Primordial Black Holes

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Abstract

The phenomenon of the primordial black hole is one that is interesting and needs to be studied. Born at the dawn of time, primordial black holes may lurk throughout the universe, should they exist. But what if one struck the Earth or even, perhaps, a human being? Perhaps it is a morbid curiosity innate to the human condition, but the prospect of death and destruction raining down from the heavens has long fascinated us. The idea that black holes might have formed soon after the Big Bang dates back to 1966, when their existence was first proposed. Our current theory for how the universe formed does not allow for black holes to be created in the early universe. Instead, stars and galaxies first formed thanks to fluctuations in the early universe. Black holes formed much later, only after the first ancient stars had died. But if primordial black holes (PBHs) did form as early as one second after the Big Bang, during the "radiation-dominated" era, things would be different. As early as 1975, other physicists began raising an intriguing possibility about these early black holes. As Hawking had first realized, black holes evaporate over time via Hawking radiation. But what about PBHs larger than 1011 kg (about the size of a small asteroid) that had not totally evaporated? Might they provide a neat explanation for part or all of the missing dark matter needed to account for the discrepancy between the cosmos' visible matter and the observed motion of the stars and galaxies? The idea has faded in and out of vogue over the decades, and, as Carr himself noted in 2020, "as with other cold dark matter candidates, there is still no compelling evidence that primordial black holes provide the dark matter."

Dark matter (partly) composed by PBHs constitutes an exciting possibility, presenting an enormous number of observable signatures that can constrain its parameter space. The variety of phenomenological effects produced by PBHs allows for placing stringent bounds on the

abundance of PBHs, usually indicated by the energy fraction of dark matter as PBHs, with ΩPBH and ΩDM the ratios of energy densities and critical density.

$$fPBH = \Omega PBH/\Omega DM$$

Moreover, since PBHs are usually expected to be formed before nucleosynthesis, BBN (Big Bang Nucleosynthesis) constraints on the baryon abundance do not apply to them, as they do not intervene in the nucleosynthesis of elements and thus can be regarded as non-baryonic dark matter. Several recent reviews are devoted to discussing PBHs in great detail.

Shortly after the first detection of gravitational waves from a merger of ~30M⊕ BHs by LIGO (Laser Interferometer Gravitational-wave Observatory), the question of whether these could be primordial was raised. Analysis of posterior data from the gravitational wave detectors LIGO and Virgo detector (the European counterpart of LIGO) showed that the detected mergers are compatible with the hypothesis of their components being of primordial nature, although there is no strong preference over stellar BHs. PBHs with a lognormal mass function have been claimed to better fit data than BHs of astrophysical origin, although this is in contrast to the results of Hall et al. (2020), and a mixed population seems compatible or even favored. Unlike stellar BHs, formed from the collapse of a massive star, which can present masses only above ~3M⊕ [the Tolman–Oppenheimer–Volkoff limit], PBHs could be produced with any mass.

Thus, a positive measurement of a BH with a mass lower than ~3M⊕ would be a confirmation of the existence of primordial, non-stellar BHs. PBHs could also conform to intermediate-mass BHs, with masses too massive to have originated from a single star. It is the case of the merger event of BHs with masses, producing a remnant BH of ~150M⊕, in a so far mostly unobserved range of masses ~10^2 M⊕ and 10^5 M⊕, too massive to originate from a single star. It is the case of the merger event of BHs with masses ~60M⊕ and ~80M⊕, producing a remnant BH of ~150M⊕, in a so far mostly unobserved range of masses.

Supermassive black holes (SMBHs) are present in the nuclei of most galaxies, with masses ranging from 10^5 M⊕ to 10^{10} M⊕, and already existing at redshifts $z > 6$. Such massive objects can hardly be produced from accreting stellar remnant BHs.

The idea that PBHs could truly be the source of dark matter in the universe received a further boost this year, thanks to a study by Yale University researcher Priyamvada Natarajan and colleagues. They propose that if the lion's share of PBHs were formed with a mass around 1.4 times that of the sun, then they could account for all dark matter in the universe. The Yale team's model suggests that these PBHs could have provided the gravitational anchors around which the first stars and galaxies formed. Indeed, these early black holes could, according to the team, have consumed the stars and gas in their vicinity, making them the predecessors of the supermassive black holes that sit at the heart of galaxies today. Primordial black holes, if they do exist, could well be the seeds from which all supermassive black holes form, including the one at the center of the Milky Way.

Reason for Research

Primordial black holes formed at the beginning of time have always served as an intriguing aspect of cosmological research. Over time, the properties and characteristics of PBHs have confounded numerous experts and scientists. To the present day, the insights provided by PBHs on dark matter have given rise to several unanswered conundrums. There is a cascade of theories and hypotheses surrounding this particular field that provides adequate room for further research. For the reasons mentioned, we opted to delve in and present a study regarding this singularly interesting topic.

Objective of the Research

This research paper intends to showcase the definition, properties, and formation of primordial black holes. At the same time, the potential benefits and harms of the existence of a primordial black hole in close proximity are also navigated. It further provides insight into the experts' opinions regarding the many possibilities that entrench PBHs. Overall, this paper may be considered a literature review of the many studies conducted on PBHs.

History of the primordial black hole

Though its existence was proposed in 1966, an in-depth study was only done in 1971. It was hypothesized to have been formed after the Big Bang. In the inflationary era and early radiation-dominated universe, extremely dense pockets of subatomic matter may have been tightly packed to the point of gravitational collapse, creating primordial black holes without the supernova compression needed to make black holes today. Because the creation of primordial black holes would predate the first stars, they are not limited to the narrow mass range of stellar black holes. Though their existence has not yet been proven, it remains theoretical. In the 21st century, specifically in September 2022, primordial black holes were proposed to explain the unexpectedly large early galaxies. PBHs have long been considered possibly important, if not nearly exclusive, components of dark matter.

Depending on the model under consideration, primordial black holes may have initial masses spanning a wide range, from tiny Planck relics with masses as low as 10^{-8} kg to those exceeding thousands of times the mass of our sun. Nevertheless, primordial black holes with original masses less than 10^{11} kg would not have endured to the present day due to Hawking radiation, which causes them to completely evaporate in a time frame much shorter than the age of the universe. Primordial black holes are characterized as non-baryonic entities. They are also regarded as strong candidates for being the precursors of the supermassive black holes found at the centers of massive galaxies, as well as intermediate-mass black holes.

Primordial black holes are categorized as massive compact halo objects (MACHOs). They naturally serve as promising dark matter candidates due to their (almost) non-collisional nature, stability (provided they are sufficiently massive), non-relativistic velocities, and their formation very early in the universe's history, typically within a second of the Big Bang. Nonetheless, skeptics argue that strict constraints on their abundance have been established through various astrophysical and cosmological observations, suggesting that they may not significantly contribute to dark matter across most of the conceivable mass spectrum. However, recent research has raised the possibility once again, proposing that these black holes could exist in clusters with a 30-solar-mass primordial black hole at their core. In March 2016, just a month after the announcement of the detection of gravitational waves resulting from the merger of two black holes weighing approximately 30 times the mass of our sun (equivalent to about 6×10^{31} kg) by Advanced LIGO/VIRGO, three separate teams of researchers independently proposed that these detected black holes might have originated from primordial sources. Two of these research groups concluded that the merger rates inferred by LIGO align with a scenario where all of the dark matter in the universe consists of primordial black holes, especially if a significant portion of them are distributed within structures like faint dwarf galaxies or globular clusters, as predicted by the standard theory of cosmic structure formation. The third group contended that these merger rates cannot be reconciled with an exclusively dark matter explanation and suggested that primordial black holes might only contribute to less than one percent of the overall dark matter content. The unexpectedly large masses of the black holes detected by LIGO have reignited significant interest in primordial black holes falling within the mass range of 1 to

100 times that of our sun. There remains an ongoing debate about whether this mass range is ruled out or still plausible based on other observations, including the absence of star micro-lensing, patterns in cosmic microwave background radiation, the sizes of faint dwarf galaxies, and the absence of correlations between X-ray and radio sources near the galactic center.

The history of primordial black holes (PBHs) is intertwined with the development of cosmology and our understanding of the early universe. Here's a brief overview of the key milestones in the history of PBHs.

> **1960s** : Initial Theoretical Concepts
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> The concept of black holes, including primordial ones, began to gain attention in the 1960s. Yakov Zel'dovich and Igor Novikov, Russian astrophysicists, were among the first to propose the idea of primordial black holes forming in the early universe due to density fluctuations.
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> **1970s** : Theoretical Advances
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> Physicists Stephen Hawking and Bernard Carr made significant contributions to the theory of primordial black holes. Hawking's work on Hawking radiation, which predicts that black holes emit radiation and gradually lose mass, was particularly important in understanding the potential evaporation of PBHs.
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> **1980s** : Hawking Radiation
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> Hawking's theory of black hole evaporation was further developed, leading to the understanding that small primordial black holes would radiate away their mass relatively quickly, while larger ones would persist for longer periods.
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> **1990s** : Cosmic Microwave Background

Observations of the cosmic microwave background radiation provided important constraints on the abundance of primordial black holes. The absence of certain signatures in the cosmic microwave background placed limits on the fraction of dark matter that PBHs could constitute.

2000s : Continued Theoretical Exploration

Research into the formation mechanisms and potential observational consequences of PBHs continued. Scientists explored various scenarios in which PBHs could be produced, such as through phase transitions or inhomogeneities during cosmic inflation.

2010s : LIGO/VIRGO Discoveries

The detection of gravitational waves by the Laser Interferometer Gravitational-Wave Observatory (LIGO) and the Virgo Collaboration marked a significant milestone in black hole astronomy. These detectors began detecting the mergers of stellar-mass black holes, reigniting interest in the existence of primordial black holes.

2016 : Re-Emergence of Interest

Shortly after the LIGO/VIRGO announcement of the detection of gravitational waves from black hole mergers, several research groups proposed that these detected black holes might be primordial in origin. This sparked a renewed interest in the study of PBHs.

From May 2016 up until September 2021, a series of findings and suggestions were made by different people. Starting with Alexander Kashlinsky's suggestion that the spatial correlations in the unresolved gamma-ray and X-ray background radiations could be due to primordial black holes with similar masses if their abundance is comparable to that of dark matter. Then, James Unwin and Jakub Scholtz proposed the possibility of a primordial black hole (PBH) with a mass of 5–15 M⊕ (Earth masses), about the diameter of a tennis ball, existing in the extended Kuiper Belt to explain the orbital anomalies that are theorized to be the result of a 9th planet in the solar system. Later, Derek Inman and Yacine Ali-Haïmoud discovered that the nonlinear velocities that arise from the structure formation are too small to significantly affect the constraints that arise from CMB anisotropies. Afterwards, NANOGrav's collaboration found a low-frequency signal that could be attributed to gravitational waves potentially associated with PBHs. But so far, they haven't been confirmed as a gravitational wave signal, and finally, the research in September 2022 found that primordial black holes were used to explain the unexpected very large early (high redshift) galaxies discovered.

Formation

Primordial black holes could have emerged during the very early stages of the universe, which occurred within a second after the Big Bang, during either the inflationary period or the early radiation-dominated epoch. The crucial factor in the primordial black hole formation is the presence of density fluctuations in the universe, which trigger their gravitational collapse. Typically, to create a black hole, one would need density contrasts on the order of $\delta\rho/\rho \sim 0.1$ (where $\delta\rho$ represents the density variation in the universe).

Various mechanisms can lead to density irregularities in the context of cosmic inflation, especially in hybrid inflation models. One such example is Axion Inflation, a theoretical model in which the axion field serves as an inflaton. During its emergence, the axion field oscillates at its minimal potential energy, causing fluctuations in energy density in the early universe.

Another example is reheating, which represents the transition from the inflationary era to the subsequent hot, dense, radiation-dominated epoch. During this transition, the inflaton field decays into other particles, initiating interactions among these particles as they approach thermal equilibrium. However, if this process is not fully completed, it can result in density fluctuations, which, if sufficiently significant, could be responsible for the formation of primordial black holes.

Lastly, cosmological phase transitions can induce density variations in diverse ways, depending on the specific characteristics of each transition. For instance, one mechanism involves the collapse of over-dense regions arising from these phase transitions, while another mechanism entails the production of highly energetic particles during these transitions, which subsequently undergo gravitational collapse to form primordial black holes.

Perspectives from renowned scientists

Nico Cappelluti (University of Miami), Günther Hasinger (ESA Science Director) and Priyamvada Natarajan (Yale University), suggest that black holes existed since the beginning of the universe and that these primordial black holes could themselves be the as-of-yet unexplained dark matter.

> *"Black holes of different sizes are still a mystery. We don't understand how supermassive black holes could have grown so huge in the relatively short time available since the Universe existed."* (Günther Hasinger)
>
> *"Our study shows that without introducing new particles or new physics, we can solve mysteries of modern cosmology from the nature of dark matter itself to the origin of supermassive black holes."* (Nico Cappelluti)

If most of the black holes formed immediately after the Big Bang, they could have started merging in the early universe, forming more and more massive black holes over time. ESA's future gravitational wave space observatory, LISA, might pick up the signals of those mergers if primordial black holes exist. Small black holes might simply be the primordial black holes that have not merged into larger ones yet. According to this model, the universe would be filled with black holes all over. Stars would start to form around these clumps of ‘dark matter’, creating solar systems and galaxies over billions of years. If the first stars indeed formed around primordial black holes, they would exist earlier in the universe than is expected by the ‘standard’ model.

Unfortunately, says physicist Anne Green from the University of Nottingham, UK, no one has yet explained why the PBH abundance should be sitting right at that one-in-a-billion tipping point. The problem, explains Green, who is the coauthor of another recent review of the PBHs-as-dark matter idea, is that PBHs must have formed from random fluctuations in the infant universe’s mass and energy density. Such primordial density fluctuations are well understood on the largest scales, where they are thought to have triggered the formation of today’s galaxies. But the fluctuations that were extreme enough to collapse into a black hole must have been small, rare, and far above the average density. Hence, they’d be “way out in the tail of the distribution,” says Green, where theorists can only guess at what is going on.

“If you'd asked me in the early days, I would have said primordial black holes are interesting, but there's maybe only a 10% chance they really exist,” says Bernard Carr, a physicist at Queen Mary University of London. Carr is referring to the early 1970s, when he and his thesis advisor, the late Stephen Hawking, did the first detailed calculations for how the infant universe could have produced black holes, which are gravitational singularities in which the fabric of space and time curves in on itself so tightly that not even light can escape. But today, says Carr, who recently co-authored a recent review of PBHs as dark matter, “I would bet you at least 50% that they exist, maybe even more.” Carr cheerfully admits that a PBH pioneer like himself is hardly a neutral observer on this subject, and he is quick to acknowledge that PBH formation requires a fine-tuning of cosmological parameters that many researchers find implausible. Still, his cautious optimism can also be heard from other cosmologists. They point to three primary reasons for the shift: first, attempts to find WIMPs or the other hypothesized dark matter particles have come up empty; second, results from gravitational wave experiments looking for ripples in space-time are surprisingly consistent with the PBH idea.

The next decade or two could bring observational evidence that either confirms the existence of PBH dark matter or rules it out.

Our conclusion about the black hole

Despite speculation about the existence of primordial black holes, it can be believed that, if these black holes really do exist, then they could account for some or all of the dark matter. Dark matter, as we know it, is the invisible glue that astronomers believe helps to hold galaxies, like our own Milky Way, together. This idea can result in multiple controversies, as many scientists in the past refused to conform to it. But as traditional ideas of what dark matter is made of continue to draw a blank, many scientists who previously refuted this hypothesis might reconsider their choices.

In other words, the quest for the true identity of dark matter can only be accomplished by re-modeling the production of primordial black holes after the Big Bang in more detail. Chiming into this idea, we could say that there could be hundreds of times more primordial black holes out there through which dark matter can be explained. That is, if they have a mass in the lower window, below that of the moon, which would make them less than one-tenth of a millimeter in diameter – about the width of a human hair.

In this case, each primordial black hole would be tiny, but together, they could provide enough gravity to keep a galaxy from flying apart. If galaxies like our Milky Way are chock full of teeny adhesive black holes, then they should be everywhere. Most intriguing, as a few scientists hypothesized, there's even a chance that one is lurking on the outskirts of our Solar System.

The impacts that black holes have and if there are any benefits

For nearly a decade, astronomers have been puzzled by the orbits of small objects beyond Pluto. Although they assumed that their paths around the sun should be random, they appeared to be pretty organized. It, therefore,seems that something is shepherding them onto similar trajectories, and if this is the case, the question as to what is causing this phenomenon might arise.

Pluto is likely considered to be a planet (Amir Siraj, 2022). Dubbed Planet Nine, Pluto would be the first newly discovered planet since Neptune was added to the register in 1846 (Pluto was called a planet upon discovery in 1930 but later demoted to dwarf planet status in 2006). However, extensive ongoing searches have failed to find any visible sign of such a world.

If direct searches continue to fail, then assuming the existence of a primordial black hole in close proximity to Pluto might provide insight as to the solution to the conundrum (Siraj, 2022).

We know how much gravity we need to account for the clustered orbits of the objects beyond Pluto. If that gravity is being provided by a primordial black hole, then it is merely the diameter of a grapefruit. Yet despite its small size, it would still be approximately 10 times heavier than the Earth. If this is really what is going on, then it is no surprise that telescopic trawls of the outer solar system have so far come up empty.

Black holes should produce the occasional accretion flare (Siraj). In other words, we should see a flash if the grapefruit-sized object gobbles up a passing comet. Such an event would release a few percent of the energy of the atomic bombs dropped on Japan at the end of WWII.

The flash may be intense, but it is happening a long way away in the backwaters of the solar system. That makes the light pretty faint by the time it reaches Earth. The flares are right on the detection limit for the Vera Rubin Observatory (an astronomical observatory currently under construction in Chile). According to Siraj, “It’s the perfect tool for ruling out a primordial black hole in the outer solar system.” The observatory should start proper observations towards the end of 2023.

Should a primordial black hole turn out to be there, it likely entered the solar system because the sun is dragging the planets through the minefield of the Milky Way as it orbits around the galactic center. Therefore, a lingering question about the possibility of a primordial black hole going further and entering the inner solar system remains. Professor Sohrab Rahvar, an astrophysicist and cosmologist from Sharif University of Technology in Iran, believes in this phenomenon. He calculated the chances of a primordial black hole passing through the Earth during our planet’s 4.54-billion-year history.

According to him, the probability of this event is one passage per billion years. This would mean that the Earth has been struck by a primordial black hole on four separate occasions. Rahvar’s calculation assumes 100 percent of dark matter is made of sub-lunar masses of primordial black holes. Even if they make up just a quarter of dark matter, Earth has still encountered a primordial black hole once before and is likely to do so again.

However, the Earth getting struck by a black hole is not essentially as apocalyptic as it seems. The worst probable outcome is that the primordial black hole settles in the Earth’s core.

Then the black hole might start to swallow all the matter on Earth, grow, and after a finite time, the Earth will collapse into the black hole (Rahvar).

Fortunately, calculations reveal that the probability of trapping a black hole inside the Earth is almost zero (Rahvar). What is far more likely is that the black hole passes straight through the planet and emerges on the other side to continue its journey through space.

How can we tell if a black hole has really passed through the planet? “During its passage through the Earth, it can heat the planet’s interior,” says Rahvar. This could show up as melting traces in rocks along the straight line that represents the black hole’s path. However, Rahvar cautions that, as this has only occurred a maximum of four times in Earth’s entire history, it would be extremely difficult to discover these traces.

PBHs also serve as an advantage in several phenomena. One of the greatest advantages of the existence of PBHs is the insight they provide into the identity, existence, and whereabouts of dark matter. Although this same point is reiterated throughout the paper, due to the fact that this singular phenomenon still stands out as one of its biggest benefits, the need to state it once again arises. Of all the candidates that could be analyzed to know about dark matter, like the WIMPs (Weakly Interacting Massive Particles) and axions, dark matter offers the most compelling advantage.

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