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THESIS ON

PRIMORDIAL BLACK HOLES (PBH)

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**Abstract**

All the black holes that astronomers have seen fall into one of three categories: stellar-mass black holes, intermediate-mass black holes, and supermassive black holes. Each is more massive than our Sun and formed at least hundreds of thousands of years after the Big Bang, as our universe grew and evolved.
But there is another type of black hole astronomers haven’t yet seen, but think could exist. These are ***primordial black holes***.

As their name suggests, primordial black holes were born very early in the life of the universe, a mere fraction of a second after the Big Bang. It was a time long before stars or galaxies (and other types of black holes) could exist. But some theories predict that primordial black holes should have popped onto the scene anyway. That’s because in that fraction of a second after the universe itself began, space was not completely homogenous (the same at every point). Instead, some areas were denser and hotter than others, and these dense regions could have collapsed into black holes.

Inflation, baryosynthesis and freezing out of the dark matter particles are processes of the early universe. Due to many uncertainties of these three phenomena lead to ambiguity in the chronology of the early cosmological evolution [1]. Primordial Black Holes (PBH) can form in the early universe and might comprise a significant fraction of the dark matter and allow us to remove the uncertainties of these models.. Interestingly, they are accompanied by the generation of Gravitational Wave (GW) signals and they could contribute to the merger events currently observed by the LIGO/Virgo Collaboration (LVC) [2].

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**Introduction to Primordial Black Holes (PBH)**

There was only a small period of time — about 1 second — following the Big Bang when primordial black holes could have formed. But in the extreme world of our expanding early universe, a lot can happen in just one second. And the later in this window of time that primordial black holes formed, the more massive they would be. Depending on when exactly they formed, primordial black holes could have masses as low as 10-7 ounces (10-5 grams), or 100,000 times less than a paperclip, up to about 100,000 times greater than the Sun.

The idea of such tiny black holes intrigued astrophysicist Stephen Hawking, who explored their quantum mechanical properties. That work led to his 1974 discovery that *black holes can evaporate* over time. And while Hawking ultimately realized a large black hole would evaporate away in more time than the universe has been around so far, small black holes could have indeed evaporated away or currently be doing so, depending on their mass. Hawking calculated that any primordial black hole with a mass greater than 1012 pounds (1012 kilograms); could still be around today, while those less massive would have already disappeared.

And depending on their mass, any primordial black holes left today could neatly explain some of the outstanding problems in astronomy. As a direct consequence of the recent development of astronomical and cosmological observations, substantial evidence for the existence of such “dark” matter was gathered, but the nature of its constituents is still, however, one of the longstanding mysteries of physics [2].

We will then proceed by introducing the main character of this thesis, i.e., Primordial Black Holes (PBHs). PBHs were first hypothesized in the late ’60s and they have been investigated for more than half a century as a potential solution to the dark matter problem [2].

* 1. **Primordial Black Holes:**

According to the theory of gravity any object with mass *M* can form a black hole, if this mass is concentrated within its gravitational radius,

$r\_{g}=\frac{2GM}{C^{2}}$ (1.1)

Historically the existence of black holes, which follows General Relativity, has been viewed within the framework of Newtonian Gravity.

In 19th century, Laplace pointed out that the parabolic velocity on the surface of a supermassive star can reach the speed of light, such that these objects may not be observable but they do exist.

Laplace derived the *equation 1.1* assuming that the sum of the kinetic energy of light particles with mass *m* equal to,

$E\_{k}=\frac{mc^{2}}{2}$ (1.2)

and its potential energy in the gravitational field of a massive body,

$E\_{Pot}=-\frac{GMm}{r}$ (1.3)

equals zero, that is, he found the value of the gravitational radius from the same equality

$\frac{mc^{2}}{2}- \frac{GMm}{r\_{g}}=0$ (1.4)

which is used to calculate the escape velocity of material bodies.

Laplace’s equation is based on corpuscular theory of light, which turned out to be valid quantitatively even in the general relativity.

In Astrophysics, Black holes are considered to be the final stage of the evolution of stars with masses greater than few solar masses. Although, natural conditions for collapse of smaller objects into black holes can hardly takes place in the present-day universe.

In 1966, Russian Astrophysicist Zeldovich and Novikov theorized that the formation of black holes with masses greater than *mpl*(Planck’s mass) could be formed in the early universe because the mass within the cosmological horizon can naturally form a black hole, if the expansion stops in this area. Such a black hole is called the ***primordial black hole (PBH).***

* 1. **Mechanisms of PBH Formation:**

PBHs can be formed by a variety of mechanisms. The most widely discussed scenario is the collapse of primordial over-densities during the radiation era. The initial over-densities could originate from quantum fluctuations in the inflationary epoch. The Jeans mass at time *t* during the radiation era is *MJ ∼ t/G*, so black holes of mass M form at

$t\_{f}\~GM\~10^{-5}\frac{M}{M\_{Θ}}s,$ (1.5)

with their Schwarzschild radius comparable to the cosmological horizon [3].

The density fluctuation required for a horizon-size region to collapse to a black hole is *δ ≡ δρ/ρ ∼ 1*. On the other hand, the rms fluctuation on scales accessible to CMB and large-scale structure observations is *δrms ∼ 10−5*, and the probability of having δ ∼ 1 on such scales is negligibly small. Hence one has to assume that the fluctuation amplitude is strongly enhanced in the range of scales corresponding to PBH formation. Here we shall assume for simplicity that the fluctuation spectrum has a narrow peak, so that all PBHs form at about the same time and have nearly the same mass. Such fluctuation spectra naturally arise in some inflationary models [3].

Suppose the fraction of horizon regions that turn into BHs at time *tf* is *λ << 1*. Then the BH density at formation is *nf ∼ λtf−3* and their average separation is *df ∼ λ−1/3tf* . The cold dark matter (CDM) mass density at that time is

$ρ\_{CDM}\~\frac{1}{Gt\_{f}^{2}}\left(\frac{t\_{f}}{t\_{eq}}\right)^{^{1}/\_{2}}$, (1.6)

So, the fraction of dark matter in the form of BHs is

$f\_{M}\~\frac{Mn\_{f}}{ρ\_{CDM}}\~λ\left(\frac{M\_{eq}}{M}\right)^{1∕2}$, (1.7)

where *Meq ∼ teq/G ∼ 1017*$M\_{Θ}$ is the horizon mass at the time *teq* of equal matter and radiation densities. The quantity *fM* does not change with time and is therefore a useful characteristic of PBHs.

Let us now indicate some cosmologically interesting values of the parameters *M* and *λ*. There are only two observationally allowed windows for the mass *M* where PBHs may account for all dark matter: *M ∼ 10−15 − 10−10*$M\_{Θ}$ and *M ∼ 10 − 100*$M\_{Θ}$ *.* With *fM ∼ 1*, eq. (1.7) then gives *λ ∼ 10−13 −10−16* and *λ ∼ 10−8*, respectively [3]. In order to account for LIGO observations, we need *M ∼ 10*$M\_{Θ}$ and *fM ∼ 10−3*, which gives *λ ∼ 10−11*. For PBHs to serve as seeds of supermassive BHs, we need *M ∼ 103 − 106*$ M\_{Θ} $and the comoving PBH density ∼ 0.1*M* *pc*−3. The corresponding range of *λ* is *λ ∼ 10−12 − 10−16*.

We now mention some other mechanisms of PBH formation. High-energy vacuum bubbles may nucleate and expand during inflation, resulting in a very wide spectrum of bubble sizes. After inflation ends, the bubbles collapse to form BHs. Small bubbles collapse to BHs much smaller than the horizon, but starting with a certain critical size the BHs form with their Schwarzschild radius comparable to the horizon. A closely related scenario is PBH formation by collapse of vacuum domain walls. Once again, sufficiently large walls form BHs at the horizon scale. PBHs could also be formed by collapse of cosmic string loops, but this requires the loops to be nearly circular and the PBH density produced in this way is not cosmologically interesting [3].

***Refrences***

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