

scarcely conceivable that they should not have detected us. F. J. Dyson responded as follows:

In reply to Maddox, Anderson, and Sloane, I would like only to add the following points which were omitted from my earlier communication.

1. A solid shell or ring surrounding a star is mechanically impossible. The form of "biosphere" which I envisaged consists of a loose collection or swarm of objects traveling on independent orbits around the star. The size and shape of the individual objects would be chosen to suit the convenience of the inhabitants. I did not indulge in speculations concerning the constructional details of the biosphere, since the expected emission of infrared radiation is independent of such details.

2. It is a question of taste whether one believes that a stabilization of population and industry is more likely to occur close to the Malthusian limit or far below that limit. My personal belief is that only a rigid "police state" would be likely to stabilize itself far below the Malthusian limit. I consider that an open society would be likely to expand by a proliferation of "city-states" each pursuing an independent orbit in space. Such an expansion need not be planned or dictatorially imposed; unless it were forcibly stopped it would result in the gradual emergence of an artificial biosphere of the kind I have suggested. This argument is admittedly anthropomorphic, and I present it in full knowledge that the concepts of "police state" and "open society" are probably meaningless outside our own species.

3. The discovery of an intense point source of infrared radiation would not by itself imply that extraterrestrial intelligence had been found. On the contrary, one of the strongest reasons for conducting a search for such sources is that many new types of natural astronomical objects might be discovered.

Freeman J. Dyson

I 2 * GRAVITATIONAL MACHINES

The difficulty in building machines to harness the energy of the gravitational field is entirely one of scale. Gravitational forces between objects of a size that we can manipulate are so absurdly weak that they can scarcely be measured, let alone exploited. To yield a useful output of energy, any gravitational machine must be built on a scale that is literally astronomical. It is nevertheless worthwhile to think about gravitational machines, for two reasons. First, if our species continues to expand its population and its technology at an exponential rate, there may come a time in the remote future when engineering on an astronomical scale will be both feasible and necessary. Second, if we are searching for signs of technologically advanced life already existing elsewhere in the universe, it is useful to consider what kinds of observable phenomena a really advanced technology might be capable of producing.

The following simple device illustrates the principle that would make possible a useful gravitational machine (see Figure 1). A double star has two components *A* and *B*, each of mass *M*, revolving around each other in a circular orbit of radius *R*. The velocity of each star is

$$V = (GM/4R)^{1/2} \quad (1)$$

where

$$G = 6.7 \times 10^{-8} \text{ cm}^3/\text{sec}^2\text{g} \quad (2)$$

is the gravitational constant. The exploiters of the device are living on a planet or vehicle *P* which circles around the double star at a distance much greater than *R*. They propel a small mass *C* into an orbit which falls toward the double star, starting from *P* with a small velocity. The orbit of *C* is computed in such a way that it makes a close approach to *B* at a time when *B* is moving in a direction opposite to the direction of arrival of *C*. The mass *C* then swings around *B* and escapes with greatly increased velocity. The effect is almost as

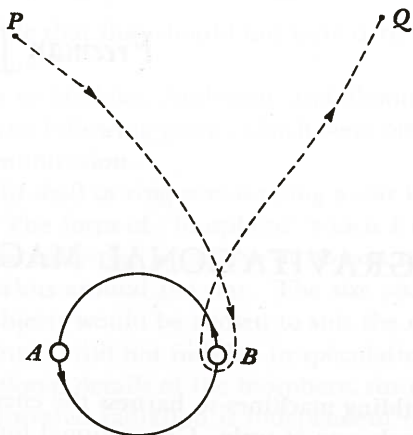


Figure 1

The solid line indicates the orbit of A and B ; the dashed line indicates the orbit of C .

if the light mass C had made an elastic collision with the moving heavy mass B . The mass C will arrive at a distant point Q with velocity somewhat greater than $2V$. At Q the mass C may be intercepted and its kinetic energy converted into useful form. Alternatively the device may be used as a propulsion system, in which case C merely proceeds with velocity $2V$ to its destination. The destination might be a similar device situated very far away, which brings C to rest by the same mechanism working in reverse.

It is easy to imagine this device converted into a continuously operating machine by arranging a whole ring of starting points P and end points Q around the double star, masses C being dropped inward and emerging outward with increased velocity in a continuous stream. The energy source of the machine is the gravitational potential between the stars A and B . As the machine continues to operate, the stars A and B will gradually be drawn closer together, their negative potential energy will increase, and their orbital velocity V will also increase. The machine will continue to extract energy from their mutual attraction until they come so close together that orbits passing between them are impossible. For a rough estimate one may suppose that the machine can operate until the distance between the centers of the two stars is equal to $4a$, where a is the radius of each star. The

total energy extracted by the machine from the gravitational field is then

$$E = GM^2/8a \quad (3)$$

If A and B are ordinary stars like the sun, the radius a is of the order of 10^{11} cm. The energy E is then equal to the luminous energy radiated by the stars in a few million years. Under these conditions the available gravitational energy may be exploited, but it is of minor importance compared with the luminous energy of the system. A technically advanced species would presumably put its main efforts into harnessing the luminous energy.

If the stars A and B are typical white dwarfs, the situation is entirely reversed. In that case the optical luminosity is less than that of the sun by a factor of about a thousand, while the available gravitational energy is increased by a factor of a hundred. It is therefore logical to expect that around a white-dwarf binary star a technology based on gravitational energy might flourish. For purposes of illustration, let us assume

$$M = 1 \text{ solar mass} = 2 \times 10^{33} \text{ g} \quad (4)$$

$$a = 10^9 \text{ cm} \quad (5)$$

$$R = 2a = 2 \times 10^9 \text{ cm} \quad (6)$$

Then we find

$$V = 1.3 \times 10^8 \text{ cm/sec} \quad (7)$$

$$E = 3 \times 10^{49} \text{ ergs} \quad (8)$$

The orbital period of the binary star is

$$P = 100 \text{ sec} \quad (9)$$

A search for eclipsing binaries of such short period among the known white dwarfs was suggested many years ago by H. N. Russell (1). The search was subsequently made by F. Lenouvel (2), with negative results. The negative result is not surprising, since the total number of identified white dwarfs is very small.

A white-dwarf binary star with the parameters (4) to (9) would have the interesting property that it could accelerate delicate and fragile objects to a velocity of 2000 km/sec at an acceleration of 10,000g, without doing any damage to the objects and without expending any rocket propellant. The only internal forces acting on the accelerated objects would be tidal stresses produced by the gradients of the

gravitational fields. If the over-all diameter of the object is d , the maximum tidal acceleration will be of the order of

$$A = GMd/a^3 = \frac{1}{8}d \quad (10)$$

For example, if A is taken to be 1 earth gravity, then $d = 80$ m. So a large space ship with human passengers and normal mechanical construction could easily survive the 10,000g acceleration. It may be imagined that a highly developed technological species might use white-dwarf binaries scattered around the galaxy as relay stations for heavy long-distance freight transportation.

An important side effect of a short-period white-dwarf binary would be its enormous output of gravitational radiation. According to the standard theory of gravitational radiation (3), which is not universally accepted, a pair of stars of equal mass moving in a circular orbit radiates gravitational energy at a rate

$$W = 128V^{10}/5Gc^5 \quad (11)$$

where c is the velocity of light. It would be extremely valuable if we could observe this radiation, both to verify the validity of the theoretical formula (11) and to detect the existence of white-dwarf binaries. Inserting the value of V from (7) into (11), we find

$$W = 2 \times 10^{37} \text{ ergs/sec} \quad (12)$$

which is 5000 times the sun's optical luminosity. Comparing (12) with (8), we see that the gravitational radiation itself will limit the lifetime of this white-dwarf binary to about 40,000 years. However, since the dependence of W on V is so extreme, a binary with $V = 5 \times 10^7$ cm/sec could live for many millions of years. A technologically advanced species might then choose the value of V to suit its particular purposes.

Assuming the value (12) for the intensity of a source of gravitational waves at a distance of 100 parsecs, we find that the signal to be detected on earth has the intensity

$$I = 2 \times 10^{-5} \text{ erg/cm}^2/\text{sec} \quad (13)$$

Unfortunately the period of the radiation is 100 sec, which is not short enough to be observed with the existing apparatus of J. Weber (4). However, it is quite likely that a detector could be built which would be sensitive to the incident flux (13) at a period of 100 sec. This would then allow us to detect by its gravitational radiation any white-dwarf binary of period 100 sec within a volume of space containing over half a million stars (5).

According to astrophysical theory (6), a white dwarf is not the most condensed type of star that is possible. A still more condensed form of matter could exist in "neutron stars," which would have masses of the same order as the sun compressed into radii of the order of 10 km. Whether neutron stars actually exist is uncertain; they would be very faint objects, and the fact that none has yet been observed does not argue strongly against their existence.

If a close binary system should ever be formed from a pair of neutron stars, the consequences would be very interesting indeed. Consider for example a pair of stars of solar mass, each having radius

$$a = 10^6 \text{ cm} \quad (14)$$

and with their centers separated by a distance $2R = 4a$. According to (1) and (11), each star moves with velocity

$$V = 4 \times 10^9 \text{ cm/sec} \quad (15)$$

in an orbit with period 5 msec, and the output of gravitational radiation is

$$W = 2 \times 10^{52} \text{ ergs/sec} \quad (16)$$

But by (3), the gravitational energy of the pair is at this moment

$$E = 3 \times 10^{52} \text{ ergs} \quad (17)$$

Thus the whole of the gravitational energy is radiated away in a violent pulse of radiation lasting less than 2 sec. A neutron-star binary beginning at a greater separation R will have a longer lifetime, but the final end will be the same. According to (11), the loss of energy by gravitational radiation will bring the two stars closer with ever-increasing speed, until in the last second of their lives they plunge together and release a gravitational flash at a frequency of about 200 cycles and of unimaginable intensity.

A pulse of gravitational radiation of magnitude (17) at a frequency around 200 cycles should be detectable with Weber's existing equipment (4) at a distance of the order of 100 Mparsecs. So the death cry of a binary neutron star could be heard on earth, if it happened once in 10 million galaxies. It would seem worthwhile to maintain a watch for events of this kind, using Weber's equipment or some suitable modification of it.

Clearly the immense loss of energy by gravitational radiation is an obstacle to the efficient use of neutron stars as gravitational machines. It may be that this sets a natural limit of about 10^8 cm/sec to the velocities that can be handled conveniently in a gravitational tech-

nology. However, it would be surprising if a technologically advanced species could not find a way to design a nonradiating gravitational machine, and so to exploit the much higher velocities which neutron stars in principle make possible.

In conclusion, it may be said that the dynamics of stellar systems, under conditions in which gravitational radiation is important, is a greatly neglected field of study. In any search for evidences of technologically advanced societies in the universe, an investigation of anomalously intense sources of gravitational radiation ought to be included.

References

- 1 H. N. Russell, Centennial Symposia, *Harvard Monographs*, 7, 187 (1948).
- 2 F. Lenouvel, *J. Observateurs*, 40, 15 (1957).
- 3 L. Landau and E. Lifshitz, *Classical Theory of Fields*, trans. by M. Hamermesh, Addison-Wesley, Reading, Mass., 1951, p. 332.
- 4 J. Weber, *Phys. Rev.*, 117, 306 (1960).
- 5 R. P. Kraft, J. Matthews, and J. L. Greenstein have discussed the extremely interesting object Nova WZ Sagittae, a binary star with one white-dwarf component and an observed orbital velocity of about 7×10^7 cm/sec. They point out that gravitational radiation from this object is certainly important and may be detectable. The author is indebted to Dr. Kraft for a preprint of this work.
- 6 J. R. Oppenheimer and G. M. Volkoff, *Phys. Rev.*, 55, 374 (1939); A. G. W. Cameron, *Astrophys. J.*, 130, 884 (1959).

Edward Purcell

I 3 * RADIOASTRONOMY AND COMMUNICATION THROUGH SPACE

It is a great privilege for me to open the series of Brookhaven Lectures. The principles on which these are conceived I heartily endorse, but I am just about to violate them by giving a talk which is really not, for the most part, a description of my own work. Indeed some of it will not be a description of any one's work, but instead some speculations about the future. In a way, you might regard this talk as a logical sequel to Dr. DuBridge's Pegram Lectures (*I*) of a year ago. It has three parts whose relation to one another will not be obvious until the end. The first part, at least, has to do with solid scientific matter, radioastronomy. Without revealing now the nature or motive of the last two parts, I would like to describe one branch of radioastronomy and what has come out of it in the last several years. I have not been active in this field myself in recent years, but I have been watching it develop.

Radioastronomy

Until 15 or 20 years ago, all man's information about the external world beyond the earth came to him in a small band of wavelengths of visible light. Everything the astronomers saw, all the images on their photographic plates, were collected by absorbing light within a range of wavelengths varying by no more than a factor of two from the shortest to the longest waves. It was the discovery, about two decades ago, that there were also radio waves coming through which started off radioastronomy.

These two great apertures, or windows, as they are often called,