13. Black Hole Evaporation

Quantum Mechanics

The *other* great revolution (besides relativity) of 20th century physics (mostly 1900-1927).

Key ideas:

Discreteness: Energy comes in discrete units (not continuous). (E.g., electron energy levels in atoms (discrete) vs. planetary orbits in solar system (continuous). Photons.)

Uncertainty:

- Some experimental outcomes can *only* be predicted probabilistically. (E.g., probability of a radioactive decay in some amount of time.)
- Position and momentum are "complementary" quantities that cannot both be well determined at the same time. (This underlies degeneracy pressure.)

"Classical" physics describes phenomena as continuous and deterministic.

The effects of quantum mechanics are mainly evident on sub-atomic scales.

On macroscopic scales, small spacing of energy levels and averaging of many events makes "classical" descriptions (continuous, deterministic) very accurate.

As formulated by Einstein, Special Relativity and General Relativity are "classical" theories.

There is a successful (i.e., physically consistent and experimentally well tested) combination of quantum mechanics and *special* relativity called quantum field theory (developed in 1930s, 1940s, and 1950s).

It is the basis of our modern understanding of sub-atomic particles and the interactions that govern them.

Thermodynamics

One of the great revolutions (along with electromagnetism) of 19th century physics.

Thermodynamics describes the physics of energy, heat, temperature, pressure, for systems composed of many atoms (gases, fluids).

Two basic "laws" (discovered empirically):

1. Energy is always conserved (though it may be transformed).

2. The entropy of a closed system can increase, but it can never decrease. (One consequence: a hot body can heat up a cold body, but never *vice versa*.)

For #1 to hold in general, the "bookkeeping" must include gravitational potential energy and $E = mc^2$ energy.

Entropy can be expressed in terms of temperature and density, but we now understand the second law (and many other aspects of thermodynamics) as consequences of the statistical behavior of large numbers of particles.

Entropy is a quantitative measure of disorder, the logarithm of the number of ways a system could be rearranged without changing its large scale properties.

For a system made of many, many particles, it is hugely more probable for disorder to increase rather than decrease.

The 2nd law refers to *total* entropy — e.g., we can get increasing order on earth because we're getting energy from the sun (which is creating entropy by radiating photons into space).

Black Hole Thermodynamics

1970: Stephen Hawking shows that in mergers of black holes, the total area of event horizons must always increase.

He and others (especially Jacob Bekenstein) note *very* close analogies between equations governing black holes and equations of thermodynamics.

Horizon area is like entropy, always increases.

Could explain why dropping stuff (with entropy) into a black hole doesn't violate the 2nd law of thermodynamics: the black hole horizon area increases, hence the entropy increases.

The Problem:

In these analogies, the black hole "surface gravity" (roughly $GM/R_{\rm Sch}^2$) plays the role of temperature.

In thermodynamics, any body hotter than its surroundings radiates energy.

Black holes don't radiate.

Hawking Radiation

Another consequence of quantum uncertainty: over short time periods, energy fluctuates.

"Empty space," a.k.a. "the vacuum," is far from empty. It is filled with "virtual particles," which pop into existence in pairs, then disappear soon after.

Despite their ghostly existence, these virtual particles have real effects that are measured experimentally to high precision.

1974: Hawking investigates behavior of virtual particles near event horizons.

Consider a pair of virtual photons with wavelength $\lambda \sim R_{\rm sch}$, created near the event horizon.

Tidal gravity of the black hole pulls them apart, gives enough energy to make them real, long-lived photons.

One falls into the event horizon, but one can escape.

Thus, "radiation" comes from the black hole.

The energy of the escaping photon must come from the black hole, so its mass goes down.

Implication: the laws of black hole thermodynamics really do describe the entropy and temperature of black holes, which are a consequence of quantum mechanics in the presence of strong gravity.

A black hole's entropy is the logarithm of the number of ways that the black hole could have been made.

Black Hole Evaporation

If a black hole is left on its own for long enough, it will radiate away all of its mass and disappear.
BUT

For a stellar mass black hole, the temperature is *extremely* low, e.g., 3×10^{-8} degrees above absolute zero for $2M_\odot$.

The lifetime is 10^{67} years compared to the age of the universe, which is 10^{10} years.

Even an isolated black hole is growing by accreting background photons at least a billion times faster than it is shrinking by Hawking radiation.

But if the universe lives forever and keeps getting colder, all the black holes will eventually evaporate.

IF mountain-mass black holes ($M \sim 10^{12}$ kg) formed in the very early universe, then they would be evaporating today, in explosions of gamma-rays.

This would be cool, but there is no evidence that these evaporating black holes exist, and no reason to think that they ought to.

Status of Hawking Radiation

Note that Hawking radiation is *not* the source of energy in X-ray binaries or quasars — it is far, far, far too feeble.

We may never have any direct empirical test of the existence of Hawking radiation from black holes, but we strongly expect it to exist because it is a consequence of quantum mechanics and General Relativity.

It is an important and deep point of principle, even if its practical consequences are negligible.

Equations in science

Equations allow us to formulate scientific theories in a precise and compact way, something that would be much more difficult with words alone.

Equations allow us to calculate the consequences and predictions of a theory, in quantitative terms that can be tested against observations or experiments.

Sometimes these predictions are surprising and exciting — e.g., the prediction of the existence of black holes from the equations of General Relativity.

Sometimes the equations seem to have a life of their own, to "know" something about the universe that goes far beyond the original theories.

Black hole thermodynamics is a dramatic example of the power of equations in physics.

Quantum Gravity and General Relativity

Hawking and others developed the theory of *quantum fields in curved spacetime*.

This theory *involves* quantum mechanics and GR, but it does not fully merge them.

One of the highest ambitions and toughest challenges of fundamental physics is to develop a theory of *quantum gravity*, in which spacetime curvature itself is treated quantum mechanically.

If we ever develop a successful theory of quantum gravity, it should reduce to General Relativity in the limit of macroscopic scales and finite curvature.

This is analogous to the way that General Relativity reduces to Newtonian gravity in the limit of slow speeds and weak curvature, or to Special Relativity in the case of flat spacetime.

There is a natural (very tiny) scale where we expect that quantum gravity *must* become important, known as the Planck length, $l_p = 10^{-33}\,\mathrm{cm}$.

(Very roughly, the ratio of the Planck length to the size of an atom is like the ratio of the size of an atom to the size of the solar system.)

We do not know whether quantum gravity will have a very different conceptual basis, like the difference between GR and Newtonian gravity.

We do not know whether there are observable effects of quantum gravity on scales that we can probe with feasible experiments or astronomical observations.

String theory is the best candidate for something that might become a successful theory of quantum gravity.

In string theory, fundamental "particles" are really tiny loops of string oscillating in a 10-dimensional space, so the conceptual change is fairly radical.

Calculating observable quantities in string theory is very difficult, so even though the ideas have been around for four decades, we don't have empirical evidence on whether string theory is correct or incorrect.

Quantum gravity and black holes

Quantum gravity certainly matters close to the central singularity of a black hole, and probably "smooths it out" to finite size (at least l_p).

Until recently, it has been thought that quantum gravity *doesn't* matter near the horizon, or through most of the black hole interior.

However, some recent theoretical studies argue that quantum gravity (and not "just" Hawking radiation) affects physics at the event horizon, in a way that would matter to an observer falling into a black hole.

Samir Mathur (OSU Physics) has argued based on string theory that the mass in a black hole is distributed in a "fuzzball" that fills the event horizon, and is not just confined to the central singularity.