Title

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Abstract

This synthesis highlights the research efforts in micro black holes in recent years and points to future prospects. Synthesizing recently published articles show that micro black holes can have a variety of properties. This paper explores articles discussing the instantaneous evaporation of micro black holes due to Hawking Radiation, the inability of a micro black hole to accrete matter, the intense recoil effects that occur if a micro black hole absorbs matter, the stability of micro black holes, as well as the spin and electric charge they may possess. Modern methods of detecting black holes have been described as looking for specific particle signatures that match a predicted profile of Hawking Radiation from a micro black hole and looking for possible signs of a micro black hole remnant. Expectations suggest that planned future projects will aid in the search for micro black holes by taking advantage of high-energy cosmic particle collisions.

Keywords: Black holes, particle collisions, particle accelerator, high energy physics

1. Introduction

The most basic definition of a black hole is a region of space, where in order to escape gravitational influence, you must go faster than the fastest speed possible: the speed of light. Anything inside this region of space is inside the black hole's event horizon, past the point of no return. Black holes can gain mass through absorbing matter in a process called "accretion" where gas and dust loses angular momentum and inspirals into the black hole. Different types of black holes can be defined by their mass: Supermassive black holes (thousands to billions of solar masses), Stellar mass black holes (3-50 solar masses), and micro black holes (smaller than atoms). One popular theory on the formation of supermassive black holes describes that they start as "seed" black holes, which are formed early in the universe from the gravitational collapse of very low metallicity gas clouds, or the remnants of massive stars, which rapidly accrete matter over time (Latif & Ferrara, 2016). Stellar mass black holes are made when large amounts of matter is concentrated in a very small space, typically after the death of a massive star. When the outward pressure of the star's nuclear fusion ceases, the star becomes unable to fight gravitational collapse causing the star to condense into a black hole (Fryer, 1999). Microscopic black holes, also known as micro black holes, are very interesting theorized objects that have been predicted to appear in particle accelerators for quite some time, but so far have not been detected. Micro black holes are made by concentrating a large amount of energy in a tiny space through high energy particle collisions (Kaloper & Terning, 2007). The amount of energy needed to create a micro black hole is variable to the effects of gravity on the quantum scale, and the amount of dimensions that space holds (Kaloper & Terning, 2007). A set of dimensions can be simply described as the minimum amount of coordinates that are needed to locate a point in space. People are familiar with the 3 spatial dimensions (ie. length, width, and height) but extra dimensions could exist at very small scales that we have not discovered yet (Arkani–Hamed et al., 1998). The more dimensions there are, the stronger gravity becomes on the Planck scale and less energy is needed to form a micro black hole than would be required in three dimensional space (Arkani–Hamed et al., 1998). The Planck scale is the scale at which the effects of gravity become important in a quantum setting. Planck values, such as the Planck mass ($2.17645 * 10^{-8} kg$) and Planck length ($1.6 * 10^{-35} m$), are considered the *smallest possible values in the universe*. These values are crucial in predictions estimating the feasibility of creating micro black holes.

Confirming micro black holes and extra spatial dimensions could help improve our theories and understanding of the universe. String Theory, a prominent contender for a "Theory of Everything" that has garnered significant attention from the scientific community in recent years, postulates the existence of additional, unobserved spatial dimensions. Because of their reliance on extra dimensions, the discovery of micro black holes could provide strong evidence to string theory being correct (Obikhod & Petrenko, 2016).

2. The Current Study

The purpose of this paper is to present what we currently know about micro black holes from recent research and to explore what we can expect to see in the near future. The nature of micro black holes is still very speculative, and the current technology is not powerful enough to produce the energy needed to create micro black holes. This synthesis is guided by the following research questions:

1. What do we currently know about micro black holes based on recent research ?
2. What can we expect to see in the near future?

3. The Properties of Micro Black Holes

Most papers discussing micro black holes are built upon research by Stephen Hawking, who theorized that black holes emit tiny particles called Hawking Radiation. In 1974, Hawking postulated that quantum fluctuations, which are tiny, random fluctuations in energy, can spontaneously create “virtual pairs” of particles and antiparticles on the edge of the black hole’s event horizon. Under normal circumstances, these particles quickly come back together and annihilate each other. However, in the case of the edge of a black hole, one particle falls into the black hole while the other forms just outside the event horizon, and radiates away as heat. This process very slowly steals energy and mass, causing the black hole to gradually “evaporate” (Hawking, 1975). As the black hole gets smaller it radiates Hawking Radiation faster. Hawking (1975) also showed that assuming the gravitational field of a black hole emits particles, the black hole would emit more particles than it absorbs. This finding further supports Hawking's argument that black holes can lose mass over time. The evaporation process is extremely slow for large objects: for a black hole with the mass of the Sun to fully evaporate due to Hawking Radiation, 10^{67} years must pass (many orders of magnitude greater than the current age of the universe).

The Large Hadron Collider (LHC) is the world's largest and most powerful particle accelerator, built in 2008. Shortly before its completion, there were concerns in the media about dangerous byproducts that may be created as a result of experiments, such as strangelets[1], vacuum bubbles[2], and micro black holes. In the wake of this public fear, Goldman et al. (2009)

[1] Well outside the scope of this paper, Strangelets are speculative exotic particles. In their hypothetical interactions with ordinary matter, there is a conjectured potential for inducing a transformation into "strange matter," a composition distinct from normal matter as it solely consists of quarks rather than atoms. This possibility raises the concern of a “strangelet catastrophe” in which the entire earth is converted to strange matter. (Witten, 1984)

[2] A vacuum bubble is a region in which the vacuum of space transitions to a lower energy state due to either an extreme energy event or spontaneously through random quantum effects. Inside this bubble, the fundamental constants of the universe likely have different values than the original vacuum, rendering the possibility of life and chemistry as we know it impossible. The conversion triggers a cascade, rapidly transforming all nearby false vacuum within a bubble expanding at the speed of light. (Coleman & De Luccia, 1980)

took a realistic approach in identifying the possible dangers of micro black holes. They examined a variety of theoretical scenarios in which a micro black hole is produced in a particle accelerator and showed that micro black holes do not pose any danger to the Earth. A notable feature of micro black holes is their inherent small size, leading to an almost instantaneous evaporation (10^{-27} seconds) due to Hawking Radiation (Hawking, 1975; *Safety of the LHC,* CERN, n.d.). Goldman et al. used this idea to show that if a micro black hole did form inside the LHC, such a microscopic entity should evaporate and cause no harm. Goldman et al. derived another property of micro black holes through calculations. If the micro black hole is somehow stable, the calculations indicate that it should not be able to accrete anything. The quantum mechanics that govern how subatomic particles could interact with the micro black hole make accretion impossible. Even in a scenario where the micro black hole is large enough to accrete a subatomic particle, the recoil effect caused by the accretion event would eject the micro black hole from earth and likely the solar system. When the LHC started operation, no dangerous byproducts were created, and its experiments led to the discovery of the Higgs boson in 2012 (Aad et al., 2012).

Chen and Adler (2002) have an interesting take on Stephen Hawking's paper. They argue that Hawking's calculations only considered macroscopic scales of physics (classical and relativistic physics) and made assumptions that must break down when the black hole is small enough to reach the quantum scale. Because of this assumption, they suggest that micro black holes should remain stable at the Planck mass, due to the generalized uncertainty principle in a similar fashion to how hydrogen atoms remain stable. The generalized uncertainty principle is a fundamental principle in quantum mechanics that states that you cannot simultaneously know both the precise position and momentum (or velocity) of a particle. As the black hole approaches a minimum mass the generalized uncertainty principle might introduce an analogous probabilistic aspect to its properties, preventing the black hole from completely evaporating. Instead of evaporating, the black hole's final state becomes uncertain, and may never reach an absolute zero mass or size. Lehmann et al. (2019) elaborates on this idea that micro black holes become stable, and show that micro black holes obtain an electric charge and have negligible spin (angular momentum). As micro black holes emit Hawking radiation, they should emit randomly charged particles of either positive or negative value. Over time, the black hole accumulates an electric charge and retains the charge once the black hole reaches stability. Hawking Radiation causes a black hole to lose angular momentum relatively quickly. As the black hole approaches the Planck scale, much of the angular momentum of the micro black hole is already gone. Dark matter is a form of matter that does not emit, absorb, or reflect light. Its existence is only inferred through its gravitational effects on normal matter such as galaxies (Faber & Gallagher, 1979). Both articles explain that stable, charged micro black holes could be viable candidates for dark matter since these objects would only interact with the universe via gravity, an important known similarity shared with dark matter.

On the other hand, Kováčik (2021) disagrees that micro black holes are a viable candidate for dark matter, and argues that as a small black hole rapidly emits Hawking radiation, the recoil created accelerates the micro black hole to a significant fraction of the speed of light. The micro black holes would be moving too fast to be gravitationally bound to anything, and this behavior would not reflect observed characteristics of dark matter. However, Lehmann and Profumo (2022) claim that micro black holes created in the early universe should move at speeds acceptable with observations of dark matter. Though initially these micro black holes would move at a significant fraction of the speed of light, Lehmann and Profumo argue that early cosmic expansion should have caused them to lose momentum over time and end up moving slow enough to remain viable as a dark matter candidate. The current accepted model for dark matter is very slow "cold" dark matter (Blumenthal et al., 1984). It is unlikely that micro black holes are the true form of dark matter.

4. Current Search for Micro Black Holes

Current searches for micro black holes assume that extra spatial dimensions exist and lower the value of the Planck scale to levels accessible by modern technology. Modern methods of detecting micro black holes are focused on direct detection experiments; speculating what kind of signatures and data we should see, should a micro black hole be produced in our laboratory experiments.

The Standard Model of particle physics describes the fundamental particles of the universe. These particles are categorized into two classes: Fermions (quarks, and leptons), which are the building blocks of matter, and Bosons (Photons, Gluons, W and Z bosons, and Higgs bosons), which are particles that mediate the fundamental forces of the universe (Electromagnetic, Strong, and Weak). Tsang (2011) explains that if a micro black hole forms in the Large Hadron Collider, we should be able to identify it through particle signatures that would match the profile of an evaporating micro black hole. A simplifying assumption that the micro black hole can emit every particle in the Standard Model with equal chance, primarily we should see jets of quarks and gluons taking up ~75% of the radiated particles. The remaining particles can be expected to be leptons, photons, W and Z bosons, and Higgs Bosons. With this in mind, a micro black hole can be identified by observing a shower of elementary particles appearing in equal probability, and carrying high amounts of energy in the GeV (giga-electron volt) scale. These data would be a direct measurement of the micro black hole which can be used to further explore micro black holes and extra dimensions (Tsang, 2011).

Similarly, Koch et al. (2019) propose that if a micro black hole is made in a particle accelerator and leaves behind a stable remnant at the Planck mass, we should be able to detect it. If the micro black hole remnant has an electric charge, the remnant should leave behind an ionizing track in the detector. This data can be used to measure some characteristics of the micro black hole, such as mass. If the micro black hole remnant is neutral, we can still indirectly analyze the remnant by examining the Hawking Radiation particles it produced shortly beforehand.

5. Future Directions

Despite numerous particle collisions tests, and scholarly articles released on the possible nature of micro black holes and methods for their detection, no micro black hole detections have been confirmed so far. One likely reason is that there are less spatial dimensions than necessary to lower the Planck scale to energy levels accessible to current particle accelerators. For this reason, some scientists believe that if much more powerful future projects could be constructed, we may finally manage to detect micro black holes (Lazanu et al., 2020, Mack et al., 2020).

Neutrinos are fundamental particles in the Standard Model and are a byproduct of various astrophysical processes, such as nuclear fusion in stars. Cosmic neutrinos can carry huge amounts of energy in hundreds of PeV (Peta-electron volt). Particles at these energy levels can only be found incoming from space; we currently lack the capability to generate them on Earth. We can exploit these cosmic particles for use within our high energy particle experiments. Mack et al. (2020) argue that it may be possible to detect micro black holes in future neutrino observatory projects. The current Neutrino observatory, IceCube Neutrino Observatory, is likely not sensitive enough to detect signals from high energy neutrino shower events. While successful at detecting slower and less energetic neutrinos, IceCube is unable to detect higher energies because of declining neutrino flux (the rate at which neutrinos pass through a unit area per unit time) in this regime, because IceCube does not cover a large enough area. If a new, larger neutrino observatory was built, e.g. IceCube-Gen2 or the Pacific Ocean Neutrino Experiment, the new observatory would perform better at locating and containing high energy neutrino showers (Mack et al., 2020). These detectors are projected to find micro black holes from a variety of particle signatures that appear after a neutrino interacts with the detector and creates a micro black hole.

In order to investigate the possibility of micro black holes as a candidate for dark matter, Lazanu et al. (2020) propose that if micro black holes can become stable and obtain an electric charge, micro black holes should be detectable by a future huge liquid argon (LAr) detector. A LAr detector is a particle detector that uses liquid argon to measure the energy of subatomic particles. Micro black holes should be able to interact gravitationally with atoms and lose some energy. These interactions can produce ionizations and excitations that can be detected via transfer of energy to molecular and electronic systems. Additionally, the excited atoms could produce very tiny amounts of visible wavelength photons which could be measured by optical detectors. These signals should be distinguishable from other ionizations and particle interactions to correctly identify micro black holes.

The Future Circular Collider (FCC) is a proposed massive particle accelerator capable of reaching energy levels up to 100 TeV (Tera-electron volt). This collider is scheduled to be built after the LHC High Luminosity Phase reaches its conclusion in 2040 (Bernardi et al., 2022). Sokolov and Pshirkov (2017) examine the different expectations of stable micro black hole production at the 100 TeV scale as well as safety concerns. Sokolov and Pshirkov showed that the majority of micro black holes produced would have a velocity larger than the escape velocity of the earth, and only a small amount would be temporarily trapped inside. Even though micro black holes at this energy level may be able to accrete subatomic particles inside the earth, Giddings and Thomas (2002) showed that the earth is not capable of successfully slowing down and trapping TeV scale micro black holes. Sokolov and Pshirkov were able to use observational data from white dwarfs and cosmic ray composition to argue that any micro black holes produced at the collider should not have an electric field.

6. Conclusion

The nature of micro black holes is still very speculative and an area of active research. Research papers published describing micro black holes tend to represent them and their properties based on the current understanding of physics but there are still many things that are missing, motivating a search for physics that is beyond the Standard Model. Current searches for micro black holes so far have turned up empty handed. This may be because there are not as many extra dimensions as theorized or we may not have powerful enough technology to access the energy levels required to create micro black holes. In order to find micro black holes we may need to wait for future higher energy capable projects to come into fruition within the next 20-50 years. While we wait for these projects, scientists are working to find better models of micro black holes as more discoveries are made in the field of physics. Hopefully one day, when we will have a better theory of how micro black holes should behave, we will detect a micro black hole in a lab.

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