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A Study Of Pulsar: Interference Of Neutron Stars And Black Holes

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Abstract
Though there have been so many claims and counter claims but the first pulsar was discovered in 1967, quite accidentally, by Anthony Hewish and his co-workers notable, Miss J. Bell, at Cambridge. Hewish and his fellow workers were engaged in studying interplanetary scintillation exhibited by radio sources of small angular size (usually less than 1" of arc) with a new radio telescope at Cambridge operating at a frequency of 81.5 MHz, that was set for the purpose. It is known that changes inter planetary scintillation, when a radio source is observed at various angles with respect to the Sun, give information about the angular size of such source. While carrying out the program, Hewish and his co-workers came across an invisible object in the sky emitting sharp pulses of radio waves at exactly spaced intervals of time. Careful search revealed soon after, the presence of a few more such objects in the sky. They were subsequently given the name pulsar, of which the first to be discovered was Cp 1919 (meaning Cambridge pulsar at R.A. 19th 19m). So exact was the periodicity of emitted pulses from these objects that some astronomers could not resist the temptation of thinking that these pulses might possibly be-transmitted into space by intelligent beings on other planetary systems.
Keywords: *Pulsar, Black holes, Neutron star.*

1- INTRODUCTION

Such a fancy, however had to be soon given up, as more and more pulsars were discovered and observational data on them began to pour rapidly which enabled scientists to understand the basic nature of these mysterious objects. The discovery of these objects escaped so long because they emit strongly in longer wavelength range where radio observations are generally not favourd and because their pulse widths are much shorter than the integration time generally used for radio observations.

Earlier, pulsars were denoted by their provisional names based on a combination of their positions in right ascension and observatories where discovered. For example, the first pulsar discovered was named CP 1919 as explained above. Now, for the sake of uniformity the prefix PSR is used for all the pulsars followed by a four digit number indicating right ascension (in 1950.0 coordinates) together with a sign and two digits indicating declination. If required, a third digit is added to cover tenths of a degree in declination. Thus for instances, the first pulsar CP 1919 is now denoted by PSR 1919 + 21. Two other very closely situated pulsars are denoted by PSR 1913 + 16 and PSR 1913+167. However, the provisional names are still very much in use. For example, the Crab pulsar PSR 0531+21 is still referred as NP 0532, its provisional name.

2- ROTATING NEUTRON STAR MODEL OF PULSARS

Various observational facts and theoretical consideration now lead us to believe that pulsars are rapidly rotation neutron stars. The current theory predicts that when a supernova explodes and its surface layers are blown off, the central core of mass of the order of 1 M_Θ gravitationally contracts to a superdense body. It is not known whether this happens in every supernova explosion. In some explosions the original stellar bodies may be completely disintegrated leaving behind only gaseous debrits. In some others, where the original stars are highly massive, the cores after explosions may shrink to black holes. Whatever may be the case, the present observational status definitely supports the theory that at least in some supernova explosions the cores contract to superdense neutron stars. Astronomers believe that these neutron stars have been observed as pulsars. They are objects with masses of the order of 1 M_Θ and with radio of the order of 10 km, which yield a density of its material of the order of 10^{14} gm cm^{-3}.

The possibility of existence of neutron stars was theoretically predicted many years ago, independently by L. Landau and J.R. Oppenetheimer. We have seen that any star whose mass exceeds the Chandrasekhar limit of 1.44 M_Θ may explode as a supernova at a certain stage of its evolution. Stars whose masses are less than this limit, however, evolve to meet their end peacefully. In the final stage. By bradual contraction, the gas attains the state fo degeneracy, and the star is called a white dwarf. The degenerate material of a white dwarf can exert sufficient pressure force to resist further gravitational collapse so that the white dwarf structure remains as a stable stellar structure. At this stage, the density attained by the material is very high. A star fo mass 1 M_Θ has, by gradual contraction, attained the size of the Earth leading to a matter density of 2 x 10^6 gm cm^{-3}. But the fate of the stars whose masses lie in the range surface layers are blown off in the interstellar space while, in the core, the gravitational pull may be so strong as to force the free electrons to stick on to protons thus producing neutrons. In this process. Free electrons are depleted thereby decreasing the resisting pressure of free elections to the gravitational pull. As a result, further gravitational contraction proceeds more or less smoothly. This contraction can be halted only when it is balance by the opposing pressure of degenerate neutrons. At this stage, the matter density has reached the nuclear density which is 10^{-14} gm cm^{-3}, as has been already mentioned. We now have a stable neutron star whose mass may lie somewhere between 0.7 to 2 M_Θ.

The intense gravitational contraction of the core necessarily leads to a corresponding increase in its rate of rotation and in the magnetic field. The material in the stellar cores is highly conducting and the theory says that in such material the magnetic lines of force become frozen-in. the magnetic lines of force therefore become packed within a small area as the star violently contracts to a small volume. The extreme contraction can therefore create a magnetic field of the order of 10^{12} gauss on the neutron star, even if the original magnetic field of the star before explosion be only a few gauss. Again, all normal stars possess at least some amount of rotational velocity (this velocity is 2 km s^{-1} for Sun and as high as 400-500 km s^{-1} in some O-B stars). Therefore, if a substantial part of the angular momentum possessed by the original star before explosion is retained by the contracting core, when its radius has decreased by about 10,000 times, its rotation in a few milliseconds is possible. Thus, if pulsars are actually such collapsed cores of supernovae, then the theory predicts that pulsars are rapidly rotating neutron stars possessing an intense magnetic field.

3- PERIOD DISTRIBUTION AND LOSS OF ROTATIONAL ENERGY

Pulsars emit radio pulses at extremely regular intervals of time. The periods in different pulsars range from 0.033 second for the pulsar NP 0532 (PSR 0531 + 31) (this is situated at the centre of the Crab Nebula, so called Crab pulsar) to 3,745 seconds for NP 0527(PSR 0525 + 21) (the pulsar closed to NP 0532), corresponding to a factor of about 120. The radio pulses emerge in trains having duration for most pulsars lying in the range 10 to 50 milliseconds. There are fine strictures (secondary pulses) within each pulse (primary pulse), a complete pulse being the envelope of these sub pulses. The schematic diagrams of the primary and secondary pulses of a typical pulsar are shown in Fig. 15.1.

A primary pulse may contain within it 20 to 30 or more sub pulses each of duration usually much less than a millisecond. The interval between any two consecutive primary pulses is repeated so exactly that it may be regarded as constant to 1 part in 10^9 although the amplitude may substantially vary from one pulse to another.

One of the most interesting observations on pulsars which has subsequently been proved to have great significance in understanding their, basic nature, was made by Frank Drake and his co-workers in Aricibo Observatory. They found that the rotation of the Crab pulsar was decreasing at the rate of nearly 1 in 2400 per year. Since the period of this pulsar is 0.033 sec, the observation implies that the period P of the pulsar was increasing at the rate of ΔP/P – 4.38 x 10^{-13}. Later investigations revealed that periods of all the pulsars are increasing with rates varying in the range 10^{-13} to 10^{-16}.

The observation of the rate of increase of pulsar periods has attributed great significance to the rotating neutron star hypothesis for pulsars. A body rotating with an angular speed ω (radians parsec) about an axis possesses a rotational energy of (1/2) ω^2, where I is the moment of inertia of the body about the rotating axis. If n be the number of rotations per sec (frequency), then w = 2πn so that, the rotational energy of the body in terms of the frequency becomes $2\pi^2 n^2$ I. For a neutron star with a period of rotation equal to 10 millisecond, a mass of 1 M_Θ and a radius of 10 km, the rotational energy is – 10^{50} erg, which is approximately equal to the energy liberated by a solar-type star during its entire lifetime. The rate of change of rotational energy of a neutron star is,

$$\frac{dE_{rot}}{dt} = \frac{d}{dt}\left(\frac{1}{2} I\omega^2\right) = \frac{d}{dt}\left(2\pi^2 \nu^2 I\right) = 4\pi^2 I\nu \frac{dn}{dt}$$

For the crab pulsar, the observed slowdown is given by

$$\frac{1}{n}\frac{dn}{dt} - 4.38 \times 10^{-13}\, s^{-1}$$

Where 1/n= 0.033 sec and I – 10^{45} gm cm^2, if it has a standard mass of – 1 M_Θ and a standard radius of 10 km. Thus the observed slowdown rate of rotation of the Crab pulsar generates energy at the rate of

$$\frac{d}{dt}(E_{\rho o\tau}) = (4\pi^2 \nu^2 I)\left(\frac{1}{n}\frac{dn}{dt}\right) - 10^{38}\ \varepsilon\rho\gamma\ \sigma^{-1}$$

This amount of energy is, in fact, observed to be radiated by the Crab nebula in all wavelengths of the electromagnetic spectrum. This remarkable coincidence between the power output by the Crab pulsar and the power radiated by the Crab nebula is not believed to be mere chance coincidence, but a physical necessity fo the theory that the neutron star formed within the Crab Nebula by the explosion of the 1054 A.D. supernova continuously refills the energy spent by the nebula itself. The observation therefore support, on the one hand, the theory that pulsars are rotating neutron stars formed by supernova explosions and, on the other, that the neutron stars thus formed continuously supply streams of relativistic particles to the surrounding nebulae which maintain the power flux from them at various wavelength. The energy lost in radiation by the nebula may be replenished by the rotational energy of the pulsar, provided an efficient mechanism of conversion of rotational energy to high energy particles actually exists. It is believed that such conversion efficiency can be achieved in a rapidly rotating intense magmatic field as is believed to be present in pulsars. Rapid rotation and intense magnetic field may combine to create large-scale eclectic fields that accelerate charge particles to very high every. These high energy particles stream into the nebula where they emit radiation in various wavelengths by synchrotron mechanism.

Unfortunately, the direct observational verification of the rotating neutron star model of pulsars can be applied only to the Crab pulse, whose rotational energy loss gives a satisfactory measure of the electromagnetic energy radiated by the crab Nebula. This is the only pulsar which has been optically identified with a small star-like object situated within the supernova remnant, namely, the Crab Nebula. Another pulsar that has been found to lie within a supernova remnant is the pulsar PSR 0833 within Vela X, but no optical identification has been made for it.

4- TEST OF ROTATING NEUTRON STAR MODEL OF PULSAR

Lets us now investigate the soundness of the rotating neutron star theory for pulsars and consider what other models could possibly simulate the observed pulsar properties. The clocklike precision of pulse periods shows that the source of the pulse could not be a planetary object or a member of a binary system. For in that case, the periodicity would be changed due to Doppler shift caused by orbital motion. The periods will be P_1 and P_2 when the source of period P is moving toward or away from the observer respectively, with a relative velocity v, where

$$P_1 = P\left[\frac{1-\frac{v}{c}}{1+\frac{v}{c}}\right]^{2/4}$$

And

$$P_1 = P\left[\frac{1+\frac{v}{c}}{1-\frac{v}{c}}\right]^{2/4}$$

Whence, $\frac{\Delta P}{P} = \frac{P_2 - P_1}{P} = \frac{2v}{c}$, if $\frac{v}{c} << 1$.

Since the measured values of ΔP/P for pulsars lie in the range 10^{-13} to 10^{-16} , *v/c* – 10^{-13} to 10^{-16}, that is, if a pulsar is a member of a binary of a binary or a planetary system,its orbital speed would lie in the range 10^{-3} to 10^{-6} cm^{-1} s, which is absurd.

There are two other possibilities, namely, pulsars are rotating or vibrating stellar objects with extremely stable structure and, at the same time, capable of generating sufficient amount of energy. The only likely candidates are, therefore, white dwarfs and neutron stars. We can now ask the question: can the pulsation or rotation of a white dwarf produce the observed periodicities kin pulsars? Calculations reveal that the rotation period of a white dwarf in stable configuration cannot be as short as the observed pulsar periods. If a white dwarf rotates in such a short period, the equatorial rotational velocity is required to exceed the critical velocity of mass escape from the surface of the white dwarf, and as such, the stable configuration of the white dwarf breaks down. Two explain the observed pulsar episodes interns of the pulsation of a white dwarf is also a difficult task. The median period of pulsars is 0.66 sec. it can be shown that the period of fundamental mode of vibration of a white dwarf cannot be much less than 2 seconds. So the fundamental mode of pulsation of a white dwarf cannot satisfactorily explain pulsar periods. Higher overtone pulsation may occur in much short periods comparable to observed pulsar. If overtone pulsations were the mechanism for pulsar periods, not only that the drift in periods would have been much more rapid, but also that the periods would have gradually decreased contrary to observed increase, because the mean radius of the source would decreased slowly. Thus, on the basis of above arguments the pulsating or rotating white dwarf model for pulsars can be discarded.

We are, therefore, left finally with a pulsating or rotating neutron star as the only possible candidate to satisfy the observed properties of pulsars. Since neutron stars are much more compact objects than white dwarfs, their rotation or fundamental pulsation periods must be much shorter than those of white dwarfs. But it is well known that the fundamental pulsation period of a self-gravitating configuration is of the order of its free-fall time which is equal to $1/\sqrt{\Gamma\rho}$ second when cgs units are used. For a neutron star with ρ – 10^{-14} gm cm^{-3} this is $<10^{-3}$ second. Also, in a neutron star, the positional modes are damped out much more rapidly than indicate by changes in pulsar periods. Thus, the pulsation of neutron stars as the manifestation of the observed pulsar periods can be ruled out. Only the rotating neutron star model can explain satisfactorily all the observed characteristics of pulsar periods.

Such a model then must also be able to explain the observed radiation characteristics of pulsars. Observations have revealed that pulse duration is only about 2-4 per cent of the repetition periods of pulsar. The width of the radiating beam associated with the Crab pulsar is about 12^0. If this width is typical of pulsars, in general, then only 1/30th of the total area is involved in radiation and by the same token, only one pulsar among 30 will sweep the solar system with its radiating beam. This probably explains why, even fi the theory of the production of pulsars by supernovae explosions be accepted as true, only two pulsars have been definitely identified within supernova debris. However, it may not be unlikely, that all supernovae explosions do not leave behind them a pulsar and that pulsar are produced only under some special conditions.

5- GOLD'S MODEL OF PULSARS

It was T. gold who first suggested a plausible mechanism by which the observed radio pulses with clock-like precision in periods could be radiated by rotating neutron star. Many other theories have since been proposed by astronomers to explain the mechanism of radiation by pulsars. We shall here make a brief discuson of Gold's model which. With a few modifications canyield a plausible model for pulsar radiation. In the intense magnetic field of apulsa, any charged particle that may escape from its surface will be constrained to move only along the magnetic lines of force. The assemblage of particles is thus whirled around with the angular velocity of the neutron star. In this manner, a co-rotating magnetosphere (consisting of frozen in plasma) is formed around the star. The tangential velocity of these whirling particles gradually increases as they move farther and farther from the stellar surface. At a certain distance, depending upon the speed of rotation of the star, the velocity of particles approaches that of light. The co-rotation will cease at a distance where the speed of particles attains the speed of light. The circle described by particles at this distance is called the velocity of light circle as shown in Fig. 15.2. The relativistic plasma bean near this circle will radiate radio waves perpendicular to the beam, but at the velocity of light circle where the particles have attained the speed of light, they will break away form the magnetosphere and flow out into the surrounding regions of space. The observations of the Crab Nebula suggest that these high energy particles after leaving the influence of the parent neutron star stream into the nebula to supply the "perennial" energy source for radiation from the nebula over the entire spectra range from X-ray to radio waves by synchrotron mechanism. This appears to explain satisfactorily as to how the Crab Nebula could maintain its high intensity of X-ray flux for about a millennium, since particles emitting X-radiation are known to lose their energy in a relatively short time.

Turning back to Gold's model, it is deduced that the radius r of the velocity of light circle for the Crab pulsar NP 0532 with shortest known period (=0.033 second) is – 1600 km, and that of the companion pulsar NP 0527 with the longest known period (=3.7 second) is – 160,000 km, as can be easily calculated from the simple formula

$$r = \frac{c}{\omega} = \frac{cP}{2\pi}$$

P being the period and c the speed of light. Near this circle the charged particle move along magnetic lines of force in helical paths producing synchrotron radiation. According to Gold magnetic activity will eject plasma from from only one or at most a few places on the surface of the neutron star. The emitinng particles are confined within a narrow cone. In fact, particles are confined in a narrow pitch angle Q ≤ t/p in radian measure, where t is the duration of a pulse and P is the pulsar period. Since the pulsars rotate with very high velocities, the radiation will be strongly beamed in a narrow cone in the forward tangential direction sweeping a particular region periodically, so that to a distant observer the pulsar behaves like a "light house" signaling radio waves.

According to this model, any asymmetry in the emission region may be responsible for the observed fine structure in pulses. Also, the observed fluctuation in pulse amplitudes may be due to the temporal changes in the interstellar medium through which the pulses propagate to great distances before reaching the Earth. It is found sometimes that the pulse structure remains fairly constant over period of several pulses. This may be due to the fact that the interstellar medium remains unchanged during this period.

A modification of Gold's theory has been suggested by P. Goldreich and W.H. Julian in respect of the mechanism for particle acceleration to high velocities. These authors suggest that a rotating magnet will, due to uni polar induction, generate an eclectic field E in its vicinity which can cause charge separation and accelerate particles away from the surface to form a radiating magnetosphere. This theory predicts that acceleration of particles to energyas high as 10^{18} eV is possible in this way. Thus, whatever be the accelerating mechanism, such a mechanism is there, implying that pulsars may be a rich source of cosmic rays.

6- DISTANCE AND DISTRIBUTION OF PULSARS

We shall now discuss the interesting problem of determination of distance to pulsrs. No direct method of distance measurement can be applied in this case. One has to use the dispersion measure which involves the average electron enmity in the intervening space between the pulsar and the observer. A pulse form a pulsar contains radiation over a large frequency band. If the intervening interstellar space were a perfect vacuum, electromagnetic radiation of all frequencies would have travelled through space with the same velocity c. But the interstellar space contains free electrons which disperse the travelling radiation, with the result that propagation velocity will depend now on the frequency of the radiation. In a dispersing medium, high frequency radiation will travel faster than the low frequency radiation. So when the radiation from a pulsar is detected on Earth, receivers tuned to high frequencies will detect it earlier than those which are tuned to low frequencies. This time lag gives us clue to the distance to a pulsar whin the average electon density over the intervening space is known. Solving the equation of motion of a free electron in the interstellar medium through which an one-dimensional electromagnetic wave of frequency □ and wave number k propagates, one can derive the dispersion relation.

$$\omega^2 = \omega_p^2 + \kappa^2\chi^2$$

Where

$$\omega_\pi = \left(\frac{4\pi e^2 n_e}{m_e}\right)^{1/2} = 5.6\ \xi\ 10^4 \sqrt{\nu_\varepsilon}\ H$$

Is the plasma frequency and n_e is the number density of electrons. Iϕ $\omega < \omega_\pi$, then k becomes imaginary and the wave will not propagate. If $\omega > \omega_\pi$, then the electromagnetic wave propagates with group velocity

$$\frac{d\omega}{dk} = V = \frac{c}{(1+\omega_p^2/c^2k^2)^{1/2}}$$

If the pulse travels a distance R with this velocity, the arrival time is R/V. The frequency dependence of this arrival time is giving by

$$\frac{d}{d\omega}\left(\frac{R}{V}\right) = \frac{R}{c}\frac{d}{d\omega}\left[1+\frac{\omega_p^2}{\omega^2-\omega_p^2}\right]^{1/2} = -\frac{R}{c}\frac{\omega_p^2}{\omega^2}$$

Where $\omega_\pi << \omega$.

We can now make a number of important deductions from

, together with the condition that $\omega > \omega_\pi$. First, by observing the cutoff frequency it

is possible to find an upper limit to the average electom density (n_e) in the line of sight. Secondly, by substituting
) we get

$$\frac{d}{d\omega}\frac{R}{V} \propto \frac{Rn_e}{\omega^3}$$

Where Rn_e is the total number of electrons within a column of 1 cm^2 cross-section in the line of sight between the source and the observer. Thus, the frequency dependence of the time lag of arrival of sign as through the interstellar medium is derectly proportional to the total number of electrons in a column of unit cross-section along the line of sight and inversely proportional to the cube of the frequency. The integrated number density of electrons in the in the line of sight, is called the dispersion measure, which is equal to

$$\int_0^R n_e\ dr = R = (n_e),$$

If (n_e) be taken as the average number density of electrons in the line of sight. Since the frequency dependence of the time lag is a measurable quantity, Eq. can be used to determine the distance to a pulsar if the average electron density (n_e) in the line of sight is known. Conversely, if the distance to the pulsar can be known by some independent method, the value of (n_e) in the interstellar space can be derived. The mean value thus devived includes contributions both from electrons in the nebula, if any, surrounding the pulsar, as well as from those pervading the general intervening space. Results of extensive observation have indicated that the second contrivution overwhelmingly predominates over the first. The vaue of (n_e), however, is not uniquely known and various values ranging from 0.01 cm^{-3} cm^{-3} to 0.1 cm^{-3} have been used by authors for calculating the distances to pulsars, with the result that discordant results on pulsar distances abound in the literature. The problem of determining electron density in interstellar space is not easy. It depends on various factors that contribute to the ionization of the medium. Some of these factors are still only poorly known. Analyses of the available literature on the subject indicate that values of (n_e) between 0.02 to 0.03 cm^{-3} are most plausible.

Uncertainties in the estimated average electron dandify in interstellar space have led to various assumptions by authors, thereby deriving distances to pulsars which differ by a factor of 4 to 5. However, if average fo the estimated distance are used, it is observed that most of the pulsars lie within – 4 per cent of the total volume of the galactic disc. The currently observed number is – 400 and beaming of radiation puts a restriction to the effect that only one pulsar out every 30 is likely to sweep the earth. Thus, considering the very crude way o calculation, at present about 3 x 10^5 pulsars are likely to exist in our Galaxy. Approximately the same value is obtained if pulsars are assumed to originate in supernova explosions and supernovae statistics are used. If one supernova explosion every 30 to 40 years in the Galaxy is assumed, since the measured slowdown rate of rotation leads to a lifetime of – 10^7 years for a typical pulsar, about 3 x 10^5 pulsars are likely to exist in the Galaxy. Regarding the distribution of pulsars, if average of the estimated distances is used, pulsars are distributed with a tendency to concentrate near the galactic plane.

7- BINARY PULSARS

Since the first hundred pulsars discovered were single objects, astronomers were used to the idea that all pulsars would be single. So the discovery of the first binary pulsar PSR 1913 +16 by R.A Hulse and J.H. Yaylor (1974) was received by astronomers with a great surprise. About a dozen binary pulsars are known to-date. Most of these are millisecond pulsars, the period of about 59 milliseconds. This period was observed to vary by about one part in a thousand every 7^h 45^m. This variation of the pulse periodicity is an indication of orbital velocities, thus confirming that the pulsar belongs to a binary system. The periodic variation of the pulse period is a very sensitive indicator of orbital motion. For most pulsars such variations have not been observed even with careful observations. Those, for which the variation has been observed, are certainly binary systems.

The orbits of most of the binary pulsars are nearly circular, except those of PSR 14913+16 and PSR 2303+46 which are highly eccentric. The periods of the binary pulsars are decreasing very slowly indicating that they will enjoy long lifetime. In fact, for binary pulsars, transfer of angular momentum takes place from binary orbit to the rotating pulsar. These binary pulsars are distinct class by themselves, their evolution running separately from general population fo pulsars. In the P, P diagram, the binary pulsars occupy distinctly the lower left corner. The orbital velocity curve of the binary pulsar PSR 1913+16 is highly no sinusoidal which indicates that the orbit is highly eccentric. The apsidal line (the line joining the periastron and plastron) of the orbit of this binary pulsar has been observed to rotate in space through a large angle of 4.2 degrees per year. This is in perfect conformity with the prediction of Einstein's general relativity. The prediction was made by Einstein himself in cse Mercury going round the Sun. He proposed that the line of asides of an eccentric orbit will rotate slowly in space, the fact which he had termed "advance of the perihelion". The perihelion of Mercury, according to his prediction, should advance by 43 seconds of are per century which was actually observed. The advance of perihelion could not be explained on the basis of Newtonian theory. The is creamy between the theory and observation was thus removed by Einstein's theory.

In the case of the binary pulsar PSR 1913+16, the masses of both the components have been carefully deduced to be – 1.4 M_{Θ} and most likely both the components are neutron stars. These heavy masses being very close to each other, the general relativistic effect should be much higher and the measured high value of 4.2 degrees per year is in perfect accordance with the theory. The observed decay of the orbital periods of binary pulsars demonstrates yet another relativistic effect. Einstein's general relativity theory predicts gravitational radiation. The gravitational radiation energy is derived at the expense of the energy and annular momentum of the orbital motion of the components. The orbital energy is thus dissipated leading to the gradual decay of the orbit. Since the decrease of periods is a common feature of binary pulsars. They serve to demonstrate the truth of the prediction of general relativity theory.

The origin of binary pulsars has not yet been well understood. Several theories have been proposed the discussion of which is beyond the scope of this presentation.

8- BLACK HOLES

Modern astrophysics is opening as a book of puzzles to the scientists. The black hole is one of these latest puzzles of astrophysics. Although the theory of general relativity and gravitation predicts the inevitable formation of black holes in the galaxy, they have not yet been observationally demonstrated. If, however, they do form according to the prediction of the theory, there may be as many as a billion or so of them in our Galaxy. As such, they should have a tremendous importance in the galactic phenomena, and fortunately, this aspect has not remained ignored by the theoretical physicists.

We have already seen that stars with masses less than about 1.4 M_{Θ} invariably end their life as white dwarfs. These stars meet heir demise peacefully. But any star having a mass greater tan 1.5 M_{Θ} has a chance to explode violently at a certain stage of its evolution, unless the catastrophe is prevented by rotation of the star or loss of part of its mass before the catastrophic stage is reached. Fi the initial mass of the exploding star is not very high, say not greater than 10 M_{Θ}. Then after the surface layers are blown off, the core will contract to form as table neutron star in which the pressure of the degenerate neutrons counteracts the gravitational onslaught. The density of the stellar material at this stage is of the order of 10^{14-15} gm cm^{-3}. If however, the original star is more massive, then after the explosion even the degenerate neutrons in the massive core may not be able to resist further gravitational contraction. Even if such a star dies not explode for some favorable reasons, it will undergo the process of contraction. Because these massive stars quickly use up their nuclear fuel) their life-time is 10^7 years), they start cooling down. So the star will contract, and during this course some of its potential energy will be transformed to heat. This fresh quota of heat, however, is not enough to prevent the collapse, and therefore, the star continues to collapse with gathering speed. We shall assume that we are dealing all along with a spherical star. As the collapse starts, fi the star cannot shed off most of its mass, the collapse continues with increasing speed, thereby producing more and more intense gravitation field and reducing the size of the star. In the process a stage is reached when the radius $R_{s'}$ of the star of mass M is given by

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

Where c is the speed of light, R_s is called the Schwarzschild radius. When this radius has been attained, the object will have such a strong gravitational field that it will prevent even light from escaping out of its influence. In Newtonian mechanics also one finds the same result that at the radius R_s the velocity of escape from the object equals the velocity of light. Since photons cannot escape, no event occurring within the Schwarzschild radius can be communicated outside this radius. The object is therefore lost to the outside universe except that its strong gravitational field will be felt by other nearby objects. The Schwarzschild radius has therefore been called the event horizon (meaning that any event within it remains hidden from view as one below the horizon) and the resulting object as the black hole.

Even at this stage, not only that the collapse does not cease, but it continues with an appalling speed. In a spherically collapsing star all the material will simultaneously reach the centre within a period of about 1μ sec after crossing the event horizon. The entire mass thus shrinks to a point of infinite density, which forms a singularity. The singularity will be formed even if the collapse is not radically symmetric. An understanding of the nature and physics of this singularity has of late become a stumbling block to physicists and relativists alike.

Equation shows that the radius of the event horizon is proportional to the mass of the collapsed object. The Schwarzschild radius for the Sun is 2.67 km and the minimum density attained by the material at this stage is – 10^{16} gm cm^{-3}, if we assume that the percentage of mass converted into energy is not significant. For a star of 10 M_Θ these quantities are respectively -27 km and – 10^{14} gm cm^{-3} while for a massive galactic nucleus of mass 10^9 M_Θ they are respectively – 10^{-4} pc and 10^{-2} gm cm^3, the last value being only about 1 per cent of the average density of the Sun.

When the event horizon has formed, light from within cannot move out, while that from the outside neighborhood of the horizon will propagate, being strongly redshirted by the intense gravitational pull of the black hole. Not only that, everything, both matter and light that may encounter the event horizon will be sucked in.

A clear understanding of the black hole physics and mechanics posed serious problems until a few years ago. But recently, the gateway to understanding these complicated problems in the field by Penrose. Hawking Bardeen, Lynden-Bell, Chandrasekhar and several others. It is now understood that a black hole may capture mass from the surrounding space by its intense gravitational pull. The probability for such capture becomes almost certain, if the black hole be the member of a binary system consisting of normal star. Owing to the intense gravitational pull the black hole will then draw gas from the upper atmosphere of the companion, this gas will form a rotating disc around the black hole by virtue of the conservation of angular momentum which the captured matter originally possessed. Frictional force will dissipate the kinetic energy of matter, particularly of that in the inner part of the disc, whereby the centrifugal balance will be upset and the matter will spiral towards the black hole to be sucked in by it ultimately, in the same manner as atmospheric friction brings down the artificial satellites to the surface of the Earth. The falling matter, before being sucked in, attains very high temperature so as to radiate intensely in very high frequencies, particularly, in X-rays. Calculations show that about 6 per cent or more of the total rest mass energy of the infilling matter may be converted to radiation energy during the process. This is about 8 times more efficient than the energy generation process by nuclear transmutation. Thus gravitational energy generation process is much more efficient than any other known process, except that of complete annihilation by matter-antimatter interaction which is 100 per cent efficient.

The works of Penrose and Hawking have shown that a still more efficient process of gravitational radiation can be achieved when two black holes come in contact and merge together. In this case, the two event horizons also merge together to be enveloped by a common event horizon of the final black hole will increase. In an ideal case, left the two black holes be of equal mass, M, and the resulting black hole be of mass M'. Now since the surface area of the event horizon is proportional to the square of the mass (the radius being proportional to the mass), we should have, according to the above theory.

$$M'^2 > M^2$$

whence,

$$M' > \sqrt{2}M$$

which corresponds to a maximum efficiency of $1-1/\sqrt{2}) = 0.29$ for the conversion of original rest-mass energy to the radiation energy. This is the upper limit of conversion efficiency in the case of non rotating black holes. It has been proved also that under certain conditions, if a mass is accreted by a rotating black hole, then before it is finally sucked in, about 43 per cent of its rest mass energy may be converted to radiant energy: and this is the maximum limit of conversion efficiency so far known.

Such highly efficient mechanisms for energy generation are called for, in order to explain the observed radiation from radio galaxies, quasars and intense X-ray sources. So black holes, although not yet observed, may come out as the final answer to the energy problem that has been seriously intriguing the physicists for more than a decade.

Lastly, we can ask- What prospect is there for a black hole to be observed and where should we look for it? If the way we have described for the formation of black holes is correct, there may be at least 10^9 black holes in the Galaxy. But the most likely place to detect them is in the massive binary systems, from both the aspects of intense gravitational pull as well as high frequency radiation. We have already noticed that intense X-ray radiation results when mass are accreted by a black hole. So if in a binary system one of the components be a normal star while the other has become a black hole, the former will move in an orbit around, the latter which will be optically invisible, but will emit copious flux of X-rays. This condition is exactly fulfilled by the most intense X-ray source Cygnus X-1. It is now believed that Cygnus X-1 belongs to a binary system having its companion as a normal BOIab supergiant. Reliable calculations have indicated that the mass of the supergiant lies in the rage (20-30) M_Θ, while that of the X-ray source lies in the range (3.4-8) M_Θ. Such a belief is supported by the observation that the X-ray brightness of Cygnus X-1 varies over a period of 0.1 second. This indicates that the radius of the source is smaller than 3 x 10^4 km, which is very small compared to the radius of a normal star (R_Θ - 7 x 10^5km). on the other hand, its estimated high mass excludes its membership among neutron stars of black dwarfs. Thus, it the source is a compact object but belongs neither to neutron stars nor to black dwarfs. Its most likely classification is thus among the black holes. There are two other likely candidates similar to Cygnus X-1 in our Galaxy, and one in the Small Magellan Cloud. Each of these is a binary system with an X-ray sources 2U 1700-37 and 2U 0900-4.0 respectively, have X-ray spectra similar to that of Cygnus X-1, but their masses have both been determined. The mass of the SMC source, SMC X-1, is estimated to be -10 M_Θ from its measured X-ray energy flux.

The observed high radiation flux from radio galaxies, quasars and nuclei of some otherwise normal galaxies cells for its explanation some energy generation mechanism as currently understood is the gravitational radiation in the intense gravitational field of black holes. So it is not unlikely that these objects contain at their centre black holes whose masses may range from 10^5 to 10^9 M_Θ.

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