Deuterium Photodisintegration Constraint on Black Hole Formation

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Introduction

Standard Big-Bang Nucleosynthesis (BBN) is one of the crucial processes of the early Universe. It describes how the dynamic interplay among the four fundamental forces during the first few seconds of cosmic time originates the lightest nuclides. The abundances of the light elements like helium and deuterium that were produced during BBN mainly depend on the ratio of the baryon density to photon density and the expansion rate of the Universe. It is plausible that the baby universe contained a substantial number of Black Holes (BHs). The high-energy particles emitted by BHs evaporation, both during and after nucleosynthesis, can be energetic enough to disrupt primordial nuclei. One vital reaction of these types is photo-disintegration which triggers the destruction of primordial nuclei by high-energy BH photons [3]. Among all the primordial nuclei, deuterium is the most sensitive to photon-disintegration. In this study, we have analysed astrophysical constraint on the initial mass fraction of BHs due to photodisintegration of deuterium, influenced by accretion of radiation in the early Universe within the context of standard cosmology.

Mathematical Formulation

The mass evolution of BHs generally depends on two aspects; the accretion of energy-matter from the surrounding that triggers the mass growth and the quantum mechanical Hawking evaporation which is responsible for the decay of mass. In that respect the evolution equation of BH can be expressed as [1, 2]

$$\begin{aligned}\dot{M}_{\rm evo} &= \dot{M}_{\rm evap} + \dot{M}_{\rm acc}\\ &= -4\pi R_{\rm BH}^2 a_H T_{\rm BH}^4 + 4\pi f R_{\rm BH}^2 \rho, \qquad (1)\end{aligned}$$

where $R_{\rm BH}$, a_H, $T_{\rm BH}$, f and ρ represent Schwarzschild radius of BH, Stephan-Boltzmann constant, Hawking temperature, accretion efficiency and density of the surrounding energy-matter respectively. The relationship between the final mass fraction of BH ($\alpha_{\rm evap}$) with the initial one (α_i) is generalised as [3]

$$\alpha_{\rm evap} = \alpha_i \frac{M(t_c)}{M(t_i)} \frac{a(t_{\rm evap})}{a(t_i)}, \qquad (2)$$

where $M(t_c)$ is the maximum accreting mass of BH and a is the scale factor.

If we consider ΔM as the BH mass evaporated between the times t_1 and t_2 (say the end of nucleosynthesis and the onset of recombination respectively) and M_b as the baryonic mass, then we can write [4]

$$\frac{\Delta M}{M_b} \leq \frac{\epsilon}{f_\gamma \beta} \frac{E_*}{m_p}, \qquad (3)$$

where E_* and β are constants, ϵ represents the depletion factor and f_γ denotes the fraction of mass that decays into photons. We consider ΔM in accordance with the BH mass evaporated shortly after nucleosynthesis and the expression in that scenario is usually expressed as [4]

$$\frac{\Delta M}{M_b} = \left[\frac{\rho_{\rm BH}}{\rho_b}\right]_{t_{\rm evap}} \qquad (4)$$

with $t_{\rm evap}$ some time after nucleosynthesis, either straight after nucleosynthesis for an extended mass spectrum or when a narrow mass

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range of BHs evaporates. Now Eq. (3) can justify

$$\alpha_{\rm evap} \leq \left[\frac{\rho_b}{\rho_{\rm rad}}\right]_{t_{\rm evap}} \frac{\epsilon}{f_\gamma \beta}\frac{E_*}{m_p}. \quad (5)$$

Since $\rho_b \propto a^{-3}$ and $\rho_{\rm rad} \propto a^{-4}$, it follows that

$$\left[\frac{\rho_b}{\rho_{\rm rad}}\right]_{t_{\rm evap}} = \frac{a(t_{\rm evap})}{a(t_e)}\left[\frac{\rho_b}{\rho_{\rm rad}}\right]_{t_e} = 2\frac{a(t)}{a(t_e)}\Omega_b(t_e), \quad (6)$$

as $\rho_{\rm rad} = \rho_{\rm tot}/2 \approx \rho_c/2$ at the time of radiation-matter equality ($t_e = 10^{11}$ s). The baryon density parameter at t_e is related to the present one, as the matter density parameter at t_e is given by $\Omega_m(t_e) \approx 1/2$. Now, we can write

$$\Omega_b(t_e) = \frac{\Omega_m(t_e)}{\Omega_m(t_0)}\Omega_b(t_0) \approx \frac{1}{2}\frac{\Omega_b(t_0)}{\Omega_m(t_0)}. \quad (7)$$

By using Eqs. (6) and (7) in Eq. (5), one can find that

$$\alpha_{\rm evap} \leq \frac{\epsilon}{f_\gamma \beta}\frac{E_*}{m_p}\left(\frac{t_{\rm evap}}{t_e}\right)^{\frac{1}{2}}\frac{\Omega_b(t_0)}{\Omega_m(t_0)}. \quad (8)$$

Using numerical values of constants [5] $f_\gamma = 0.1$, $E_* = 10^{-1}$ GeV, $\beta = 1$, $\epsilon \sim 1$ and considering the ratio of the present baryonic density to the total matter density as 0.1, we found the expression as

$$\alpha_{\rm evap} \leq 1.066 \times 10^{-28}\left(\frac{t_{\rm evap}}{t_{\rm pl}}\right)^{\frac{1}{2}}. \quad (9)$$

Considering $t_{\rm evap} = 400$ s, the constraint turns into

$$\alpha_{\rm evap} \leq 6.74 \times 10^{-6}. \quad (10)$$

By comparing the Eq. (2) and Eq. (10), the initial mass fraction can be written as

$$\alpha_i \leq 6.74 \times 10^{-6} \times \frac{a(t_i)}{a(t_{\rm evap})}\frac{M(t_i)}{M(t_c)}. \quad (11)$$

Results and Discussion

We present our results in FIG. 1 and TABLE I, where $f = 0$ corresponds to no accretion case. It is clear enough that due to the inclusion of accretion, the constraint coming from deuterium photodisintegration on the initial mass fraction of the BHs gets more stronger than Brans-Dicke theory [3]. Further, within the standard model, the upper bounds on the initial mass fraction of the BHs are found to be tightened when we increase the accretion efficiency.

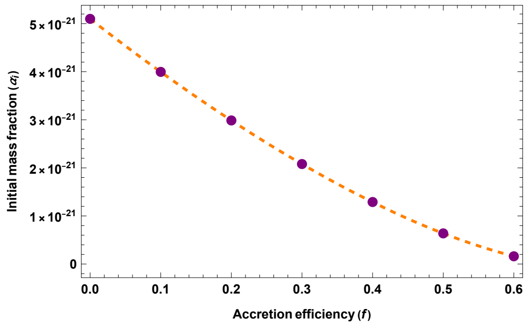

FIG. 1: Variation of initial mass fraction of BHs (α_i) with different accretion efficiencies (f) for deuterium photodisintegration.

TABLE I: Estimation of initial mass fraction of BHs (α_i) for various accretion efficiencies (f).

Deuterium Photodisintegration Constraint	
Accretion efficiency (f)	Initial mass fraction $\alpha_i \leq$
0	5.0991×10^{-21}
0.1	3.9960×10^{-21}
0.2	2.9864×10^{-21}
0.3	2.0799×10^{-21}
0.4	1.2900×10^{-21}
0.5	6.3740×10^{-22}
0.6	1.6125×10^{-22}

References

[1] E. Babichev et al., Phys. Rev. Lett. **93**, 021102 (2004).
[2] B. Nayak, and L. P. Singh, Pramana **76**, 173 (2011).
[3] B. Nayak et al., J. Cosmol. Astropart. Phys. **2010**, 039 (2010).
[4] D. Lindley, Mon. Not. Roy. Astron. Soc. **193**, 593 (1980).
[5] D. Clancy et al., Phys. Rev. D **68**, 023507 (2003).