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Primordial Black Holes

Primordial black holes are hypothetical black holes that formed under conditions of extreme density in the very early universe. Studying primordial black holes provides a probe into both high energy physics and cosmology, setting limits on several cosmological parameters.

The mass of a black hole depends on the order of the particle horizon mass when the black hole collapses. By comparing the cosmological density at a time t with the density of a black hole of mass M, we can derive the formula

$$M(t) = \frac{c^3 t}{G} = 10^{15} \left(\frac{t}{10^{-23}\,\mathrm{s}}\right) g$$

for the mass of a black hole at formation as a function of the age of the universe [1].

This relationship yields a wide range of possible masses for primordial black holes, since black holes may have collapsed from t > 0 until the time of recombination. Plugging into this equation,

at $t = t_{\mathrm{planck}} = 5.4x10^{-44} s$, $M=10^{-5}$g

at t = 1sec, $M=10^{5}M_{\mathrm{sun}}$

at $t = t_{\mathrm{rec}} \sim$ 280,000 years, $M=10^{15}M_{\mathrm{sun}}$

In actuality, there are strong observational limits on the number of primordial black holes that can exist beyond a mass of $10^5 M_{sun}$. For instance, too many high mass primordial black holes would have an observable impact on primordial nucleosynthesis, skewing the elemental abundances we observe today. Additionally, if primordial black holes form with a large enough mass then they would begin to grow by accretion rather than evaporating. This means that if primordial black holes do exist, there must be very few or they must have formed very early in the universe.

According to quantum theory, black holes may emit Hawking radiation, which is particle-antiparticle radiation that is emitted just beyond the event horizon. Vacuum fluctuations cause the particle-antiparticle pair to appear close to the event horizon; one of the pair falls in to the black hole and the other escapes. The result is that a black hole radiates as a blackbody with temperature

$$T = \frac{\hbar c^3}{8 piGMK}.$$

Hawking radiation causes black holes to lose mass as they radiate thermally, and thus evaporate slowly over time. From the temperature we can derive the time it takes for a black hole to evaporate [3],

$$t_{ev} = \frac{5120 piG^2 M_0^3}{\hbar c^4} = 10^{64} (M / M_{sun})^3 \text{ years.}$$

We can see that only primordial black holes would have had the chance to evaporate today. Only black holes with a mass smaller than $M=10^{15}$g would have evaporated by t_0. This corresponds to black holes that collapsed at a time earlier than $10^{-23} s$.

One of the most important applications of studying primordial black holes is that they act as a probe into the inhomogeneities of the very early universe. By imposing observational limits on models of their gravitational collapse, it is possible to constrain cosmological parameters.

For gravitational collapse to occur, the density perturbation must be larger than the Jeans length. This is a length of the square root of γ times the horizon size, where γ is the factor from the equation of state, $P= \gamma\rho$. For the early radiation dominated universe, $\gamma=1/3$. From this we can derive the fraction of regions of mass M that collapse [2], given by

$$B(M) \sim \varepsilon(M) \exp[-\gamma^2 / 2\varepsilon(M)^2],$$

where $\varepsilon(M)$ is the value of the energy density when the horizon mass is M. The current density parameter is related to β by

$$\Omega_{PBH} = 10^6 \beta (t/s)^{-1/2}$$

for black holes formed at time t, or equivalently

$$\Omega_{PBH} = 10^{18} \beta (M/10^{15}g)^{-1/2}$$

for black holes of mass M.

Constraints on the density parameter can be placed directly from observations. For instance, evaporating primordial black holes may be the cause of short-period gamma ray bursts, and observations of these can be used to limit the current density [2]. Limits also come from nucleosynthesis and other observations. These constraints on Ω_{PBH} can be converted into constraints on $\beta(M)$ and hence $\varepsilon(M)$, giving us insight into the evolution of cosmological density.

Primordial black holes can also be used to study phase transitions in the early universe. Phase transitions may cause the fractional collapse $\beta(M)$ to depend on other factors, thereby changing constraints on the cosmological parameters. For instance, a phase transition might produce a “soft” equation of state, where $\gamma<<1$ over a period of time. In this case our equation would look like $\beta \sim 0.02\varepsilon^{13/2}$. This would have the effect of producing primordial black holes in a narrow range of masses [1].

Inflation also has consequences for the formation of primordial black holes. Any primordial black holes formed before the end of inflation will be diluted to a very small density; this imposes a lower limit on the mass of primordial black holes [1], given by

$$M > M_{pl} (T_{reheating} / T_{pl})^{-2}$$

On the other hand, inflation creates fluctuations that can lead to gravitational collapse. This would have the effect of creating primordial black holes after reheating, again in a specific range of mass. For an inflaton potential $V(\phi)$, the fluctuations for a mass M are on the order of

$$\varepsilon(M) = [V^{3/2} / (M_{pl}^3 \, dV/d\phi)] \, H$$

The existence of primordial black holes and their evaporations could have several other cosmological consequences. Planck-mass relics formed after black holes have evaporated, or even larger primordial black holes that we have not detected could be candidates for dark matter. As mentioned earlier, primordial black holes could modify primordial nucleosynthesis, as well as contribute to baryon asymmetry. Finally, if primordial black holes accounted for a large enough portion of dark matter today we might expect to see distortions in the cosmic microwave background, and the energy released due to the accretion of gas could keep the universe partially reionized after recombination [5].

Observational evidence for primordial black holes may soon be found. GLAST is launching soon. It may be able to detect gamma ray bursts caused by evaporating primordial black holes. Additionally, the LHC could theoretically create micro black holes and observe their evaporation. If Hawking radiation does not actually exist, detecting primordial black holes would be difficult. It has been suggested that primordial black holes, with their small sizes and relativistic speeds, could pass through the earth with only a few impacts on nucleons, making them virtually impossible to detect [4].

References

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