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Cosmic Tachyons: An Astrophysical Approach

The interaction of tachyons—faster-than-light particles—with gravity leads to results of interest to cosmology and black hole physics

There was a young girl named Miss Bright
Whose speed was far faster than light.
She departed one day
In a relative way
And came back the previous night.

This limerick by Reginald Buller reflects the unease felt by most scientists at the mention of particles traveling faster than light. Doesn't relativity forbid this? Don't such particles violate causality? Wouldn't these particles have imaginary mass? These are some of the questions which are almost invariably raised whenever faster-than-light particles are discussed. Nevertheless *tachyons,* as these particles are called, are today a respectable part of speculative physics.

Speculative, because tachyons still remain to be created or detected in the laboratory. While the theoretician is primarily concerned with sorting out the conceptual problems of tachyons, such as those mentioned above, his counterpart in the experimental area is interested in the ways and means of detecting tachyons and in nailing down their physical properties, such as mass (!), spin, and electric charge. So far attempts in this direction have not proved successful, and tachyons continue to be elusive.

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It is here that astronomy may come to the aid of the laboratory physicist. The physical processes in the cosmos operate on a much bigger scale and often cannot be easily reproduced in the terrestrial laboratories. The controlled thermonuclear fusion achieved in the stars, cosmic ray particles with energy as high as 10^{20} ev, gigantic extragalactic radio sources, pulsars, etc., involve the extrapolation of physical laws far beyond the range over which they have been tested in the laboratory. As I will show in this article, the discussion of tachyons under cosmic conditions does lead to many interesting results and even holds out a (distant) hope of detecting them.

Tachyons and special relativity

Before describing some of the recent results on cosmic tachyons, we will review here the basic properties of these particles and make brief reference to some of the questions raised earlier. Figure 1 is a spacetime diagram, with time denoted by the vertical axis and the space vector $\mathbf{r}$ by the horizontal axis. A light ray passing through the origin 0 has the track given by

$$r \equiv |\mathbf{r}| = \pm ct$$

where c equals the speed of light. This is known as the light cone. However, unlike the ordinary cone in 3 dimensions, the light cone is a 3-dimensional surface known in technical jargon as a *null hypersurface.*

The track of an ordinary particle (which travels more slowly than light) passing through 0 will lie *inside* the light cone; such a particle is called a *tardyon.* If we accelerate it, its velocity increases and its trajectory bends closer toward the limits of the light cone. However, it never escapes the light cone or even reaches its limit as it moves toward the $\mathbf{r}$-axis. The limit of the cone is the so-called *light barrier* implied by the special theory of relativity. If the tardyon in Figure 1 has a velocity $\mathbf{v}$, then its mass is expressed by the formula

$$m = \frac{m_0}{\sqrt{1-\frac{v^2}{c^2}}}, \qquad v = |\mathbf{v}|$$

Here m_0 is the *rest mass* of the particle—its mass measured in the frame of reference in which it is at rest. The momentum and energy of the particle are given by

$$\mathbf{P} = \frac{m_0\mathbf{v}}{\sqrt{1-\frac{v^2}{c^2}}}$$

$$E = \frac{m_0c^2}{\sqrt{1-\frac{v^2}{c^2}}}$$

$$E^2 = |\mathbf{P}|^2c^2 + m_0{}^2c^4$$

These relations indicate why it is impossible for a tardyon to attain the speed of light, let alone exceed it. As v approaches c, the energy and momentum rapidly increase, and by Newton's laws of motion an *infinite* force would be needed to increase $\mathbf{P}$ and E to the infinite values obtained by putting $v = c$ in the above formulas.

The inability of a tardyon to attain

the speed of light does not, however, preclude the existence of a separate species of particles that travel *with* the speed of light. These are the so-called luxons (see Fig. 1), examples of which are the photon (the carrier of light) and the neutrino. What is precluded is the change of a particle from one species to another. An electron (which is a tardyon) cannot be accelerated to become a luxon; nor can a photon be decelerated to become a tardyon. The concept of rest mass has no meaning for a luxon since it can never be brought to rest. It can, however, have finite energy E and momentum $\mathbf{P}$, which are related by

$$E = |\mathbf{P}|c$$

Thus, in a purely formal sense we may ascribe a "zero" rest mass to a luxon.

The tardyons and the luxons do not cover all the directions from 0 in Figure 1. To complete the picture we need to postulate a third species of particles, whose trajectory lies *outside* the light cone. Such a particle travels with a velocity $\mathbf{v}$ faster than light:

$$v = |\mathbf{v}| > c$$

No contradiction with special relativity is implied if we continue our policy of not mixing up the three species of particles—tardyons ($v < c$), luxons ($v = c$), and tachyons ($v > c$)—and remember that a tachyon cannot slow down to become a luxon or a tardyon. The momentum and energy of a tachyon moving with velocity $\mathbf{v}$ are expressed by

$$\mathbf{P} = \frac{\overline{m}_0 \mathbf{v}}{\sqrt{\frac{v^2}{c^2} - 1}}$$

$$E = \frac{\overline{m}_0 c^2}{\sqrt{\frac{v^2}{c^2} - 1}}$$

$$|\mathbf{P}|^2 c^2 = E^2 + \overline{m}_0^2 c^4$$

Notice that if we had insisted on extending the energy-momentum formulas for tardyons to the region $v > c$, we would have got the above formulas provided

$$m_0^2 = -\overline{m}_0^2$$

Thus a tachyon rest mass is imaginary, which need not disturb us since

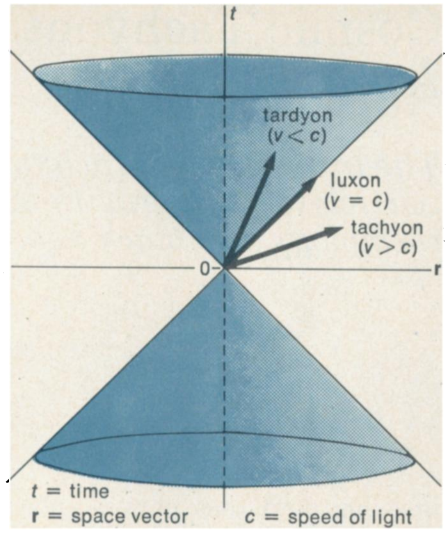

Figure 1. The tracks of a tardyon, a luxon, and a tachyon through a typical spacetime point 0 are shown in relation to the light cone. Both the tardyon and tachyon tracks approach the surface of the light cone from the inside and outside, respectively, if they become more energetic.

a tachyon can never come to rest. An imaginary rest mass for a tachyon has the same formal status as the zero rest mass for a luxon (which also cannot come to rest).

We can nevertheless give a meaning to $\overline{m}_0$, which is often called the *meta mass* of the tachyon: $\overline{m}_0 c$ is the magnitude of the momentum of the tachyon when it is traveling with infinite speed. From the above formulas such a tachyon has zero energy. Paradoxically, a tachyon *gains* energy as it slows down and loses energy as it speeds up.

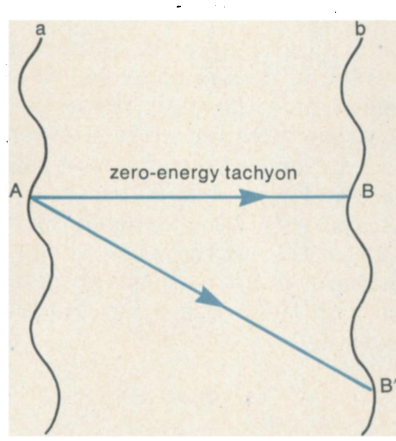

Figure 2. The zero-energy tachyon conveys momentum instantaneously from point A to point B on worldlines a and b. By the reinterpretation principle the tachyon along AB' traveling backward in time may be reinterpreted as having been emitted at B' and absorbed later at A.

Figure 2 shows a tachyon of infinite speed connecting two particle worldlines a and b. Such a tachyon expresses the Newtonian concept of instantaneous action at a distance. Notice that if a emits the tachyon at A, and b absorbs it at B, momentum is exchanged between a and b but no energy!

In Figure 2 we consider what happens if we depress the velocity vector of the tachyon farther down along AB'. This tachyon has negative energy and is traveling backward in time (see the adventures of Miss Bright). According to the "reinterpretation principle" we may reverse the direction of this tachyon so that it moves forward in time with positive energy, but from B' to A. Thus the roles of the absorber and the emitter are reversed. Most causality paradoxes can be resolved by the reinterpretation principle (Sudarshan 1970 discusses several such paradoxes), and we will use this principle later in the article.

Finally, let us ask what intrinsic spin a tachyon is expected to have. Normally the spin states of an elementary tardyon or a luxon are determined by the Lorentz group and its unitary irreducible representations. From these considerations, for example, the half odd integer spin states (e.g. for the electron) or the integral spin states (e.g. for the photon) follow. If similar considerations are applied to tachyonic particles, many possibilities emerge—e.g. the tachyon may be spinless or it may have an infinite number of spin states. Only further specific theoretical models or experiments can narrow down these different possibilities.

Gravitational interaction of tachyons

Any specific experiment designed to detect the tachyon or to measure any of its physical parameters must depend on a specific model describing how tachyons interact with ordinary matter (i.e. tardyons and luxons). Bilaniuk and Sudarshan (1969) have described several such attempts which have proved fruitless. These negative results do not rule out the existence of tachyons; rather, they disprove the interaction models underlying the predictions being tested. Since constructing such models is like groping in the dark, in this process it is worthwhile to begin with as general a scenario as possible. Such a scenario is provided by gravity as interpreted in Einstein's general theory of relativity.

Einstein described all gravitational phenomena in terms of curved spacetime (see Smarr and Press 1978). The distribution of matter and energy, according to Einstein's general relativity, produces a non-Euclidean geometry for the ambient spacetime. A particle subject only to the gravitational force of this matter and energy will move in this spacetime according to Newton's first law of motion—"in a straight line with uniform speed." Such tracks, known as *geodesics*, play the role of straight lines in the curved spacetime. Thus a tardyon will move in a timelike geodesic—i.e. in a geodesic always lying within the local light cone. A luxon will move in a null geodesic (lying *on* the light cone).

How will the tachyon behave in the presence of this matter and energy? A simple generalization of the above picture suggests that a tachyon will move on a spacelike geodesic—i.e. on a geodesic lying *outside* the light cone. It is remarkable that with this simple assumption a number of interesting properties of cosmic tachyons can be deduced. Throughout the remainder of this article we shall confine ourselves to this assumption.

A cosmic time barrier

Most cosmologists today work within the framework of the expanding universe models, which were first indicated by Hubble's observations of remote galaxies. What Hubble found was that the spectra of visible light from distant galaxies were systematically shifted toward the "red" end. That is, if from our local physics and the observations of nearby galaxies we expect a certain spectral line to have a wavelength λ_e, the actually observed wavelength turns out to be

$$\lambda_r = \lambda_e(1 + z)$$

where z is a positive quantity, often called the *redshift*. Hubble found that the redshift increased with distance (D) according to a linear law

$$cz = HD$$

where H is now called the Hubble constant (see Fig. 3). The present estimate of H^{-1} (which has dimensions of time) is in the range of $(1–1.8) \times 10^{10}$ years.

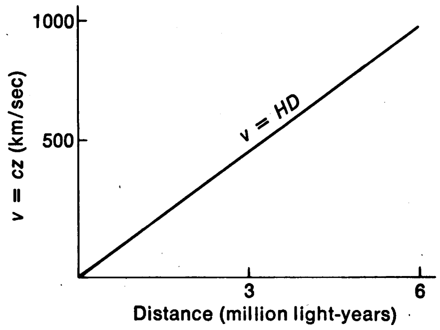

Figure 3. Hubble's original observations, which led to Hubble's law, extended to distances (as estimated by him) of the order of 6 million light-years, with redshifts corresponding to Doppler recession velocities of the order of 1000 km/sec. The distance scale has since been revised several times, and the present value of the Hubble constant is nearly 10–20% of Hubble's original estimate. (This range covers the present-day uncertainty of extragalactic distance estimates.)

Hubble's observations have been interpreted in terms of the expanding universe; this picture describes a non-Euclidean spacetime in which the space is expanding. The galaxies that are embedded in this space therefore appear to be moving apart from one another (see Fig. 4). The Hubble effect of redshift is obtained when we consider the propagation of photons in such an expanding universe. In particular, if we denote by $S(t)$ the behavior of the characteristic scale of separation of galaxies with the cosmic epoch t, then we get the simple result

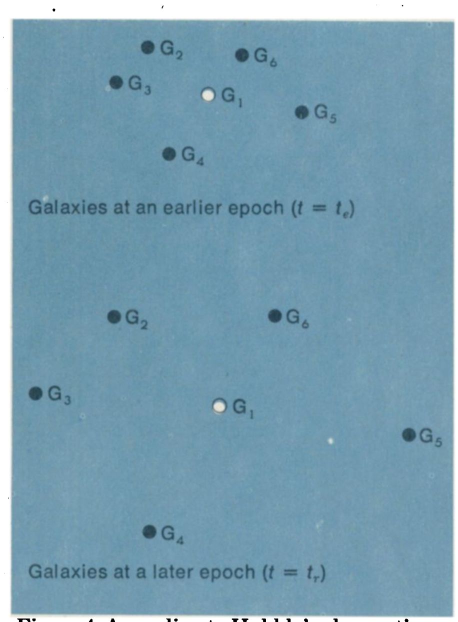

Figure 4. According to Hubble's observations, the distance scale between typical galaxies G_1 and G_6 has increased with time in the expanding universe. All galaxies appear to recede from a typical galaxy G_1.

$$\frac{\lambda_e}{\lambda_r} = \frac{S(t_e)}{S(t_r)}$$

where t_e is the epoch of emission of the photon and t_r is the epoch of reception of the photon. Since in an expanding universe $S(t)$ increases with t, we have $S(t_r) > S(t_e)$ and hence $\lambda_r > \lambda_e$.

This result is obtained by considering null geodesics, since photons are luxons. What will happen if we consider the propagation of tachyons in the expanding universe? The answer to this question is provided by the spacelike geodesics in the expanding universe. The immediate consequence is analogous to that for photons. If we denote by P_e and P_r the tachyon momenta at epochs t_e and t_r, we get

$$\frac{P_r}{P_e} = \frac{S(t_e)}{S(t_r)}$$

When we note that the momentum of a photon is inversely proportional to its wavelength, the analogy between the two results becomes obvious.

However, for a tachyon this result has more startling consequences. As the tachyon moves on, its momentum decreases so long as the universe continues to expand. But we must remember that the momentum must always exceed the quantity $\overline{m}_0c$. How can these two results be reconciled? If we use the standard model for an ever-expanding universe, S increases to infinity, and so according to the above formula eventually the tachyon momentum must drop below $\overline{m}_0c$.

This paradoxical situation simply illustrates the flaw in our tacit assumption that a tachyon must forever travel forward in time. What in fact happens is that at a critical epoch t_c, when

$$S(t_c) = \frac{P_e}{\overline{m}_0c} S(t_e)$$

the tachyon encounters a *time bar-*

rier. It is turned back at this barrier and goes backward in time.

The trajectories of a typical tachyon and luxon are shown in Figure 5. Note that the luxon continues to travel forward in time (as does the tardyon), whereas the tachyon turns back. As we indicated earlier, the reinterpretation principle can be invoked at this stage: we could then argue that the part of the trajectory left of the turn-back point denotes a tachyon traveling forward in time while the right part denotes an antitachyon traveling forward in time. The two annihilate at C. However, unlike the electron-positron annihilation, this is a gentle process with no release of energy. This peculiar behavior of tachyons in the expanding universe was noted by A. K. Raychaudhuri (1974) and several others.

In 1975 George Sudarshan and I used the concept of a time barrier to place an upper limit on the meta mass of a primordial tachyon (1976). A primordial tachyon is one that was created at the time of the origin of the universe in the big bang (assuming that there was such a big bang). According to the ideas first put forward in the late 1940s by George Gamow and developed subsequently by several research workers, the synthesis of nuclei like deuterium and helium took place in the first few moments after the big bang. For example, the temperature of the universe when it was only one second old is estimated to have been $\sim 10^{10}$ °K. At such high temperatures neutrons and protons can be brought together to form these nuclei. At this epoch the different species of particles (neutrons, protons, electrons, neutrinos, etc.) are believed to have been in thermodynamic equilibrium, with an equipartition of energy per particle.

If we assume that the primordial tachyons also participated in this equipartition process, we can identify t_e (in our formula above) with that epoch. We then ask the question: What should be the meta mass of such a tachyon for it to have survived up to the present epoch? For this to happen the present epoch must precede the epoch t_c of the time barrier for such tachyons.

The answer to this question of course depends on the cosmological model chosen. If we take the nearly empty,

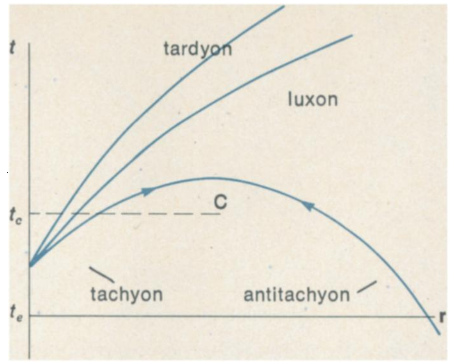

Figure 5. The trajectories of a tardyon, a luxon, and a tachyon emitted from the same space-time point are shown. The first two keep traveling forward in time, while the tachyon encounters a time barrier at C and turns back in time. By reinterpretation we may look upon C as the point of annihilation of a tachyon and an antitachyon.

uniformly expanding big bang model the answer comes out to be

$$\overline{m}_0 < \sim 1.6 \times 10^{-16} m_e$$

where m_e is the mass of the electron ($\cong 9 \times 10^{-28}$g). The result that the meta mass is so low suggests that the tachyons may be more like neutrinos or photons, which are sometimes considered as tardyons of very low rest mass. We will now consider the reverse question: Could the neutrino or the photon be tachyonic?

Suppose we want to argue that the neutrinos are tachyons. Then if the primordial neutrinos are to survive to this day, their meta mass must be as low as given by the above limit. This limit may be compared with the limit on the neutrino rest mass from the laboratory experiment of beta decay:

$$m_\nu < \sim 5 \times 10^{-4} m_e$$

A limit of the same order would be implied (by the uncertainty of the beta decay data at the high-electron energy end) on the meta mass of the neutrino, if it were assumed to be tachyonic. It is significant that the cosmological limit is much more stringent than the laboratory limit.

Can we argue that photons themselves are tachyonic? It would indeed be ironic if light itself were not to travel along the light cone. However, people have from time to time placed an upper limit on the rest mass of a photon because they assumed that it was a tardyon. One technique, suggested by Feinberg (1969), uses the Crab Pulsar NP 0532. Here if the pulsar emits two photons of different frequencies simultaneously, then the photon of higher frequency will be received *later*. The effect of a finite nonzero rest mass is therefore qualitatively similar to the effect of interstellar plasma dispersion. An interstellar electron density of one particle per cm^3 will produce the same delay in arrival times as a photon rest mass of $\sim 2 \times 10^{-17}\, m_e$.

For a tachyonic photon, the two effects are of opposite kinds. Owing to a nonzero meta mass a higher-frequency photon will tend to arrive *earlier* than a lower-frequency photon. Again, for a meta mass of $\sim 2 \times 10^{-17}\, m_e$, this effect will be canceled by the interstellar plasma dispersion of 1 electron/cm^3. Hence a null result rules out a tardyonic photon, but not a tachyonic photon.

One final cosmological speculation. Could the microwave background be tachyonic? This background was first discovered by Arno Penzias and Robert Wilson in 1965, at 7 cm wavelength. Subsequent observations have covered a range of $\sim$75 cm to $\sim$2.6 mm, over which an excellent fit is obtained for a black-body curve of temperature 2.7°K. The fit at shorter wavelengths remains to be confirmed.

For a tachyon to look like a photon, its energy must be very large compared to $\overline{m}_0 c^2$. (In this case, in Fig. 1 the tachyon trajectory will lie very close to the light cone.) If we want to argue that the microwave background is tachyonic, at least two conditions must be satisfied. The first is that, over the entire wavelength range observed, the above energy condition must be satisfied. It is interesting to note that for the cosmological limit on the meta mass mentioned earlier, this condition *is* satisfied.

The second condition is that the tachyonic photon must exhibit only two polarization states as done by the luxon photon. Certainly, if the tachyon has an infinite number of spin states, the interference between the various states will disappear at such high energies. However, it would still be a problem for the proponents of this hypothesis to explain why only two polarization states are seen and no others.

Tachyons and black holes

In cosmology the effects of non-Euclidean geometry are spread over the entire universe. There are, however, situations in astrophysics where one encounters (or is likely to encounter) localized non-Euclidean effects. As implied in Einstein's theory, such effects will be found in strong concentrations of matter and energy, e.g. in supermassive objects and black holes (Smarr and Press 1978). We will now consider what peculiar effects are to be expected when tachyons interact with black holes.

Black holes are believed to have formed in the process of gravitational collapse, i.e. through an unrestricted continual contraction of a massive object under its own gravitational pull. As is evident from Newton's inverse square law, and as is also borne out less directly by the general theory of relativity, gravitational effects grow as the object contracts, with the result that the contraction tends to be more and more rapid. Other forces in nature, like the thermal pressure in stars, may initially oppose the contraction, but beyond specified mass limits gravitational contraction cannot be halted. For example, the pressure that withstands gravitational contraction in neutron stars may not be effective if the star mass exceeds, say, three times the mass of the sun (there is still some controversy about the precise upper limit).

A sufficiently massive object collapsing gravitationally becomes a black hole—that is, it shrinks so much that its surface gravity is strong enough to pull back even light leaving its surface. Thus, a spherical object of mass M becomes a black hole when its surface area becomes as small as

$$A_S = 16\pi \left(\frac{GM}{c^2}\right)^2$$

corresponding to a "radius" of $2GM/c^2$. Of course, because the geometry is highly non-Euclidean at this stage, this notion of radius is only a formal one. For the sun to become a black hole its radius would have to be as low as ~3 km. (The actual radius of the sun is ~700,000 km.) Such a spherical black hole is called a Schwarzschild black hole, after the original solution of the spherical problem by K. Schwarzschild (1916). The quantity $2GM/c^2$ is called the Schwarzschild radius of the black hole.

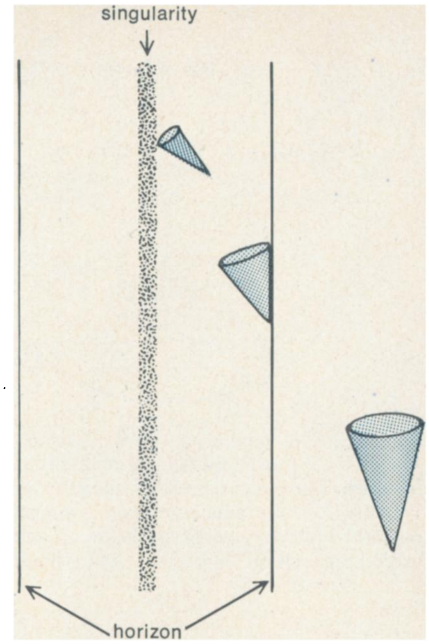

Figure 6. The light cones are oriented in this manner near a Schwarzschild black hole. Once inside the horizon all directions within the future light cone lead toward the central singularity.

Normally, a collapsing object shrinks to a point which is a singular point of spacetime manifold; but this singular fate is hidden from an external observer by a *horizon* which develops around the collapsing body. The surface area of the black hole refers to the surface area of this horizon. No light signal can travel outward across the horizon (see Fig. 6).

If the collapsing body has rotation and hence nonzero angular momentum it goes into what is known as the Kerr (1963) black hole. This black hole is characterized by two parameters: mass M and angular momentum S $(= acM)$. The surface area of the Kerr black hole is expressed by

$$A_K = 8\pi \left(\frac{GM}{c^2}\right) \cdot \left\{\frac{GM}{c^2} + \sqrt{\left(\frac{GM}{c^2}\right)^2 - a^2}\right\}$$

Notice that the area decreases if M decreases or if a increases. A Kerr black hole with an angular momentum

$$S = \frac{GM^2}{c}$$

is known as the extreme Kerr black hole. If S were to exceed this limit the black hole topology would change drastically. The spacetime singularity at the center of the object would then become visible to the external observer. A black hole can also have an electric charge (Newman et al. 1965), but we shall discuss here only the chargeless black holes.

An important property of a black hole with which we will be concerned here relates to its area. We have already noted that the horizon of a black hole acts as a one-way membrane: it allows matter (i.e. tardyons and luxons) to come in but does not allow it to go out. In the case of a Schwarzschild black hole, it is clear that any interaction between the black hole and ambient matter will lead to the capture of matter and an increase of its mass M. This also increases its surface area A_S.

The Kerr black hole exhibits more interesting properties. By suitable ingenuity (Penrose 1969) it is possible to extract energy from a Kerr black hole, which leads to a decrease of M. However, any such process also leads to a decrease of a in such a way as to *increase* A_K. In fact, this is a particular case of the general property of axisymmetric stationary black holes, which is more popularly known as *the second law of black hole physics:* "In any physical process involving ordinary matter and black holes the total surface area of all participating black holes can never decrease."

This law was stated and the reasoning given for it by Stephen Hawking in 1972. This law, in an obvious analogy with the second law of thermodynamics, establishes the surface area in black hole physics on the same footing as entropy in thermodynamics. We will now examine what happens if black holes are bombarded with tachyons.

In 1974 Raychaudhuri showed that, if a tachyon falls radially into a Schwarzschild black hole, it does not reach the central singularity but is bounced at a finite radial distance from the center. This is contrary to the behavior of a tardyon or a luxon, both of which head toward the singular point.

At first this result may appear paradoxical. In order to bounce—which requires a reversal of direction—the tachyon must momentarily come to rest. But we have already seen that the tachyon can never cross the light barrier, let alone come to rest.

The paradox is resolved when we note that the bounce occurs *inside* the horizon. Figure 7 shows the incoming route of the tachyon by a line which extends up to the point P; here the bounce occurs, and the dashed line denotes the outgoing route. The point P is inside the horizon sphere. Now inside the horizon the geometry is so peculiar that the radial coordinate R and the time coordinate T switch their character: R becomes timelike and T spacelike. Hence at P, although we have $dR/dT = 0$, in physical terms it only means that the tachyon has zero energy and infinite velocity ($dT/dR = \infty$). At this stage we may, if necessary, use the reinterpretation principle and argue that the tachyon and the antitachyon annihilate at P.

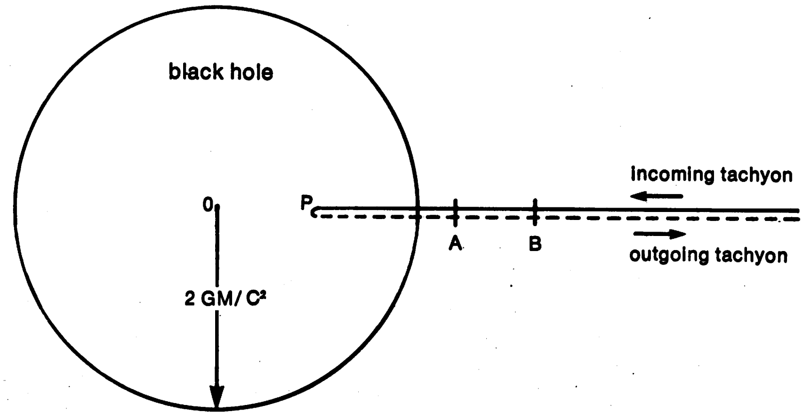

Figure 7. The section of the Schwarzschild spacetime at a constant Schwarzschild time T is shown. The circle represents the horizon at $R = 2GM/c^2$. The radial coordinate R increases outward. However, inside the horizon R and T interchange their spacelike and timelike characters. Thus when the incoming tachyon turns around at P and goes out, its bounce at P occurs not at a spacelike barrier but at a timelike barrier. An observer between the horizon and A will see the outgoing tachyon before the incoming one.

Although in Figure 7 we show the two radial routes in the same physical space, the mathematical interpretation is not so simple. The (R,T) coordinates originally used by Schwarzschild are inadequate to describe the physical spacetime. It turns out that there are two sections of spacetime; one in which the tachyon crosses the horizon inward and another in which it crosses the horizon outward. The situation shown in Figure 7 depends on an *assumed* identification of the two sections.

In that case we may expect to see certain acausal phenomena. In Figure 7 the two points A and B are *outside* the horizon with radial coordinates 2.56 (GM/c^2) and 3.27 (GM/c^2), respectively. An observer situated between the horizon and A will see the outgoing tachyon before the incoming tachyon. Whether such an acausal effect is seen by an observer between A and B depends on the tachyon energy per unit meta mass $(E/\overline{m}_0)$. Beyond B there are *no* acausal effects.

In general, for tardyons and luxons, angular momentum relative to the black hole acts in such a way as to resist the infall into singularity. For tachyons the reverse is the case. While a radially infalling tachyon is prevented from falling into the singularity, a tachyon with a sufficiently high angular momentum will spiral into the singularity.

A more interesting situation therefore arises when we consider tachyons heading toward a rotating (Kerr) black hole. The problem of computation of tachyon trajectories is more involved in this case since four parameters now enter into the picture. We have two parameters, M and S, for the black hole and two parameters for the tachyon. The tachyon parameters are

$$\Gamma = \frac{E}{\overline{m}_0 c^2}$$

(i.e. energy per unit meta mass $\times c^2$) and

$$h = \frac{L}{\overline{m}_0 c}$$

(the angular momentum per unit meta mass $\times c$).

Recently, Sanjeev Dhurandhar and I examined this problem for the tachyons in the equatorial plane of the Kerr black hole and found that there are essentially two types of tachyons. Type I tachyons are bounced by the black hole without reaching the central singularity, while type II tachyons make their way right up to the singularity. Type I tachyons leave the black hole (as in the case of radially falling tachyons bounced off by the Schwarzschild black hole), and, assuming that they have no other nongravitational interaction, they leave the black hole unchanged.

Type II tachyons, on the other hand, by falling into the singularity, contribute their mass and angular momentum to the black hole. Thus the black hole parameters change from M and S to

$$M + \overline{m}_0\Gamma \text{ and } S + \overline{m}_0 h$$

An interesting question now arises: Has the area of the black hole increased in this process?

Hawking's reasoning leading to the second law of black hole physics applies only to tardyons and luxons and it breaks down when tachyons enter into the picture. Hence only by explicit calculation could this question be answered.

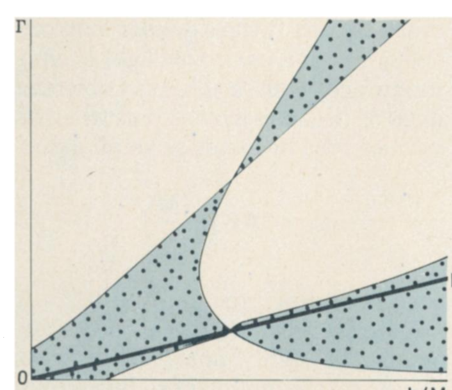

Figure 8. Each point represents a type I tachyon of a given energy and angular momentum; these tachyons (shaded region) do not affect the black hole. Of the type II tachyons, which occupy all the unshaded region in this plot, those above the line OP increase the area of the black hole; those below this line reduce the area of the black hole. This figure corresponds to $\lambda = 0.8$.

Second law violated?

Figure 8 plots Γ against *h/M*, for positive values of these quantities. Each point of this plot represents a tachyon of a given energy and angular momentum (per unit meta mass). How a particular tachyon fired in the equatorial plane of the rotating black hole behaves is decided by its location in this plot. For instance, if it lies in the shaded region it is a type I tachyon and it eventually leaves the black hole unaffected. The rest of the region corresponds to type II tachyons. A point in the unshaded region represents a tachyon that will fall into the singularity and change the area of the black hole. But in what way?

The white region lying above the line OP represents the type II tachyons, which increase the area of the black hole as required by the second law. However, there is a small region lying *below* the line OP that corresponds to type II tachyons which *reduce* the area of the black hole. Figure 8 is drawn for a specific ratio

$$\lambda \equiv \frac{cS}{GM^2} = 0.8$$

However, calculations show that such regions exist for all values of λ in the range of $0 \le \lambda \le 1$. Thus by a judicious bombardment of a Kerr black hole it is possible to decrease its area (Narlikar and Dhurandhar, in press). In this process the value of λ is increased until we reach $\lambda = 1$, when the black hole becomes the extreme Kerr type. If the bombardment is continued further, the horizon will disappear and naked singularities will be visible!

Black holes as tachyon detectors

This strange sequence of events does not violate or contradict any of the conventional wisdom in black hole physics. It simply illustrates the peculiar effects to be expected if tachyons are around. And we can use this result to suggest that black holes may act as detectors of tachyons.

Coming at a time when the detection of black holes is still to be confirmed, this suggestion may sound premature. However, the lack of confirmed cases of black holes has not stopped theoreticians from suggesting that black holes are the primary agents in diverse astrophysical phenomena like x-ray sources in binaries and globular clusters, gamma-ray bursts, quasars, etc. The above suggestion should therefore be looked upon as one more item in the growing theoretical repertoire of black holes.

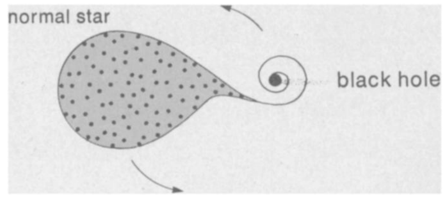

Figure 9. The double star scenario with one member a normal star and the other the black hole. The binary system rotates in the direction shown. The tachyons originating in the normal star and captured by the black hole might reduce the area of the black hole.

Figure 9 shows a binary system of stars in which one star is a black hole and the other, a close companion, is an ordinary star. The ordinary star may be a source of tachyons which approach the black hole with an angular momentum in the same direction as the rotating black hole. If the parameters of the tachyons in this case fall in the grey region of Figure 8, the surface area of the black hole should appear to decrease with time.

At present the mass of a black hole can be estimated fairly accurately if it lies in a binary system like that described above. However, its angular momentum is difficult to estimate. In principle the precession of an orbiting gyroscope can estimate *S*. It may well be that a future technology can find a solution to this problem: by measuring *M* and *S* at different times we may look for a possible *decrease* in the area of the black hole.

The scenario described here has the advantage that it makes the smallest number of assumptions about the properties of tachyons. Simply by requiring them to follow spacelike geodesics, it is possible to conclude that, wherever the second law of black hole physics appears to be violated, tachyons must be around to cause that violation.

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