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5: Black holes and quanta

How empty is the vacuum?

The excitement due to black holes began in astronomy at the end of the 1950s and the beginning of the 1960s. Years passed, and the riddle was considerably clarified. It was understood that the death of a massive star inevitably yielded a black hole; and quasars were discovered, probably containing at the center a supermassive black hole. Finally, the first black hole of stellar origin was identified in the X-ray source of the Cygnus constellation. Physics theorists found order in the baffling properties of black holes, and gradually grew accustomed to these gravitational abysses that can only absorb matter and swell; black holes seemed doomed to eternal existence.

Nothing foreshadowed a new grandiose discovery. Nevertheless, the discovery did come, as a bolt from the blue, and amazed even the old hands of physics.

The message was that black holes are not eternal! They may disappear as a result of quantum processes occurring in strong gravitational fields. We shall begin this story from rather afar, in order to make the gist of this discovery more understandable.

Let us begin with empty space: the vacuum. For physicists, empty space is not at all empty. This is not a pun. It was established quite long ago that the 'absolute' emptiness, the 'nothing-nothing', is impossible in principle. What then is the empty space for a physicist? The vacuum is what is left after all particles, all quanta of any physical field are removed. The reader (provided he has not recently refreshed his picture of physics) could be expected to remark that *then* nothing will remain. Oh, no, something will. Physicists say that the space will be filled with a sea of unborn, so-called virtual, particles and antiparticles. Virtual particles cannot just be 'removed'. They cannot convert into real particles in the absence of external fields, that is, when no energy is imparted to them.

A particle–antiparticle pair appears at each point of the empty space for only a very short time, after which the two particles again merge and disappear, returning to their 'embryonic' state. Of course, this simplified language creates only a crude image of the quantum processes that take place. The presence of the sea of virtual particle–antiparticle pairs was established long ago by direct physical experiments. We will not discuss this aspect here, otherwise the digression would take us too far from the main topic.

In order to avoid unwanted puns, physicists refer to empty space as the vacuum. We too will use this terminology.

A sufficiently strong or oscillating field (e.g., an electromagnetic field) may trigger the transformation of virtual particles of the vacuum into real particles and antiparticles.

Both theorists and experimenters became interested in such processes quite a long time ago. Let us consider the process by which an a.c. field creates real particles. This is the process that is important in the case of the gravitational field. Quantum processes are known to be unusual, and often constitute a challenge to 'common sense'. Correspondingly, before discussing the creation of particles by alternating gravitational field, we will look at one simple example from mechanics. It will make the further story clearer.

Imagine a pendulum. Its suspension cord passes through a pulley and the length of the suspension can be varied by taking the cord in or letting it out. Push the pendulum. It starts to swing. The period of vibration depends only on the length of the suspension: the longer it is, the longer the vibration period. Now we pull the cord up very slowly. The pendulum length decreases, the period decreases as well, but the range (amplitude) of vibrations increases. Let us slowly play out the cord to the initial position. The period is restored, as well as the vibration amplitude. If we neglect the damping of vibrations in response to friction, the energy carried by vibrations obviously remains the same in the final state: the same as it was before the entire cycle of changing the pendulum length. However, it is possible to vary the pendulum length in such manner that the vibration amplitude is changed when the suspension length returns to the initial value. To achieve this, one has to jerk the cord at twice the pendulum vibration frequency. This is what we do on a swing. We stretch or pull up our legs in unison with the swinging motion, so that the amplitude increases constantly. Of course, the swing can be stopped if our legs are pulled up in 'counter-unison'.

Electromagnetic waves in a resonator can be 'swung' in a similar manner. A resonator is a cavity with mirror walls that reflect electromagnetic waves. If a cavity with mirror walls and mirror piston encloses an electromagnetic wave, we can change the wave amplitude by displacing the piston forwards and backwards at a frequency twice that of the electromagnetic wave. The amplitude, and hence the intensity, of the electromagnetic wave can be enhanced by moving the piston 'in unison' with wave oscillations, or they can be damped by moving in 'counter-unison'. But if the piston is moved randomly – both in unison and in counter-unison – the wave will on average always be enhanced, that is, the energy is 'pumped' into electromagnetic oscillations.

Now let our resonator enclose waves of all possible frequencies. No matter how we move the piston, there is always a wave for which the movements are in unison. The amplitude and intensity of this wave are amplified. The greater the wave intensity, the larger the number of photons (quanta of electromagnetic field) that the wave contains. Therefore, the piston motion changes the shape of the resonator and thereby creates new photons.

Having outlined these simple examples, we return to the vacuum, to this sea of all possible virtual particles. For the sake of simplicity, we will now consider only one species of particles, namely, virtual photons. It is found that a process similar to the oscillation of resonator size discussed above, which in classical physics results in enhancement of the contained oscillations (waves), produces in quantum physics an 'amplification' of virtual oscillations, that is, it transforms virtual particles into real ones. Thus a variation of gravitational field with time must produce photons whose frequency corresponds to the time in which the field changes. As a rule, these effects are negligible because gravitational fields are weak. In strong fields, however, the situation is quite different.

Another example: very strong electric field creates in the vacuum pairs of charged particles (electrons and positrons).

Let us return to black holes from our short digression on the physics of the vacuum. Can particles be created from the vacuum in the neighborhood of a black hole?

Yes, they can. This has been known for a long time, and was held to be nothing sensational. Thus when an electrically charged body is compressed and transforms into a charged black hole, its electric field is so enhanced that it creates electron–positron pairs. Such processes were studied by Markov and his students. In fact, this process is also possible without a black hole, but in that case the electric field must somehow be enhanced to a sufficiently high level. The effect is not at all specific to black holes.

Zel'dovich proved that particles are also created in the ergosphere of a rotating black hole, and subtract some of its rotational energy. This phenomenon is somewhat similar to the process discovered by Penrose and outlined in Chapter 3.

All these processes are caused by fields around a black hole and changes produced in these fields, but they neither reduce the black hole nor diminish the size of the region from which light or other radiation or particles are allowed to escape.

Hawking's discovery

A sensational discovery was made in 1974 by the English theorist Stephen Hawking. A textbook on gravitation, written by the American theorists Misner, Thorn and Wheeler and published before this discovery was made, gives the following characterization of Hawking's work:

> In such scope is exhibited not only a considerable insight, depth, and versatility, but also the gift of an extraordinary determination to overcome severe physical handicaps, to seek out and comprehend the truth.

Hawking was able to show that there exists a quantum process of particle creation by the black hole itself, and by its gravitational field, and that this process reduces the mass and size of the black hole.

At a first glance, this is surprising. Indeed, when a black hole is being formed, all processes on a contracting star are rapidly slowed down and 'freeze out' for distant observers; the gravitational field becomes constant everywhere, not changing with time. This field cannot create particles. Hence, if a varying field produces a (very small) number of particles during the formation of a black hole, the flux of these particles from the newborn black hole will rapidly decay, as will all other processes, as the surface approaches the gravitational radius. Hawking's result actually states that this conclusion is

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wrong, that the flux will not die out but will continue even after the black hole has already formed. Is there a contradiction?

The point is that the field inside the black hole is not at all frozen. No constancy in time is possible there, and everything inside the black hole has to move, to fall on the center. This is the factor leading to the fantastic process discovered by Hawking. The reader will remember that virtual particles under ordinary conditions in vacuum form, for a short time, antiparticle–particle pairs, which then merge and vanish. In the gravitational field of the black hole, one of the particles created in this way may be below the horizon and immediately start to fall centerwards, while the other particle stays beyond the horizon. The latter particle flies away into space and carries part of the energy of the black hole, and hence, of its mass.

There appears, therefore, the quantum radiation of particles by black holes. Actually, this process is usually quite negligible. Hawking's calculations show that a black hole emits radiation as an ordinary body heated to a very low temperature. Thus the emission from a black hole of one solar mass corresponds to a temperature of one-ten-millionth of one degree. Of course, this radiation is negligibly small. The wavelength of emitted photons equals the size of the black hole: 10 km. Energy loss to this radiation can be completely ignored.

Energy gain due to the rarest atoms in interstellar space and to minute fluxes of light that propagate through the Universe and fall into such a black hole is much greater in the real conditions of today's Universe than the loss due to radiation. Hence, black holes do not shrink but, in fact, grow. The larger a black hole, the lower its radiative temperature. As a result, quantum radiation of giant black holes is absolutely negligible.

Black holes explode!

Having read the preceding paragraphs, the reader may shrug his shoulders in disbelief: 'This is such an insignificant phenomenon. How could it cause such a storm of astonishment and delight among physicists?'

It did so, first of all because physicists were sure before Hawking's discovery that the static gravitational field outside the black hole cannot in any way create particles. As for the variable field within the black hole horizon, it is 'invisible and impalpable' to distant observers and thus can be safely forgotten. However, it is typical of quantum processes that a particle may show up where classical physics would definitely forbid it. For example, a particle may 'seep' through an energy barrier when its energy is insufficient for it to go over this barrier. Hawking proved that this property of quantum particles produces a qualitatively new effect in the case of black holes: quantum evaporation of black holes. Left alone, free of external influences, black holes slowly disappear, transform into thermal radiation, and slowly shrink in space and time. The principal importance of Hawking's discovery lies in the fact that the notion of the eternity of black holes has been rejected.

But this is only part of the story. The smaller a black hole, the higher the temperature of its radiation.

As the black hole mass diminishes in the course of evaporation, its temperature increases and hence the process of evaporation is intensified. When the mass of the black hole drops to a thousand tonnes, its radiative temperature increases to 10^{17} degrees! Evaporation turns into a fantastic explosion. These last thousands of tonnes, compressed into a microscopic volume, are radiated away, or rather exploded, by the black hole in one tenth of a second. The energy released thereby is equivalent to the explosion of a million hydrogen bombs of one megatonne each. This fantastic firework display wipes out what earlier seemed to be a perpetual gravitational abyss.

Of course, this can happen over a very long period of time. Calculations show that if no external factors are involved, a stellar-mass black hole evaporates and explodes at the end of a period of 10^{66} years. Even astronomers give up when faced with such a long stretch of time.

Nevertheless, these processes may become important in the remotest future of the Universe. We will return to this point in the next part of the book.

Let us turn from the final moments in the life of a black hole to its normal state, and see what particles are emitted in this process.

A black hole creates not only photons but other particles as well. Relatively large black holes of several solar masses have such a low temperature that they cannot generate anything but massless particles. These particles always fly at the velocity of light and have no 'rest mass'. These are photons, electron and muon neutrinos, their antiparticle counterparts, and also the not-yet-discovered gravitons, that is, quanta of gravitational waves. A black hole of typical stellar mass produces copious neutrinos (81 per cent of the entire flux), photons (17 per cent), and gravitons (2 per cent). Different particles are emitted in different amounts because they possess different properties. Mostly neutrinos are emitted because their quantum

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rotation (what is called *spin* in quantum physics) is minimum $(\frac{1}{2})$, and the fraction of gravitons is the lowest because their spin is maximum (2).

Low-mass black holes have high temperatures. Thus the temperature of black holes of mass less than 10^{17}–10^{16} g exceeds 10^{9}–10^{10} degrees. In addition to the particles listed above, these black holes produce electron–positron pairs. Note that such black holes are a mere 10^{-11} cm in size: a thousand times smaller than the atomic diameter.

Black holes of mass less than 5×10^{14} g can also emit muons and even heavier elementary particles.

Such black holes are smaller than an atomic nucleus. Obviously, such tiny black holes could not be formed in the course of stellar evolution. However, they could have appeared in the distant past. If such 'primary' black holes of mass less than 10^{15} g were born at the beginning of the expansion of the Universe when the matter was very dense (this is theoretically possible, as was pointed out by Zel'dovich and myself and later proved in detail by Hawking), they would all have evaporated by now. For this reason the process discovered by Hawking is extremely important for cosmology.

If I may allow myself a dream (even though a strictly scientific dream), I can imagine the artificial production of tiny black holes in space (in the very distant future). They would accumulate energy spent on their formation and then would radiate it at a prescribed rate at a given particle energy which is determined by the mass of the black hole. Thus a black hole with a mass of 10^{15} g (the mass of a medium-sized mountain) will emit 10^{17} erg per second for about 10 billion years.

Some things remain unclear in this new phenomenon. For instance, we do not know whether a black hole leaves behind no remnant, or the remnant is a particle of the so-called Planck mass (10^{-5} g). It is not clear whether the process of black hole evaporation is observable in the Universe. As for any experiments with black holes in physicists' laboratories, they sound only like science fiction. But even what we already know makes us reconsider a number of aspects of the evolution of matter in our Universe.

This is the end of our story about holes in time and space. Less than a century ago people were not only unaware of these objects but they could not have imagined them even if a space traveller from our time arrived and tried to describe to them these marvels of nature.

I hope that this story has explained at least in part the unusual popularity that the theme of black holes has enjoyed recently. It will be proper to finish this part of the book with a poem that describes the feelings of a person who faces one of the grandest puzzles in nature, contemplating the vast new world that arises when stars die.

Stars perish in an endless universe.
A star falls into its own decay –
The call of death, –
An end to breath and passion –
into the dark void of oblivion
leaving behind a gulf against the shore
of space and time, a crater of gloom
cocooned within the stellar dust.

This hungry maw of other, new-wrought world
would dwarf the dreaded gap of Dante's wild inferno.
This endless, worldless, spherical abyss
where time and space are madly mixed,
where all roads lead to dire annihilation,
where the black wind roars large and everywhere ...
... a maelstrom of stellar dust, stock-still –
a guard of honour on a crater's verge.

Marina Katys
(Translated by Phil Nix
and Jim Beall)

Part II
To the bounds of infinity

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