COSMIC ENERGY MACHINES

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NEW astronomical techniques which came into use after World War II have revealed the existence of powerful sources of energy both within and outside our Galaxy. Radio astronomy has discovered extragalactic radio sources with energy reservoirs estimated at 10^{58}–10^{62} ergs. Optical and radio techniques together were responsible for the discovery of the remarkable quasistellar objects (QSOs), which while keeping a star-like appearance, can outshine an entire galaxy. Satellites with x-ray detecting instruments were responsible for revealing to us the strong x-ray sources in binary star systems. Apart from such steady emitters of energy there are sources which pour out energy in x-rays or gamma-rays in a series of bursts of short duration.

From where do these sources derive their energy? What are the mechanisms which release such vast quantities of energy in so dramatic a fashion? While astronomical observations led to the discoveries of the various energetic sources in the cosmos, theoretical astrophysicists have been actively searching for the answers to these questions. Indeed, some of the theoretical scenarios described here appear no less esoteric than the phenomena themselves. However, one has to remember that what appears unusual or impossible in the context of a terrestrial laboratory may be quite plausible in the cosmic setting.

STELLAR ENERGY

To illustrate the above point consider the now familiar example of energy generation in stars Stars like the Sun shine because they produce energy deep in their interiors through thermonuclear fusion of hydrogen to helium. Nuclear physics tells us that the fusion reaction has the following form

$$4\ {}^1\mathrm{H} \rightarrow {}^4\mathrm{He} + 2e^+ + 2\nu + 26.72\ \mathrm{MeV}. \qquad (1)$$

The last term on the right side denotes the energy released in the fusion process. Using Einstein's famous mass energy relation $E=Mc^2$, we conclude that of the mass put into fusion, a fraction $f \sim 0.007$ is converted to useful energy. Even though the mass energy conversion process is relatively inefficient, it is sufficient to keep the Sun shining for billions of years.

Controlled thermonuclear fusion has not yet been possible in a terrestrial laboratory. Although the high temperature ($\sim 10^7$ K) needed for the process can be achieved in the laboratory plasma, the problem of stabilizing the reactor remains to be solved. What makes the process possible in the stars? The answer to this question highlights the way in which the massive astronomical systems described in the beginning differ from their terrestrial counterparts.

A star is able to control thermonuclear fusion in its core region because of its strong selfgravity. A simple calculation based on Newtonian dynamics and gravitation shows that if there were no internal pressures in the star of mass M it would collapse from a sphere of radius R to a point, under its own gravitational force, in a time

$$\tau = \frac{\pi}{2}(R^3/2GM)^{1/2}. \qquad (2)$$

For $M=M_\odot \cong 2\times 10^{33}$ g, $R=R_\odot \cong 7\times 10^{10}$ cm, the present mass and radius of the Sun, τ is a mere 29 minutes!

The equations of stellar structure relate the gravitational force in the star to the pressure gradient, the pressure to density and temperature, and the temperature gradient to the flow of energy from the interior to the surface[1]. From these equations stable models of stars emerge, with central temperatures high enough to start and sustain thermonuclear fusion. The controlling force of gravity is absent in terrestrial systems, which makes their problem so much more difficult.

The gravitational energy of a body of mass M and radius R is of the order of GM^2/R. The largeness of M in astronomical systems makes gravity an important (often the most important) factor in determining their behaviour. This is why, as we shall see in the following examples of cosmic energy generation, gravity always plays a key role in high energy astrophysics.

ACCRETION DISCS

More than three decades ago, Hoyle and Lyttleton[2] and Bondi[3] proposed the mechanism of accretion of interstellar matter by stars. The idea found an echo in the 1960s and 1970s in the work of Zeldovich and Guseynov[4], Pringle and Rees[5] and of Shakura and Sunyaev[6]. This later work was concerned with the binary star system and its eventual outcome was to provide an explanation for x-ray sources in binaries.

The ideal situation for this model to work arises when we have two stars going round each other, with one star, A, a giant or supergiant and the other star, B, a compact neutron star as shown in Figure 1. In a close binary system the separation between A and B is not much more than the sum of their radii. Under these conditions the star B exerts strong tidal forces on star A, pulling out material from its surface which goes round B and ultimately falls onto it. The dynamics of the infall suggests that the infalling matter forms a disc round B. In steady state the disc preserves its structure and shape; however, it is fed with a supply of infalling matter from A which winds its way towards B.

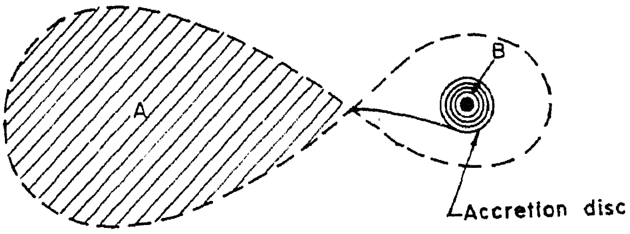

Figure 1 A schematic description of a close binary system. The star A is usually a giant or supergiant star while B is a compact star. Material flowing from A to B forms a disc round B. This disc emits radiation predominantly in x-rays.

Viscous forces in the disc are strong enough to cause dissipation of energy with the result that there is thermal radiation from the disc. If M denotes the accretion rate and M the mass of star B, then the temperature of the disc is estimated at

$$T \cong 10^7 \left[\frac{M}{10^{-9} M_\odot/\text{year}}\right]^{-1/4} \left[\frac{M}{M_\odot}\right]^{-1/2} K. \qquad (3)$$

At this temperature the characteristic radiation is in the soft x-ray range (~0.2 to ~4 KeV).

Among the early x-ray sources to be discovered was Hercules X-1, which has been identified with the binary system containing the star HZ Hercules. The compact companion is not visible in the optical observations (nor is it expected to be if it is a neutron star). Nevertheless its presence can be deduced from the observations of A. Further the x-rays from B are periodically cut off, because the star is eclipsed by A. This is therefore an example of an eclipsing binary. The mass of B is estimated to be $\sim 1 M_\odot$ which is well within the maximum permitted limit for the mass ($\sim 2M_\odot$) of a neutron star.

Another binary source, Cygnus X-1, is more interesting. This is because in this case the estimated mass of the compact companion B is at least $5M_\odot$ It therefore cannot be a neutron star. Indeed at present there is no known state of matter which, in a highly dense form, could generate large enough pressures to support such a massive star in equilibrium. Hence the conclusion is usually drawn that this member of Cygnus X-1 binary system is a black hole.

Cygnus X-1 is todate the only apparently clear-cut example of a binary containing a black hole. All other x-ray binaries are explainable on the assumption that the star B is a neutron star. This circumstance has led some astronomers to doubt the black hole interpretation for Cygnus X-1. However, if there is no black hole in this system, what is the source of its x-radiation?

Accretion discs can also form around rotating massive objects which are sufficiently collapsed. It has been suggested that such discs may form around massive black holes and give rise to radiation that is observed in QSOs for example. Before we come to this picture we consider an interesting idea of extracting energy from rotating black holes proposed by Penrose[7] in 1968.

THE PENROSE PROCESS

A black hole, by definition gobbles up all matter and radiation coming sufficiently close to it. Infall from surroundings tends to increase the gravitational mass of the black hole. With this one-way process going on it seems unlikely at first sight that energy could be extracted from a black hole. Yet this is precisely what the Penrose process is designed to achieve.

To see how this comes about let us take into account a crucial property of a *rotating* black hole, namely its surface area. Kerr[8] was the first person to give an exact solution of Einstein's equations describing a rotating black hole. The geometrical features of the space outside such a black hole are shown in Figure 2 (a) and (b).

Figure 2(a) shows the meridional section of space through the axis of rotation of the black hole. The inner (circular) curve is the section of the horizon which acts as an absolute barrier for any physical signal from inside to outside The outer curve is the so called static limit which touches the horizon at the poles but is otherwise outside it. No physical observer can maintain a fixed position relative to distant stars if he is on or inside the static limit: he is carried along in the direction of rotation of the black hole no matter how hard he resists this tendency. Figure 2(b) shows the equatorial sections of the horizon and the static limit, the former lying inside the latter. The space between the horizon and the static limit is called the *ergosphere*. This is the region where it is possible to extract energy from the black hole.

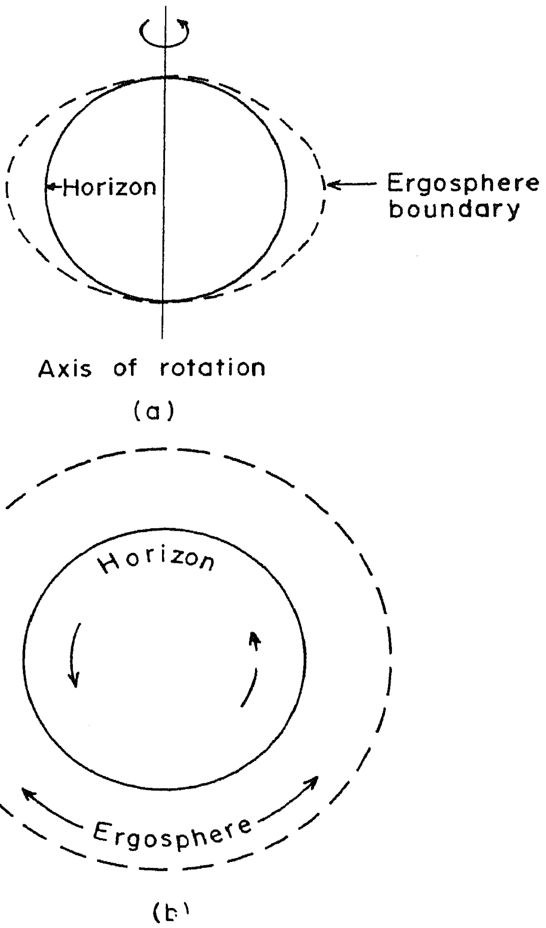

Figure 2 **(a)** The meridional section of a Kerr black hole. The inner (thick) circle is the horizon while the outer (dotted) curve is the static limit.
(b) The equatorial section of the Kerr black hole shows two concentric circles, the inner (thick) one being the horizon and the outer (dotted) one being the static limit.

For a black hole of mass M and angular momentum S, the surface area of the horizon is given by

$$A = 2\pi R\,[R+(R^2-4a^2)^{1/2}] \tag{4}$$

where $R = 2GM/c^2$, $a = S/Mc$. (5)

Now, one of the fundamental rules governing the interaction of a black hole with ambient matter is that whatever happens, the area of the horizon cannot decrease. Like the entropy of a physical system, any change δA in A produced by a physical process must be non negative:

$$\delta A \geq 0. \tag{6}$$

Bearing in mind this rule (known as the second law of black hole physics by analogy with the second law of thermodynamics) we see that to extract energy from a black hole we must keep A

fixed and decrease M. From (4) we see that this is possible if we *decrease* the angular momentum of the black hole also. This is the basis of the Penrose process.

The process itself is illustrated in figure 3. A piece of matter of mass m is hurled towards the ergosphere. While it goes round the black hole it is split into two parts I and II. Part I falls into the black hole while part II emerges from the ergosphere with total energy $E_{II} > mc^2$. The energy of part II has been acquired through rotation in the ergosphere. The amount of energy and angular momentum gained by it are at the expense of the black hole.

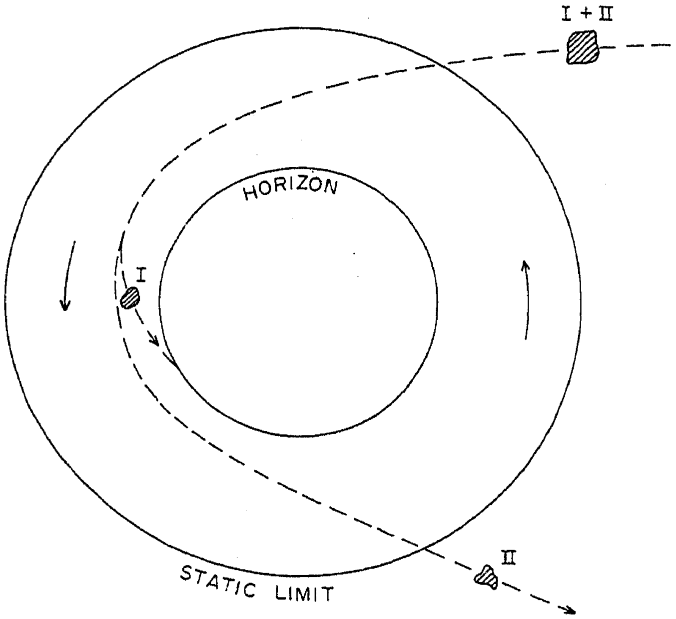

Figure 3 Penrose's scheme of extracting energy from a rotating black hole by diminishing the black hole's angular momentum. The final residual mass (II) which emerges has greater energy than the total mass (I+II) which went into the ergosphere.

Clearly the process works at its most efficient level if A is not allowed to increase. It can be shown that at most ~ 30% of the total rest mass energy of a black hole can be extracted this way. Although this is the highest efficiency factor known for any cosmic energy machine, the black hole theoreticians have not been clever enough yet to think of an astrophysical scenario where this process can actually work.

We describe below a scenario which has been advocated by many as the 'best buy' amongst the various energy machines.

RADIO GALAXIES AND QUASARS

The discovery of radio sources outside our Galaxy in the early 1950s and of quasars in the early 1960s brought the energy problem to a head. The early identification of the radio source Cygnus A with a pair of colliding galaxies led to the belief that radio sources arose from such spectacular phenomena as collision of galaxies. However, this belief turned out to be false, on several counts.

One of the reasons was theoretical. Galactic collisions are not improbable. Indeed, in a cluster of galaxies such close encouters are to be expected once in a while. The difficulty arises when we consider the amount of energy that can be released in a typical collision. Newtonian dynamics tells us that the energy of collision between two galaxies of masses M_1 and M_2 is of the order

$$E_{\text{coll}} \cong GM_1M_2/\text{d} \qquad (7)$$

where d is a typical linear size characteristic of galaxies. For $M_1 = M_2 \simeq 10^{11} M_\odot$ ($M_\odot$ = mass of the Sun $\cong 2\times 10^{33}$ g) and $d \cong 10^4$ parsecs (1 parsec $\cong 3\times 10^{18}$ cm) we get $E_{\text{coll}} \cong 10^{59}$ erg.

Large though this number is, it is not large enough! In 1958, Geoffrey Burbidge[9] made an estimate of the store of energy needed in a typical strong radio source. In making his estimate Burbidge assumed that radio waves arise from synchrotron emission from fast electrons accelerated by ambient magnetic fields. Using the observed parameters of radio sources Burbidge calculated that the *minimum* energy needed in a typical radio source had to be as high as 10^{60}–10^{62} erg.

Clearly even if energy conversion to radio waves was assumed to be 100% efficient, the collision process would be unable to deliver the requisite amount of energy. This theoretical reason was later substantiated by observations which clearly demonstrated that colliding galaxies were not involved on the site of radio emission, even in the classic case of Cygnus A.

Detailed studies of the large scale structure of radio sources reveal a picture shown schemati-

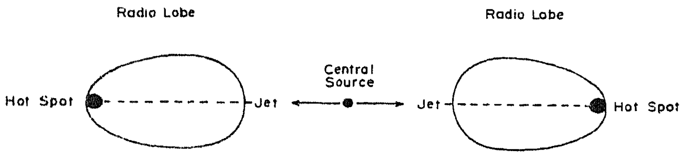

Figure 4 Schematic diagram of a double radio source. Jets from the centre seem to connect with hot spots at the ends.

cally in figure 4. There we see two blobs of radio emitting regions well separated from each other with an optical source in between. The alignment is very good, suggesting a linear structure. In many cases radio contours show jet-like features leading to hot spots (*i.e.*, radio bright compact regions) within the blobs. What do these jets contain? What astrophysical process is responsible for highly collimated beams from the centre to the periphery?

This is where the twin exhaust model of Blandford and Rees[10] comes in. This theory is briefly illustrated in figure 5. There we have a supermassive black hole which is surrounded by a gas cloud, the entire system rotating about a fixed axis. It is assumed that in this system there is an energy source in the nuclear region which ejects plasma. In a spherically symmetric system this plasma could come out spherically. However, in a rotating system the ejected particles come out asymmetrically, choosing the line of least resistance. This happens to be along the axis of rotation.

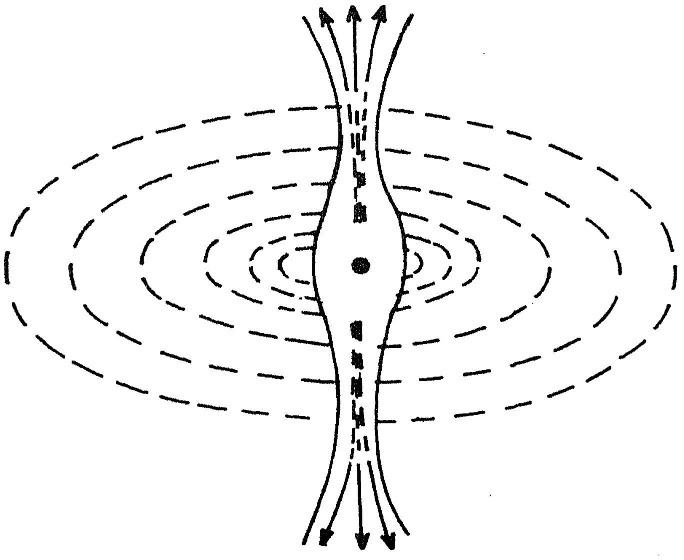

Figure 5 The twin exhaust model of Blandford and Rees. The plasma is squirted out along the two nozzles aligned with the axis of rotation.

Blandford and Rees showed that the ejection process can be described in gas dynamics by the process of the de Laval nozzle. This leads to a highly collimated jet, or rather a couple of oppositely oriented jets. Two such jets are necessary in a stable system conserving momentum.

The supermassive black hole accretes matter from the surroundings in a disc perpendicular to the axis of rotation. It is estimated that not only radio emission but also the optical and x-ray emission in quasars may be due to such an accretion disc. The black hole needed to account for the observed emission has to have a mass in excess of $10^8 M_\odot$ For such a blach hole the total energy is $\gtrsim 2\times10^{62}$ erg. If it is assumed that an efficient energy conversion mechanism exists which converts, say, 10% of this energy to the observed radiation, we can explain the phenomena of quasars.

There are, however, several issues still to be resolved regarding the detailed working of the Blandford-Rees model. One major problem for example, is to understand why many radio sources show only one jet. Further calculations are needed to study the complex structures of jets, the mode of their formation and their stability.

MASSIVE OSCILLATORS

In a classic paper[11] which anticipated the role of supermassive objects and their gravitational energy reservoirs Fred Hoyle and William Fowler had suggested that gravitational collapse could be a process leading to the formation of such objects. In the case of the Sun we saw that the pressures generated by thermonuclear reactions can succesfully withstand the gravitational contraction. However, by and large, such pressures are ineffective if the mass of the object is considerably in excess of $M_\odot$ For example, an object of $10^6 M_\odot$ can barely survive as a stable star on its hydrogen burning[12]. A more massive object will inevitably collapse unless it breaks apart under some internal instabilities. What will happen to such objects if they manage to retain a coherent shape during collapse?

General relativity tells us that the end-product of gravitational collapse is space-time singularity[13]. If the conjecture about the non-existence of a naked singularity is correct, the collapse to a singularity is preceded by the formation of a black hole. Hence the key role played by the black hole in most mechanisms for cosmic energy generaton.

However, the black hole suffers from one defect: it cannot be observed! Its existence must be deduced indirectly, as we saw in the example of Cygnus X-1. And indirect or circumstantial evidence is always subject to the criticism: Is this (*i.e.*, the black hole) the only way to explain what is observed?

If we reverse the collapse process, we get explosion. The big-bang universe is an example of such an explosion, although it is somewhat unusual in the sense that the universe is not a subset of any larger system. Can we have finite or compact explosions which are the time reversed versions of gravitational collapse? Since relativity is a time-symmetric theory such explosions are permitted by it and these are called white holes.

It has been conjectured[14,15] that white holes could exist as delayed explosions after the universal big band. Apparao and the present author[16] had studied the astrophysical behaviour of white holes and shown that radiation or particles thrown out by a white hole would be 'blueshifted', *i.e.*, upgraded in energy. This effect lasts for a short (and early) stage of a white hole's life. Nevertheless it is directly observable and could account for gamma ray bursts or x-ray transients. White holes could exist in the stellar mass range or on the supermassive scale of exploiding galactic nuclei such as those found in Seyfert galaxies.

There have been calculations[17] to show that white hole as a delayed core of a big bang universe is highly unstable and too short-lived to be of any astrophysical interest. Apart from this result astrophysicists are unhappy about the existence of white holes because they have an origin in a space-time singularity. (Strangely enough, this oft-quoted objection to white holes is conveniently forgotten by the proponents of the big bang universe which also originates in a singularity.)

Both these objections to white holes are, however, eliminated if the white hole does not begin in a singularity. Suppose a collapsing object encounters a hard repulsive force which makes it bounce when it is very dense. If the bounce radius is very small but finite the object, in its expanding phase, would still behave like a white hole and fulfill its role of energizing particles and radiation.

Recently Apparao and the present author[18] have considered such objects which we call *massive oscillators*. These objects oscillate because at large radius they begin to contract under self-gravity while at small radius they bounce. The kinetic energy stored in these oscialltors is comparable to their rest mass energy. As such these objects could be good candidates for cosmic energy machines.

What is the repulsive force which causes the bounce? Apparao and the present author used the scalar field of zero rest mass, called the C-field, which was used by Hoyle and me for describing the dynamics of the steady state universe[19]. The existence of massive oscillators does not depend on any particular form of the repulsive force, but it does depend on the assumption that such a dominant short range force exists in nature.

Astronomy provides a laboratory much wider in scope than any that exists on the Earth. The theory of nuclear fusion in the 1930s and the present work on grand unified theories show that fundamental physics can get valuable inputs from cosmic observations. The high energy reservoirs seen in the cosmos pose challenges to the theorist to account for their existence with the physics he knows. It will not be surprising if in this process he uncovers some new law of fundamental physics.

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