

# GRAVITATIONAL MACHINES

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## Summary

A gravitational machine is defined as an arrangement of gravitating masses from which useful energy can be extracted. It is shown that such machines may exist if the masses are of normal astronomical size. A simple example of a gravitational machine, consisting of a double star with smaller masses orbiting around it, is described. It is shown that an efficient gravitational machine will also be a powerful emitter of gravitational radiation. The emitted radiation sets a limit on the possible performance of gravitational machines, and also provides us with a possible means for detecting such machines if they exist.

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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 Fig. 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

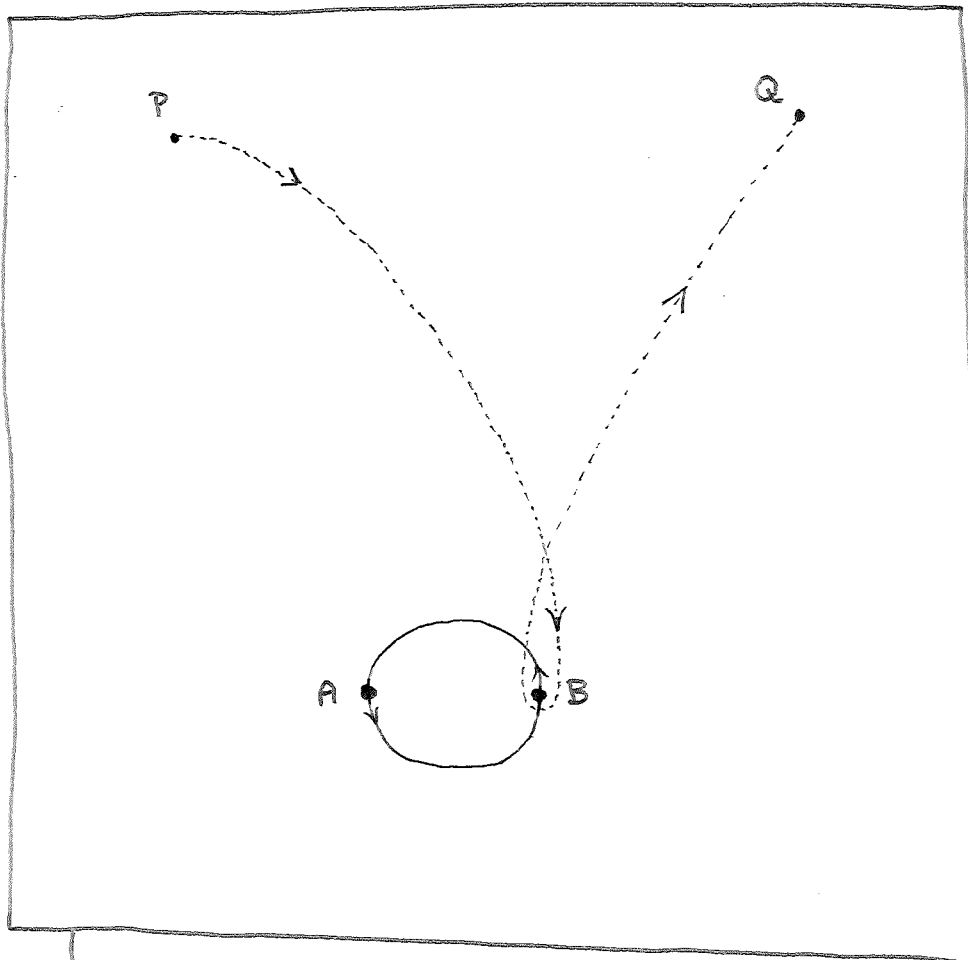
$$V = [GM/4R]^{1/2}, \quad (1)$$

where

$$G = 6.7 \times 10^{-8} \text{ cm}^3 \text{ sec}^{-2} \text{ gram}^{-1} \quad (2)$$

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 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.

Figure 1.



— Orbit of A and B.  
- - - Orbit of C.

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 inwards and emerging outwards 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  $10^{11}$  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

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

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

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

Then we find

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

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

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.<sup>1</sup> The search was subsequently made by F. Lenouvel<sup>2</sup>, 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) - (9) would have the interesting property that it could accelerate delicate and fragile objects to a velocity of 2000 Kilometers per second at an acceleration of 10000 g, 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 overall 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  $d = 80$  meters. So a large space-ship with human passengers and normal mechanical construction could easily survive the 10000 g 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<sup>3</sup>, which is not universally accepted, a double star radiates gravitational energy at a rate

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

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 life-time of this white-dwarf binary to about 40000 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~~<sup>parsecs,</sup> 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 seconds, which is not short enough to be observed with the existing apparatus of J. Weber<sup>4</sup>. 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 seconds. This would then allow us to detect by its gravitational radiation any white-dwarf binary of period 100 seconds within a volume of space containing over half a million stars.

According to astrophysical theory<sup>5</sup>, a white dwarf is not the most condensed type of star which 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 kilometers. 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 milliseconds, 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 two seconds. A neutron-star binary beginning at a greater separation  $R$  will have a longer life-time, 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<sup>1</sup>'s existing equipment<sup>4</sup> at a distance of the order of 100 megaparsecs. So the death-cry of a binary neutron star could be heard on Earth, if it happened once in ten million galaxies. It would seem worthwhile to maintain a watch for events of this kind, using Weber<sup>1</sup>'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 technology. However, it would be surprising if a technologically advanced species could not find a way to design a non-radiating 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, anomalously intense sources of gravitational radiation ought to be primary objects of suspicion.

References

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## Biographical Sketch

Freeman J. Dyson, born in England on December 15, 1923. Educated at Cambridge (B.A. 1945) and Cornell Universities. Came to U.S. with a Commonwealth Fund Fellowship in 1947. Returned to Cornell as Professor of Physics, 1951. Became U.S. citizen, 1957. Has been since 1953 Professor in the School of Mathematics of the Institute for Advanced Study, Princeton, New Jersey. Fellow of the Royal Society, London, since 1952. Publications on quantum field theory and other topics in mathematical physics, mostly in the Physical Review.