{-3}GeV^{-1}. This leads to $\Omega_{PBH}(M_*) < 3.3\times10^{-9}$.

From the cosmological point of view, this new limit improves directly the estimates of the maximum allowed PBH mass fraction β:

$$\beta(M_H) = \frac{1}{\sqrt{2\pi}\,\sigma_H(t_k)} \int_{\delta_{min}}^{\delta_{max}} e^{-\frac{\delta^2}{2\sigma_H^2(t_k)}}\,\mathrm{d}\delta \approx \frac{\sigma_H(t_k)}{\sqrt{2\pi}\,\delta_{min}} e^{-\frac{\delta_{min}^2}{2\sigma_H^2(t_k)}} ,$$

where t_k is the horizon crossing time for the considered mode, δ the density contrast ($\delta_{min} \approx 0.7$), M_H is the Hubble mass at t_k and $\sigma_H^2(t_k) \equiv \sigma^2(R)|_{t_k}$ where $\sigma^2(R) \equiv < (\frac{\delta M}{M})_R^2 >$ is computed with a filtering window function with $R = \frac{H^{-1}}{a}|_{t_k}$. The latest computations [9] relate this value to the density parameter by

$$\Omega_{PBH}(M)h^2 = 6.35 \times 10^{16} \times \beta(M) \left(\frac{10^{15} g}{M} \right).$$

Our new limit leads to $\beta(M_*) < 1.3 \times 10^{-26}$ which is compatible with antiprotons estimations [10] and remains the only observational access to such small scales in the early Universe.

Measurements from the GLAST satellite and more refined theoretical predictions on the background could slightly improve these results but both gamma-rays and antiprotons seem to have closed their detection windows. One of the last hopes could reside in antideuterons which are very rarely induced by spallation below 1 GeV for kinematical reasons [11].

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