THREE AND HALF CENTURIES OF BINARY STAR RESEARCH

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INTRODUCTION

IN India there is a prevalent belief that Astronomy, which includes Astrophysics, is an esoteric subject which has no relevance in a general Physics curriculum. However, names such as Newton, Lagrange, Fraunhoffer, Pickering, Russell, Eddington, Edlen, Saha, Einstein, Bethe, Jansky, Chandrasekhar, etc. vividly illustrate the intimate connection between laboratory physics and the universe of stars and galaxies. In fact the universality of the laws of laboratory physics has to be tested in astronomical objects where conditions can be markedly different from those in the laboratory. For example, we meet with temperatures ranging from 4° K in interstellar space to those exceeding 10^{10} °K at the start of the big bang, densities from 10^{-34} gm/cc in intergalactic space to 10^{15} gm/cc in neutron stars, pressures from 10^{-14} dynes/cm^2 in interstellar space to 10^{36} dynes/cm^2 at the centres of compact stars, and magnetic fields from 10^{-6} G in interstellar space to 10^{12} G on the surface of a neutron star. These extreme conditions put severe constraints on the validity of physical laws and often force us to question the fundamental postulates. Further, we have to deal with vast time and distance scales when we consider the properties of the whole universe which is itself a unique physical object. Hence it is necessary that physicists should have a basic knowledge of Astronomy and Astrophysics to appreciate the real significance of the physical laws. This is all the more important in the present space age when planetary exploration and new techniques of radio, infrared, ultraviolet and X-ray astronomies are changing our ideas about the solar system and the universe in which it is situated. Hence the author wishes to illustrate how even a non-glamorous branch of Astronomy like Binary Stars has contributed to our understanding of the physical world. It is hoped that physicists will realise the importance of going deeper into the study of Astronomy rather than be satisfied with the newspaper accounts of quasars, pulsars, black holes, expanding universe, missing mass, Vikings and Voyagers.

THE LAW OF GRAVITATION

The solution of the problem of planetary motions by Newton's law of gravitation and the establishment of the science of celestial mechanics was the first great triumph of the scientific method, which has served as a model for all later scientific theories. Soon after the publication of Principia by Newton, Halley had demonstrated that Newton's law applied to comets which moved in highly elliptical orbits around the sun. But the extension of the law to the stellar universe was ascertained only when it was applied to binaries which consist of two component stars revolving around a common centre of mass on account of their mutual gravitational attraction.

TABLE 1
Tally of Visual Binaries

Year	Total	Catalogue of	Rate of discovery
1650	1	Riccioli	1 in 10 years
1700	5		1 per year
1779	80	Mayor	1 per month
1821	845	W. Herschell	1 per day
1827	3110	F. G. W. Struve	2½ per week
1906	13665	Burnham	3½ per week
1927	17180	Aitken	
1960	50000	Jeffers and Van den Bos	2 per day

The first visual binary was discovered in 1650 by Riccioli who found that Mizar (ζ U Ma) has a fainter companion 14″ away. In the next 50 years only four more binaries were discovered, the last one being α Centauri (now known to be our nearest neighbour in space), which was found by Father Richaud in 1689 while observing a comet at Pondicherry. The increase in the number of known visual binaries since then is shown in table 1. The accelerated rate of discovery after 1820 was due to the realisation of the importance of binaries and that after 1927 due to the use of larger telescopes which reached fainter magnitudes.

At first it was thought that a double star represented just the chance coincidence in the directions of the two stars which are otherwise far apart in distance. Mitchell[1] argued in 1767 that the number of double stars having a particular maximum angular separation is far greater than what one would expect from a random distribution of stars on the celestial sphere with the implication that they may be physically connected. However, it was William Herschel[2] who demonstrated in 1803 that the observed changes in the relative positions of the components of Castor and 5 others visual binaries observed by him over a period of 25 years were according to Newton's law of gravitation. In the case of a visual binary we observe only the path of the fainter component around the brighter one as projected on the sky plane. It is an ellipse, but the brighter star is not at the focus; nevertheless the law of constant areal velocity holds. Universality of the law of gravitation was thus firmly established and one could proceed to derive the elements of the orbit of the binary by applying the known formulae of Celestial mechanics. An analytical method was first given by Kowalsky[3] in 1873.

One of the elements of a visual binary orbit is the semi-major axis of the relative orbit a″ in seconds of arc. If the distance of the binary can be found through the method of trigonometric parallax (π''), we can obtain $a = a''/\pi''$ in astronomical units (a.u.). Now the relative semi-major axis ($a = a_1 + a_2$) and period P are related by Kepler's third law which can be written as

$$P^2 = a^3/(M_1 + M_2) \qquad (1)$$

where 'P' is measured in years, 'a' in astronomical units and the masses of the two stars 'M_1' and 'M_2' in units of solar mass $M_\odot$ ($=2\times10^{33}$ gm). We can thus get $M_1 + M_2$ immediately; masses of individual stars can be obtained if one can locate the centre of mass by observing the motion of the system with respect to distant background stars, so that we can get a_1 and a_2 which are related by $M_1 a_1 = M_2 a_2$. A study of visual binaries thus furnishes us with an important physical parameter of stars; in fact a large fraction of reliable stellar masses are derived from visual binaries.

A binary with reasonably short period will show as two point sources of light through a telescope if the separation between its components is large and the system is comparatively close to us. Hence we do not expect to see such visual binaries beyond a few hundred light years. However there are two other ways by which the binary nature of a star can be inferred. If the orbital plane of the system lies along the line of the sight (*i.e.* the inclination of the orbit to sky plane (i) is clost to 90°), then the two components will mutually eclipse each other at roughtly half period intervals. The first such eclipsing pair was discovered in 1782 by a deaf and dumb amateur astronomer, Goodrick, who found that Algol rapidly diminishes in brightness at intervals of about 2.9 days. The latest (5th) Finding list[4] of eclipsing binaries published in 1980 contains 3564 entries. Assuming a random distribution of orientation of orbital planes of binary stars, the probability of observing an eclipsing pair is small. But the variation of brightness is quite easy to detect even at large distances, hence photometry provides a powerful tool for locating binary stars not only in the milky way but also in nearby galaxies; the 5th Finding List contains 17 systems in Magellanic clouds which are at a distance of 180000 light years.

The binary nature of a star can also be inferred spectroscopically. As the components move around the common centre of mass their receding motion in half of the orbit and advancing motion in the other half will be reflected in the Doppler shifts of spectral lines towards longer and shorter wavelengthes, respectively. Here also, the inclination 'i' of the orbit with respect to the plane of the sky has to be high and the period has to be short (days to weeks) so that the components will have large enough radial velocities for producing measurable shifts of spectral lines. However the need to spread the light into a spectrum makes it difficult to detect fainter binaries by spectroscopic method. The first spectroscopic binary was discovered by E. C. Pickeving in 1889; it happened to be the brighter component of Mizar which was also the first visual binary to be discovered. The latest (7th) Catologue of Spectroscopic Binaries[5] published in 1978 contains 978 systems.

One of the earliest method of determining the orbital elements of a spectroscopic binary from its radial velocity curve was given by Lehmann-Filhes[6] in 1894. The problem of obtaining the elements of an eclipsing binary from its light curve was first solved by Russell[7] in 1911–12. Both methods have been tremendously improved by later workers. In the case of a double lined spectroscopic binary in which the spectra of both the stars are visible, we obtain in particular '$a_1 \sin i$' and '$a_2 \sin i$' while the eclipse curve gives us not only 'i' but also 'R_1/a' and 'R_2/a' where R_1 and R_2 are the radii of the two components. Hence if the system happens to the both a double lined spectroscopic binary as well as an eclipsing binary we can derive $a = a_1 + a_2$ in kilometers which gives M_1 M_2 by Keplers third law, M_1 and M_2 by the condition $M_1 a_1 = M_2 a_2$ and R_1, R_2 the radii of the two stars in kilometers. Thus the masses, absolute dimensions and densities of the components can completely be determined. Further, since the surface temperature can be found from the colour or spectrum of the star, we can calculate the absolute luminosity of each star by the formula $L = 4\pi R_2 \sigma T_4$. Again the binary stars are the only source which provide reliable values of the these fundamental parameters of stars.

PHYSICS OF THE STELLAR INTERIORS

It was found as early as 1911 by Halm[8] that the luminosity of stars increased with mass roughly as 3.5th power of mass ($L \propto M^{3\cdot5}$) as shown in figure 1. On combining with the temperature luminosity relation, represented by the Hertzsprung-Russell diagram, where $L \propto T^7$ for the majority (main sequence) of stars, we see that the radius of the main sequence star also increases with its mass at a much slower rate as $R \propto M^{3/4}$. A recent discussion of these relations is given by Harris *et al*[9]. The binary stars had thus posed a problem to astrophysicists to explain the M-L and M-R relations. It has been successfully solved by others[10,11] who have given additionally information as to how the stars evolve. We shall now briefly describe the main results of this theory; for further reference in this article, interested readers can look up details in a standard book like that of Cox and Giuli[12].

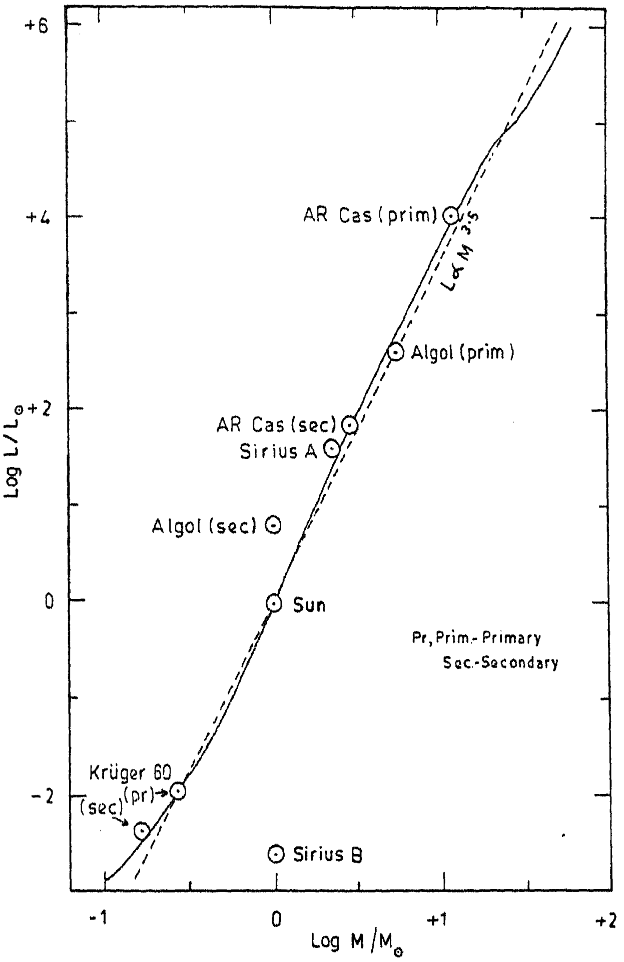

Figure 1. Mass-luminosity law-sun and 4 binaries are shown.

(i) Majority of the stars are gaseous spheres in hydrostatic and thermal equilibrium with a composition of 70 percent hydrogen, 28 percent helium and 2 percent heavier elements having $\gamma = C_p/C_v = 1.3$, or polytropic index $n = 3.5$, approximately. Their central temperatures range from 10 million degrees for a star of 0.5 $M_\odot$ to 40 million degrees for star of 50 $M_\odot$

(ii) The narrow range of central temperatures indicates that stars derive energy from thermonuclear reactions in which hydrogen gets converted into helium. While CN-cycle proposed by Bethe[13] in 1939 operates in stars more massive than the sun, the pp-chain reaction proposed by Bethe and Critchfield[14] one year earlier provides the energy in lower mass stars.

(iii) Mass-luminosity relation is a reflection of the fact that more massive stars burn up their hydrogen fuel faster as a result of the higher central temperature, which also accelerates their general evolution.

(iv) As hydrogen gets depleted in the centre the luminosity of the star increases slowly; however, after exhaustion of hydrogen in the central 10 percent, there is a major change in the structure of the star as shown by Schonberg and Chandrasekhar[15] in 1942. At this stage the helium enriched core begins to contract while the outer envelope expands and the star becomes a highly luminous cool object called giant or supergiant. The evolution of 1,3 and 15 solar mass stars in the temperature - luminosity - radius diagram, according to Iben[16] is shown in figure 2 where time scales are also indicated.

(v) In the giant or supergiant phase, the central temperature becomes quite high and thermonuclear reactions proceed in such a way as to produce heavier and heavier elements according to a scheme first given by Burbridge *et al*[17] in 1957. A nuclear physicist has to be thoroughly familiar with this thermonuclear cooking of elements if he is to explain the observed relative abundances of elements. Ultimately, the star explodes as a nova or supernova leaving behind the compact core in the form of a white dwarf, neutron star or black hole.

It is interesting to see how the masses, radii and other fundamental parameters provided by binary stars have indirectly led to the above theories of stellar structure and evolution. The binary stars have also provided checks on the theory in many ways as explained below:

a) A study of the observed masses of wide and detached binaries by Stephenson and Sanwal[18] has confirmed that it is the more massive primary which becomes a giant or supergiant before its less massive companion and that most massive stars become supergiants, medium mass stars become giants and less massive one become subgiants as expected from the theory of stellar evolution, (see figure 2.).

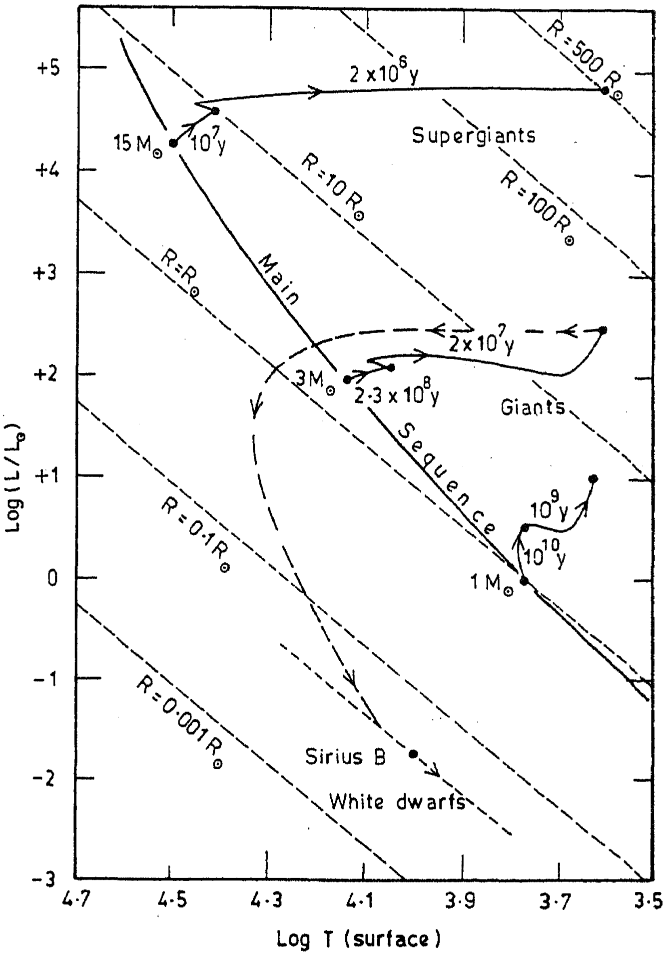

Figure 2. Stellar evolution for 1, 3, 15 M.

(b) In close binaries the components are distorted due to mutual tidal action the distortion being a function of central condensation or polytropic index n. One effect of this distortion is the rotation of the apsidal line which can be observed for spectroscopic and eclipsing binaries with eccentric orbits. Kushwaha[19] and Semeniuk and Paczynski[20] have found that the observed rotation of apsidal lines in binaries is consistent with the theory.

(c) The distorted stars also show the effect of polar or gravity brightening which can be studied from the light curves of eclipsing binaries (c.f. Kopal[21]).

However all binaries do not conform to the general evolutionary picture outlined here. There are important exceptions which take us to other areas of Physics.

DEGENERATE STATE OF MATTER

Sirius, the brightest star in the night sky, has a radial velocity of approach equal to 8 km/sec and a transverse velocity of 16.5 km/sec; the latter gives rise to a change in its position in the sky *i.e.* a proper motion of 1″.32/Yr. If the motion of Sirius were rectilinear, the proper motion should occur strictly along a great circle. However in 1834 Bessel found that the actual motion of Sirius is wavy and he attributed it to the presence of an invisible companion. The companion was later observed by Alvan Clark in 1866 while testing the 18½-inch telescope of Dearborn observatory, its brightness being nearly 10000 times less than that of Sirius. This was the first detection of an unseen component by the astrometric method, which is now being regularly used by astronomers. It was by this method that van de Kamp[22] has inferred the presence of two companions of Barnard's star having masses equal to 1.0 and 0.4 times the mass of Jupiter. The astrometric method is thus a powerful tool for detecting planetary systems in the solar neighbourhood.

Coming back to Sirius it is now being regularly observed as a visual binary and its elements are well determined. They give: $P = 49.94$yrs. $a \doteq 7''.62$ and $e = 0.59$. From its distance of 9 light years ($\pi = 0''.378$) we get $a = 20$ *a. u* and $M_1 + M_2 = 3.26 M_\odot$ Further from the wavy path of Sirius A, the brighter component, we find $a_1 = 8.6$ a.u. so that $M_1 = 2.28$ M. and $M_2 = 0.98$ M. Sirius B, the fainter component, is thus as massive as the sun, but it is 100 times fainter than the sun. Obviously it does not obey the mass-luminosity law as can be seen from figure 1, this fact has to be explained. It is now understood that such stars, known as white dwarfs, represent the hydrogen exhausted cores of stars which would be left after the removal of the outer envelope by some process. As there are no sources of energy left therein the star has to draw upon its store of thermal energy which explains their faintness.

Photometry indicates that both Sirius A and B are white in colour and an examination of their spectra in the light of Saha's equation of ionisation and Botzmann's equation of excitation gives for them, a surface temperature of about 10000° K. Since the luminosity of a star is given by $L = 4\pi R^2 \sigma T^4$ equality of temperature and extreme faintness of Sirius B ($L_B = 10^{-4}\ L_A$) indicates that its radius is 100 times smaller than Sirius A. In absolute units it comes out to be only 2½ times the radius of the earth. The star has therefore a density of about 1.5×10^5 gm/cc; Eddington has dramatically stated that one matchboxful material of Sirius B will weigh one ton on earth. At these extreme densities, matter is completely pressure ionised and electrons behave like a free Fermi gas. We are thus provided with a nice opportunity to test the equation of state for such dense material.

Electrons obey Pauli's exclusion principle and follow Fermi-Dirac statistics according to which the occupation number (n/g) for an energy state between E and E + dE is given by

$$\frac{n}{g} = \frac{1}{\exp(E - E_F)/kT + 1} \qquad (2)$$

where the Fermi energy E_F is related to particle density N by

$$E_F = \frac{h^2}{8\pi^2 m} (3\pi^2 N)^{2/3} \qquad (3a)$$

for non-relativistic particles, and

$$E_F = \frac{hc}{2\pi} (3\pi^2 N)^{1/3} \qquad (3b)$$

for relativitistic particles, m being the mass of the particle. If the average energy per particle $\bar{E} \gg E_F$ we have $(n/g) = \exp(-E/kT)$, which is Boltzmann or classical statistics; this is called non-degenerate state. On the other hand if $\bar{E} \ll E_F$ we have $(n/g) \approx 1$ for most particles, which is called degenerate state of matter.

Table 2 shows the state of matter in various objects. We see that the electrons in a white dwarf are degenerate while the nuclei (α particles) are not. In this case most of the pressure is contributed by the fast moving electrons which fact can be used for studying the structure of a white dwarf as was done by Chandrasekhar[23] in 1935. The equation of state for a degenerate gas can be written as follows:

TABLE 2

Properties of various materials

Material	Density gm/cc	Temp. °K	Particle	m/m_e	N/cc	E_F (eV)	$E = \frac{3}{2} kT$ (eV)	E_F/E	State
Air	1.3×10^{-3}	3.0×10^2	$N_2 + O_2$	52880	2.72×10^9	6.24×10^{-7}	3.9×10^{-2}	1.6×10^{-5}	ND
Copper	9.0	3.0×10^2	Free e	1	8.51×10^{22}	7.07	3.9×10^{-2}	1.8×10^2	D
H in Sun's Centre	1.3×10^2	1.6×0^7	e	1	7.83×10^{25}	6.68×10^2	2.1×10^3	3.2×10^{-1}	WD
			p	1836	7.83×10^{25}	3.64×10^{-1}	2.1×10^3	1.7×10^{-4}	ND
Helium White Dwarf	6.0×10^5	1.0×10^7	e	1	1.81×10^{29}	7.34×10^4	1.3×10^3	5.7×10	D
			α	7344	9.03×10^{28}	1.00×10	1.3×10^3	7.7×10^{-3}	ND
Neutron Stars	5.0×10^{14}	5.0×10^8	n	1836	2.89×10^{38}	8.69×10^7	6.5×10^4	1.3×10^3	D
			p	1836	1.20×10^{37}	1.07×10^7	6.5×10^4	1.6×10^2	D
			e	1	1.20×10^{37}	1.40×10^8	6.5×10^4	2.2×10^3	RD

Notes: D = Degenerate, ND = Non-degenerate, WD = Weakly degenerate, RD = Relativistically degenerate.

$M_0C^2 = 5.1 \times 10^5$ eV for e, and 9.31×10^8 eV for p and n.

$$P \propto (\rho/\mu_e)^{5/3} \qquad (4a)$$

for non-relativitistic case, and

$$P \propto (\rho/\mu_e)^{4/3} \qquad (4b)$$

for relativistic case, where μ_e is the molecular weight associated with one electron; it is 1 for hydrogen and nearly 2 for all other elements at high densities. Now dimensionally.

$$P \propto \frac{GM^2}{R^4} \text{ and } \rho \propto \frac{M}{R^3} \qquad (5)$$

Then combining equations (4) and (5) we find

(i) In non-relativistic case which holds for less massive stars

$$\frac{M^2}{R^4} \propto \left(\frac{M}{\mu_e}\right)^{5/3} \frac{1}{R^5}$$

or $R\,\mu_e \propto (M\mu_e^2)^{-1/3}$ (6).

(ii) In relativistic case which holds for more massive stars

$$\frac{M^2}{R^4} \propto \left(\frac{M}{\mu_e}\right)^{4/3} \frac{1}{R^4}$$

or $M\mu_e^2 = \text{Constant} = 5.8\, M_\odot$ (7).

We have already seen that the material inside a white dwarf consists mostly of helium for which $\mu_e = 2$.for lower mass white dwarfs, the radius decreases with increasing mass as $M^{-1/3}$, but instead of approaching zero as $M \to \infty$ it will vanish for a finite mass of 1.4 $M_\odot$ For intermediate masses the mass radius relation should cross over from equation (6) to equation (7). The consequence of the above discussion is that white dwarfs have a limiting mass of 1.4 $M_\odot$; most white dwarfs are indeed found to have masses ranging from 0.4 to 1.0 $M_\odot$ and they follow the theoretical mass-radius relation of white dwarfs fairly well. It is obvious that bigger stars must be shedding a large fraction of their mass before they become white dwarfs at the end of the their career.

SUPERCOMPACT OBJECTS

Two other types of compact objects, much more dense than white dwarfs, have been proposed *viz.*, neutron stars and black holes. We shall now discuss their relation to the binary star research.

Neutron Stars:- Soon after the discovery of the neutron by the physicist Chandwick in 1932 astronomer Zwicky speculated that at very high densities exceeding those found in white dwarfs by many orders of magnitude protons and electrons would combine to form neutrons giving rise to neutron stars. From table 2, we see that at densities of the order of $10^{14} - 10^{15}$ gm/cc which are likely to exist in them neutrons as well as small percentage of protons that will be present are degenerate. Since both are Fermions, applying the theory of white dwarfs to them with $\mu_n = 1$, we would obtain a limiting mass of 5.8 $M_\odot$ provided neutrons behave as free particles. However at very high densities we expect short range nuclear forces to take over. Detailed theoretical calculations which take them into account by using a proper equation of state show that the mass of a neutron star cannot exceed 2 to 3 M. and its radius would be of the order of 10 km.

The discovery of neutron stars was accidental. In 1967 Hewish and his collaborators[24] discovered the first pulsar, since then their number has risen to somewhere between 150 and 200. All of them have periods between 33 milliseconds to about 4 seconds. These periods are too small for pulsation of white dwarfs and too large for pulsation of neutron stars. Hence pulsars have been identified as rotating neutron stars with high magnetic fields in which the magnetic axis makes a large angle with the axis of rotation. Neutron stars are also found in X-ray binaries such as Her X-1, discovered by Tannanbaum *et al*[25] and Cen X-3 discovered by Baity *et al*[26]. Like white dwarfs neutron stars also represent cores of massive stars which have been compressed during an explosion of the whole star in the form of a supernova in their case. This is evidenced by the presence of a pulsar at the seat of the Crab supernova of 1054.

Pulsars have served as a fertile hunting ground for particle physicists, solid state physicists and plasma physicists. The discovery of the binary pulsar PSR 1913 + 16 by Hulse and Taylor[27] has brought them in the perview of workers in the field of binary stars. The changes in the period of the pulsar are governed by Doppler effect caused by its motion in the orbit and they can be treated exactly like changes in the radial velocity of a spectroscopic binary. Such an analysis indicates that we are dealing with two neutron stars moving around a common centre of mass in an orbit of high eccentricity e = 0.615 and period P = 0.^{d}323. Here we have an opportunity to test the general theory of relativity because the strong gravitational field between the two supercompact objects should produce a fast rotation of the line of apsides several orders of magnitude faster than that of planet Mercury. The relativistic effects in the binary pulsar are discussed by Brecher[28].

Black Holes: Binary stars have also provided an opportunity to test another consequence of the general theory of relativity. If we consider spherical objects which are much more condensed than neutron stars we find that at

$$R_s = 2GM/c^2, \text{ — — — — —}(8).$$

the energy of a photon will be just sufficient for it, to escape from the surface of that body. Hence from any object with radius smaller than R_s, known as Schwazschld radius, the photons cannot escape and the body will be invisible, hence it is called a 'black hole'. It is believed that the X-ray source Cyg — X_1 contains a black hole. It has been identified with an optical object which shows orbital motion[29]. The visible component is a hot star of mass greater than 12 $M_\odot$ with an invisible companion of mass greater than 3 $M_\odot$ As the latter exceeds the limiting mass of a neutron star, the invisible companion is likely to be a black hole. X-rays are produced when matter leaving the hot component is gobbled up as it falls into the potential well of the black hole companion.

Possible real existence of a black hole has led Hawkins[30] to study its properties. He finds that black holes can emit particles and antiparticles by interaction with virtual particles in empty space. The emission is thermal in character, the temperature of the black hole depending on its mass with some high inverse power of mass.

HIGH ENERGY ASTROPHYSICS

Our sun has a power output of 2×10^{33} ergs-sec. The most massive blue stars and red supergiants are 10^6 times brighter because of the high rate of thermonuclear reactions at their centres. However we meet with other phenomena where there is a sudden release of energy at high rates which include supernovae (10^9 to 10^{10} $L_\odot$), Novae (10^5 $L_\odot$) and X-ray Sources (10^4 to 10^5 $L_\odot$). Many of these high energy events are associated with binary stars. Since the discovery of the binary nature of nova DQ Herculis, by Walker[31] in 1954, there is an overwhelming evidence which shows that classical novae, recurrent novae and U Gem stars or dwarf novae involve a white dwarf like compact object in a binary system. Similarly remnants of supernovae *viz.* neutron stars are found in X-ray binaries and the binary pulsar. It appears that the intense gravitational field of the compact object plays an important part in the high energy phenomena. The importance of the gravitational field of the companion star first came to light from the study of the oldest known eclipsing binary Algol.

Algol, which is both an eclipsing binary as well as a single lined spectroscopic binary is found to have a brighter blue star of mass 5.2 $M_\odot$ and a giant cooler secondary of 1.0 M. which is 6 times overluminous for its mass as shown in figure 1. It looks as though the less massive star is more evolved than the more massive one, which is contrary to the well tested general picture of stellar evolution. Similar situation was found to prevail in many close binaries of Algol type (*e.g.* T T. Hya studied by Kulkarni and Abhyankar[32]). A solution to this Algol paradox was given by Crawford[33] who suggested that the secondary might have been originally the more massive component, which evolved faster and, while expanding towards giant phase, transferred its material to the companion which has now become the more massive component. Transfer of material in this fashion is a direct consequence of the gravitational field of the companion. This path of investigation has been so successful that several computations have been made for the evolution of close binaries with different combinations of initial masses and periods which have been able to explain a variety of peculiar objects that have been found as members of binary systems. Interested reader may refer to the review articles by Plavec[34] and Paczynski[35]

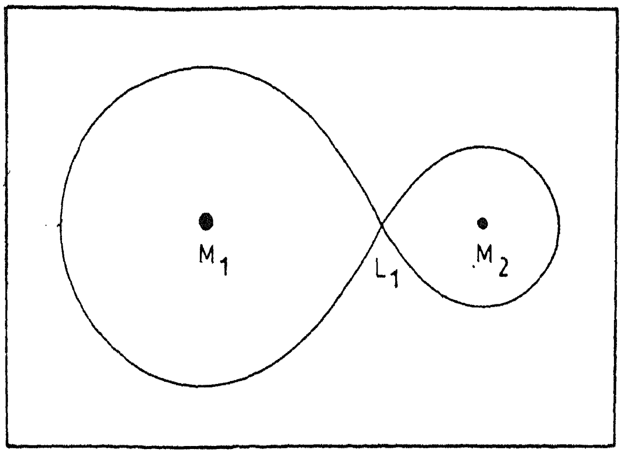

Figure 3. Common roche equipotential for two masses: $M_1 > M_2$, L_1 is first langrangian point.

The gravitational influence of the companion is illustrated by the common equipotential surface for the system of two stars revolving round a common centre of mass. In figure 3 the figure of 8 represents the common or Roche equipotential for two stars of masses M_1 and M_2 such that $M_1 < M_2$. As the more massive star evolves towards the giant phase, it fills its Roche lobe after which, matter can easily flow towards the secondary through L_1, the first Lagrangian point of contact. During the process of mass transfer the separation between components, period of the binary and the sizes of Roche lobes go on changing so as to produce fast or slow mass transfer at different stages. If the combined mass $M_1 + M_2$ is smaller than 3 to 4 solar masses, material will be transferred from M_1 to M_2 so that eventually M_2 becomes a more massive normal star while M_1 becomes a less massive giant as found in Algol. When sufficient mass is transferred, M_1 will contract and becomes a white dwarf. Later, when M_2 evolves and fills its Roche lobe, matter will flow back to M_1. But now since M_1 is a white dwarf, it cannot accommodate much material on its surface. As the temperature there is high, the accreted hydrogen undergoes rapid thermonuclear fusion, causing an expulsion of the outer layers in the form a nova explosion. The process can repeat at semi-regular intervals so long as material can flow from M_2 to M_1. The recurrent nova phenomena can thus be satisfactorily explained. That the white dwarfs can trigger such nova explosions as it accretes material while travelling through interestellar space was suggested first by Shatzman[36] in 1950. However the binary nature of novae has provided a ready and more plausible source for accretion of material *viz.* the companion.

The evolution of massive systems is found to produce a large variety of peculiar binary systems found in our galaxy. A particular case of a binary starting with two components of masses $M_1 = 20$ M. and $M_2 = 8\ M_\odot$ with a separation of 35 $R_\odot$(solar radii) and a period of 4.56 days has been studied by De Loore *et al*[37]. The various stages of evolution of the system are: (i) After 6.2 million years, M^1 fills its Roche Lobe and begins to transfer mass to M_2. (ii) In the next 30000 years, sufficient mass has been transferred so that M^2 has a mass of 22.6 M. while M^1 has become a helium star of 5.4 $M_\odot$The latter shows the characteristics of Wolf-Rayet (WR) star and is thus the prototype of WR stars which are found in binaries with massive companions. In the present case it has a period of 10.86 days with a separation of 62.4 $R_\odot$ (iii) In the next half million years the helium star explodes in the form of a supernova leaving behind a neutron star of 2$M_\odot$ which may be a pulsar. The binary now has a period of 11.7 days and a separation of 69 $R_\odot$(iv) After another 41.2 million years M_2 evolves sufficiently to produce strong stellar wind a part of which is intercepted by the neutron star to produce strong X-ray emission as found in cir X-1. (v) In the next 50000 years M^2 loses most of its mass through stellar wind leaving behind a WR type helium star of mass 6.3 $M_\odot$ As the companion neutron star is too small the WR star appears as single. However if the stellar wind is still strong, it can appear as an ultra short period (1.44 hour) X-ray binary with separation 1.35 $R_\odot$(vi) Finally after another 1.4 million years (total about 12 million years from the beginning) M_2 also explodes as a supernova, leaving behind a young pulsar moving in an eccentric orbit around an older nonpulsing neutron star with a period of 7.87 hours and separation of 3.18 $R_\odot$ as found in the binary pulsar mentioned earlier.

CONCLUSION

As stated at the beginning we have shown how binary star research in the last three and half centuries has taken us to various areas of Physics. There are several problems which are still unsolved and they may lead us to some other areas of Physics.

The components of Sirius are so far apart that the process of mass transfer which is so efficient in close binaries cannot operate there. The mechanism by which the more massive companion trimmed itself to a mass below the Chandrasekhar limit is still not known. Once that is understood, we may be able to answer the question whether we can have white dwarf binaries like the binary pulsar. The periods of close white dwarf pairs will be of the order of a few minutes. Kopal has urged observers to search for such binaries for answering this important question.

Binary and multiple stars account for about 60% of the total stellar population. Hence any theory about the formation of stars has also to explain the formation of binary systems. Even planetary systems are incipient binaries where the smaller mass was not sufficient to form a star. The formation of highly rotating single stars, binaries and planetary systems thus represent the end products of one and the same process which differ on account of the initial mass and angular momentum per unit mass. Study of binaries will undoubtedly throw light on this problem in future.

If we extrapolate the times of significant discoveries, in the binary star research given below, we find that the next important discovery in this field might occur in 2028 AD!

First visual binary	1650 + 132 − 25
First eclipsing binary	1782 + 107 − 25
First spectroscopic binary	1889 + 82 − 25 ?
First X-ray binary	1971 + 57 ?
Next important discovery	2028 ?

This is perhaps the best way to end this article.

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