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ON THE EVOLUTION OF A ROTATIONALLY UNSTABLE STAR

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ABSTRACT

The fission theory of binary star systems is reexamined and important objections to it are removed. The presence of a magnetic field in the atmosphere of a rotationally unstable star prevents loss of momentum through the loss of atmosphere at the star's equator. By interaction with the atmospheric electric and magnetic fields, the ions are constrained to move systematically in the direction of rotation and add angular momentum to the star proper. Eventually the star divides, and whereas the parent star was radially symmetrical the resulting components are highly asymmetrical and one-half of the star is at a much higher mean temperature than the other half. Tidal couples orient the components just after fission so that the newly exposed faces are oriented inward but are displaced through a small angle. The comparatively high temperatures of the hot faces cause the star to lose mass asymmetrically by radiation or by loss of atmosphere. The lost mass carries off momentum and the reacting forces add both angular momentum and kinetic energy to the massive components; the mechanism being analogous to that of a skyrocket or a pin wheel. When the excess mass lost from the hot face of the components amounts to roughly one five thousandth of the total mass, the added kinetic energy is sufficient to account for the evolution of any type of binary system and for the remarkable differences noted by Sears in his study of the kinetic energies of various types of stars. The relation of such a mechanism to Novae and Cepheid variables is considered. The introduction of reacting forces due to the asymmetrical loss of momentum removes the serious objections that heretofore faces the fission theory and it now seems probable that almost all stars have become rotationally unstable and divided sometime during their life. The magnitude of the radiation reaction forces makes it seem probable that many companion stars have been separated to infinity and that our sun is one star of such a pair. This conclusion has led to a new and more satisfactory theory of the origin of the solar system.

OBSERVATIONAL astronomy shows that at least one star out of four has associated with it a companion star of comparable mass. The chance of capture of one star by another seems far too small to account for the prevalence of star pairs and it seems necessary to assume that the pairs occur either as a result of condensation on two independent nuclei or that they originate by fission. The fission theory, developed by Poincaré, Darwin, Russell and others, suggests that a star becomes unstable as a result of rapid axial rotation and eventually breaks up into two components of nearly equal mass. The theory together with tidal evolution accounts fairly well in its present form for the occurrence and evolution of close binary systems but seems entirely inadequate to account for the visual pairs. While the detailed calculations of the stability of a rapidly rotating liquid star by Darwin yield considerable information regarding the mass ratios of the components, the figures of equilibrium, etc., they fail to describe the process of fission because during this most interesting interval the equilibrium is essentially unstable and events proceed cataclysmally. The qualitative picture presented by the fission theory seems, however, essentially correct.[1] In the present paper we draw attention to certain additional physical processes which take place immediately after fission and show that the presence of these processes will enable us to account for the observed properties of all types of binary star systems.

The fission theory requires that a parent star shall rotate so rapidly on its axis that it becomes unstable. It was originally thought that this rapid rotation resulted from the original angular momentum of the parent nebula and that condensation of a star was sufficient to account for its presence. Moulton[2] has objected to this interpretation and shown that such a hypothesis leads to an improbably large ratio for the initial and final densities. His contention is further supported by Jeans[3] who has shown that a rotating and evolving star radiates angular momentum as well as mass. In a recent paper[4] we showed that the contraction hypothesis was not a necessary one and that sufficient angular momentum could be added to a star in the course of stellar time by purely electromagnetic means to make the star rotationally unstable. Another objection closely related to the foregoing has been raised by Chamberlin[5] who suggested that a rapidly spinning star will lose its atmosphere at the equator and that the lost particles will carry off angular momentum in such a manner as to stabilize it. This objection need no longer be considered, for these stars are observed not to lose their atmospheres[1] and we have shown that their retention is due to the presence of the star's magnetic field.[4]

A very serious limitation of the fission theory was discussed by Jeans[3] who showed that unless the mass ratio of the two components was less than three-tenths, the angular momentum of the critical Jacobian ellipsoidal configuration of the parent star was insufficient to separate the two resulting components to regions where they could be in stable equilibrium. That is to say, if the mass ratio of the two components is near unity (as is indicated by both observation and Darwin's calculations) each component will be inside the Roche limit of the other and hence it will disintegrate as a result of tidal and centrifugal forces. Such disintegration is not observed, and we are required to believe either that binary star systems are born with a low mass ratio and by unequal radiation of mass evolve into pairs of nearly equal mass, or that the fission theory is incomplete. Many actual cases are known, however, in which the mass ratios do approach unity, yet those systems must be so youthful that loss of mass by radiation could not be important. For this class of star pairs as well as for visual binaries the fission theory, in its present form at least, is inadequate.

Jeans[3] has already worked out the effect of radiation of mass on the orbits of the components and shown that a spectroscopic binary cannot well evolve

[1] H. N. Russell, Astrophys. J. **31,** 185 (1910).

[2] F. R. Moulton, Tidal and Other Problems, Carnegie Inst. Publication **107,** 79 (1909).

[3] Jeans, Astronomy and Cosmogony, Cambridge Press (1928).

[4] R. Gunn, Phys. Rev. **37,** 1129 (1931); **37,** 1573 (1931); **38,** 1052 (1931).

[5] Chamberlin, Carnegie Inst. Pub. **107,** 169 (1909).

into a visual pair by this simple means. Jeans' treatment has been criticised by Brown[6] who gave a substitute derivation yielding a different answer. Jeans[7] defended his treatment, and his result is in agreement with that obtained by the present author who employed the principle of adiabatic invariance in a modified form. The principle of adiabatic invariance, one of the fundamental principles of modern physics, seems well founded on observation and was developed to handle just the type of problem presented by the changing orbit of two stars which constantly radiate mass. The principle states that the mean value of the action integrated over a complete period is invariant. This form of the principle is incorrect if the mass varies, and in the degenerate case it is easy to see that the kinetic energy of a particle moving in a straight line and whose mass is changing cannot be conserved unless external forces act. A form of the principle, broader in application than the usual one and directly applicable to our problem, is

$$\int_0^T \frac{E_{\mathrm{kin}}}{M}\, dt = \text{constant} \qquad (1)$$

where E_{kin} is the kinetic energy of the system and M the mass function; and the integration is carried out over a complete period T. It does not appear necessary to carry out the complete calculation of our problem here for it leads directly to Jeans' result. The eccentricity of the orbits are unchanged as the masses dissolve into radiation, the major axis increases, varying as $(M+M)^{-1}$ and the period of the orbit increases, varying as $(M+M)^{-2}$. Thus, radiation of mass cannot help account for the observed differences in the orbits of binary stars and we must continue our search for other important mechanisms.

In case a star is gaseous instead of liquid it might appear that its expansion during the process of division would add considerable mechanical energy to the component stars and perhaps permit the stars to recede to positions of stability outside the Roche limit. By Poincaré's theorem the change in the internal thermal energies can be estimated, and it turns out that the energy converted is but a fraction of the original kinetic energy and is thus inadequate to account for the major observed discrepancies.

In light of the foregoing theoretical difficulties and available observational data it seems necessary either to abandon the fission theory entirely or to complete it by adding a physical mechanism capable of adding enough momentum and energy to the star to account for the observed mass ratio and orbits. In the following paragraphs a new mechanism is considered which seems quite adequate and is perhaps not unreasonable.

Relation of Rotational Evolution to a Star's Magnetic Field

We have seen in a series of earlier papers that most dwarf stars probably possess magnetic and electric fields and that these fields accounted well for many puzzling characteristics and properties of stellar atmospheres. It has

[6] E. W. Brown, Proc. Nat. Acad. **11**, 274 (1925).
[7] J. Jeans, Monthly Notices **85**, 904 (1924).

been shown that these fields impose systematic high velocity electromagnetic winds on the ions making up the stars atmosphere and that these winds transfer angular momentum to the star proper.[4] The calculations indicate that in the course of stellar time the angular momentum so communicated is ample to make the star rotationally unstable and it can break up. However, if the star could lose its atmosphere at the equator in the manner contemplated by Laplace in his nebular hypotheses, momentum would be lost at the equator as fast as it could be supplied, and the star could never quite accumulate angular momentum enough actually to divide. In a magnetized star this loss at the equator is never important because the magnetic field entraps the atmospheric ions[4] and to all intents and purposes the star behaves much as if it were liquid. Darwin's calculations therefore apply, in a degree at least, to a wholly gaseous star, but only if that star possesses a magnetic field. Thus a star's magnetic field is of paramount importance in bringing that star into such a condition that it can divide and form two companion stars. Because there is no clear-cut evidence that the interior of a star is other than effectively liquid, in the following we continue this usual assumption.

Tidal Effects

With the exception, perhaps, of tidal disintegration inside the Roche limit, the most important effect of tides on a rotating and evolving body is their ability to develop a torque about the axis of spin. These tidal couples play a major role in the transfer of angular momentum of axial rotation to that of orbital revolution in a recently divided star.

The magnitude of the angular acceleration due to tidal couples is readily evaluated if the two bodies are not too close. For example, Jeffries[8] shows that a uniform spinning sphere of density ρ_e, radius a and mass m changes its angular velocity Ω at a rate given by

$$-\frac{d\Omega}{dt} = \frac{18\pi\gamma\rho_e}{5}\left(\frac{M}{m}\right)^2\left(\frac{a}{R}\right)^6 \sin 2\delta \tag{2}$$

where M is the mass of the tide generating body, R the separation of the two bodies, γ the gravitational constant and δ the angle of phase lag due to tides. Strictly the expression applies only to well separated bodies but calculations show that it applies roughly, even when the bodies are close, if the coefficient is modified somewhat and if $1/R^6$ is replaced by $R^2/(R^2-a^2)^4$. Thus when R becomes comparable to a the tides and tidal couples become tremendous. Unfortunately the angle δ cannot be estimated precisely by known methods; but it evidently increases in an unknown manner with increasing ratio of the relaxation time of the body to the tidal period. It is readily shown that the relaxation time is given very approximately by

$$\tau = \left(\frac{3\pi}{2\gamma\rho_e}\right)^{1/2} = 0.325\tau_c \tag{3}$$

[8] Harold Jeffreys. The Earth, Cambridge Press.

and is thus comparable to τ_c the period of rotation of the body when it is ready to break up rotationally. In the case of the earth $\tau = 3000$ seconds and is small compared to the period of the earth's rotation. Thus in agreement with observation, the angle δ due to body deformation by the moon is very small. If, however, the period of rotation of the body should approach its critically unstable period the angle δ becomes quite large and tidal couples become large.

Two component stars immediately after fission are oriented in the manner shown in Fig. 1 and because they are each inside the other's Roche limit the tidal forces are tremendous. Precise calculations of the tidal couples are difficult, but the periods of rotation of the two component stars are initially close to their unstable value so that δ will be moderately large and rough

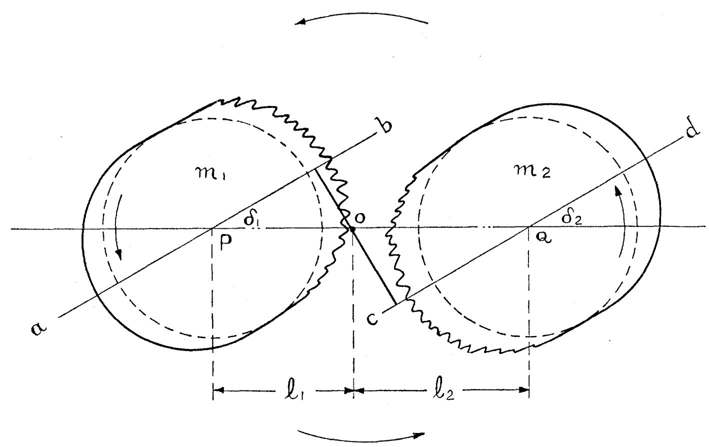

Fig. 1.

calculations show that *if the angle δ amounts to as much as a few degrees, the tidal couples are sufficient to cause the two components to separate to the Roche limit at least; with their internal faces always oriented nearly as shown.* Thus if the two components are of comparable size the process of fission is essentially a stabilizing mechanism. Tidal couples convert the axial rotation almost completely into orbital revolution and therefore there is no immediate tendency for the components to break up again. Electromagnetic mechanisms are probably operative in the components and these add angular momentum until, if the star is energetic enough, it breaks up again some 10^{12} years later. While the axial momentum is being transferred to momentum of revolution the value of δ is necessarily positive but after the transfer is complete it may change sign and even become periodic; however, by this time the initial evolution will be complete and we are no longer concerned with the mechanism.

Reaction Effects Due to Temperature Asymmetry

According to Darwin's calculations a rotationally unstable liquid star breaks up into two sections of substantially equal mass. The parent star is radially symmetrical but the components must necessarily be unsymmetrical, for the hemisphere of each component, born from deep inside the parent star will be at a far higher mean temperature than the hemisphere born from the surface layers. The asymmetry is especially pronounced at the surface for one face of a component star is hardly disturbed by the cataclysm while the other, orginally deep in the interior of the parent star, suddenly becomes the surface. That the initial surface temperature of the inner face must be very high follows at once from the fact that the act of fission is cataclysmic. Thus the change is adiabatic and it seems legitimate to assume in our calculations that the initial temperatures of the inner faces are at an appreciable fraction of the original central temperature of the parent star. Obviously these surface temperatures are not maintained for long because radiation carries off the energy very rapidly as soon as the hot face is exposed to free space. On the other hand, a comparatively small fractional drop in the surface temperature of a hot face will set up large internal temperature gradients and energy will be rapidly transmitted to the surface either by radiation or by conduction. If the temperatures are unexpectedly high the process could, perhaps, be more accurately described by saying that the exposure of the hot face will give rise to a "radiation explosion" which is dynamically equivalent to the comparatively slow processes we use in the following calculations.

The asymmetrical loss of matter by radiation or by gaseous ions produces a reacting force on the star proper, and the reacting momentum is precisely equal and opposite to that carried away by radiation or by the lost atmosphere. Thus a recently divided component star with one face much hotter than the other behaves in a manner analogous to a skyrocket, and if there are two stars rotating about their center of mass and if the angle δ (see Fig. 1) is different from zero, the pair behaves like a pinwheel. When the hot face is at a sufficiently high temperature the mechanism has a profound and immediate effect on the orbit of the pair and may even operate to separate them to infinity. If the thermal asymmetry is not particularly pronounced the phenomena, of course, proceed at a slower rate but in the course of stellar time the asymmetrical loss of mass may greatly modify the original orbit.

A dividing star may lose momentum asymmetrically by the loss of its atmosphere. This loss will take place instantly when the thermal energy of the particles approaches that of the negative gravitational energy of the particle. The critical temperature corresponding to this condition is given by

$$T_c = \frac{2\gamma M m_1}{3kR} \tag{4}$$

where γ is the gravitational constant, M the mass of the star, R its radius, k the Boltzmann constant and m_1 the mass of the atmospheric particle. We have seen in an earlier paper that a star ordinarily does not lose its atmosphere because the star's magnetic field entraps the ions. Whether this mechanism is still operative in a star that has just divided cannot be stated, for one can only guess what actually happens to the magnetic field of a star on division. Experiments on superconductivity suggest that the magnetic field may be maintained while other evidence[9] indicates that the magnetic field may be greatly reduced. Because of the high energies of the ions their curvature by a magnetic field is less than that at the surface of an ordinary star and it seems quite reasonable to expect a slight loss of atmosphere to result even if the star is magnetized. In Fig. 1 we assume that the lost ions on the average leave the stars in the direction Qc and Pb which are axes of thermal symmetry. If ΔM_i is the total loss of ponderable mass, u the mean thermal velocity of escape, ΔV the change in velocity of the star proper and M the mass of the star, we will have by aid of the principle of the conservation of momentum that

$$-\frac{\Delta M_i}{M} = \frac{\Delta V}{fu} \tag{5}$$

where u may be calculated from the mean value of

$$u = (3kT/m_1)^{1/2} \tag{6}$$

and f is a numerical factor somewhat less than unity whose value depends on the mean direction of emission of the mass elements with respect to the axis of thermal symmetry.

Radiation Reaction Forces and Couples

Perhaps the most important effects arise from the asymmetrical loss of mass by radiation. A star will lose radiation as long as it is a star irrespective of any local condition, such as a magnetic field, and a deep seated thermal asymmetry guarantees that the loss of mass by radiation will be asymmetrical whether the process is rapid or slow.

Momentum considerations lead immediately to

$$-\frac{\Delta M_r}{M} = \frac{\Delta V}{fc} \tag{7}$$

where c is the velocity of light. The relation is perhaps more useful in its differential form

$$\frac{dM}{dt} = \frac{-Ma}{fc} \tag{8}$$

where a is the reaction acceleration of the mass M. Now the rate at which the energy E is radiated is

$$\frac{dE}{dt} = c^2\frac{dM}{dt} = \sigma A T^4 \tag{9}$$

so that Eq. (8) can be written

$$Ma = \frac{fA\sigma T^4}{c} = F \tag{10}$$

where F is the reacting force on the star, A the effective radiating area, σ the constant in Stefan's law, and T the effective surface temperature.

[9] R. Gunn, Phys. Rev. **34**, 335, 1621 (1929).

In the case of a star pair we may write down entirely simi'ar expressions for the angu'ar momentum $\boldsymbol{M}$ and torque $\boldsymbol{T}$. If the two stars of the pair are separated by a distance l_1+l_2 and the distance from the center of gravity of each star to the center of the gravity of the system is l_1 and l_2 respectively, (see Fig. 1) we have that

$$\frac{d\boldsymbol{M}}{dt} = \boldsymbol{T} = \frac{\sigma}{c}[f_1A_1T_1^4l_1 \sin \delta_1 + f_2A_2T_2^4l_2 \sin \delta_2] \tag{11}$$

and the final total angular momentum of the system is

$$\boldsymbol{M} = \boldsymbol{M}_0 + \int_0^\infty \frac{d\boldsymbol{M}}{dt}\, dt \tag{12}$$

where $\boldsymbol{M}_o$ is the initial angular momentum. This quantity can be evaluated precisely when l, T and δ are specified as functions of the time. We can make estimates of the magnitudes of the forces and torques acting with sufficient precision to test the ideas here proposed if we assume that the quantities are constant over a relatively short period of time.

Very little really satisfactory information is available regarding the internal temperatures of stars and the estimates of the central temperature vary from 10^{11} degrees down to 4×10^7 degrees. The freshly exposed surface that has just emerged from the depths of the parent star may reasonably be assumed to be at a temperature of 4×10^7 degrees; it could well be much higher or even lower. We assume further that the component stars in size, mass and structure are not unlike the sun. The radiation from the cool side may be neglected in comparison to the hot face and we calculate the acceleration of the star by aid of Eq. (10) taking $T=4\times10^7$ degrees, $\sigma=5.71\times10^{-5}$, $A=1.5\times10^{22}cm^2$, $f=0.63$ and $M=2\times10^{33}$. We find that the acceleration of the component star amounts to 232 cm/sec.^{2} and represents an unbalanced acceleration since the original centrifugal and gravitational forces are precisely balanced. Even if the star were initially at rest such an acceleration would displace it a distance of 9×10^{11} cm or more than 10 solar radii in the course of a single day. The increase in angular momentum will also necessarily be large and the net result of the asymmetrical radiation process will be a cataclysmal increase in the kinetic energy of the system and its angular momentum.

Even if our estimate of the surface temperatures has been much too high the mechanism is still effective and the evolution instead of being cataclysmic for the most part will be slow and persist throughout the life of the star. A star radiates an appreciable fraction of its mass in some 10^{12} years and it is clear that an initial deep seated thermal asymmetry of the star will guarantee that a small excess fraction of the total radiated mass will eventually be radiated from the hot side, even if the temperature differences between the hot and warm faces are relatively small. The internal temperatures are eventually equalized by radiation and conduction but this process will require some 10^8 years for the asymmetry to be reduced by half and at the same time the surface constantly cools off by radiation. For these reasons and evidence that the interior of a star is effectively liquid we believe that the evolution of a binary pair is largely cataclymic, but this is not a necessary conclusion. It is interesting to contemplate what would happen to a Milne model star if it broke up. The internal temperatures of this model approach 10^{11} degrees and most of the internal mass is in the form of radiation. If one side of such a star was exposed to free space for a short time only, an appreciable fraction of the total mass of the star would certainly be lost and the reacting star, by Eq. (10), would shortly be shooting off through space at a velocity comparable to that of light! This, of course, is not observed and we must conclude that these stars do not break up by fission, do not have such excessively high temperatures or that the radiation from the surface so cools it that the radiation is almost immediately reduced to small values. Our calculations indicate that the asymmetrical loss of mass in a typical star seldom exceeds 1/10 percent of the total mass so that it is clear that powerful equilizing mechanisms are brought into play immediately after the star parts. If for some special reason a star breaks up so that the axis of symmetry of the reacting forces does not pass through the center of mass of the star the mechanism may produce axial rotation and destroy the organized kinetic energy and momentum imparted to the system. We neglect this relatively improbable type of asymmetry in the present discussion.

Stellar Equipartition of Energy

In a classical paper, Sears[10] has compiled statistical data on the masses and mean velocities of various classes of stars. His study shows that the mean kinetic energy for most types of stars is surprisingly close to a constant. However, the B type stars, many of which abundant evidence show to be well on the way to rotational instability, are notably deficient in energy of motion and on the average have only one-half the mean kinetic energy of other type stars.

The considerations of the foregoing paragraphs suggest that the type B stars are actually deficient, but the process of breakup releases energy by means of the reaction forces that we have considered and the mean kinetic energy of the resulting pair (which presumably evolves with great rapidity into a star of a later class) is actually greater than the original configuration.

The kinetic energy W added to a star by radiation reaction forces by aid of Eq. (7) is

$$W = \Delta M_r \left[fcV_0 + \frac{f^2c^2}{2} \frac{\Delta M_r}{M} \right] \tag{13}$$

where V_0 is the initial velocity of the star. By using Sear's numerical data it is found that the required kinetic energy will be added to a typical star if the star loses one five thousandth (0.02 percent) of its mass by radiation from one face. This amount of energy is evidently ample to change a close binary system to an open visual system or if the initial velocity has a moderate value, the parabolic velocity is exceeded and the component stars are separated to infinity.

[10] Sears, Astrophys. J. 55, 165 (1922).

Our interpretation of Sear's statistical data suggests that the *O* and *B* type stars are the youthful members of our Universe and that the evolution toward the cooler types proceeds along both the main series and the giant branch. The matter deserves a closer inspection than can be given at the present time.

Orbital Development

It should be evident from the foregoing calculations that the radiation reaction forces must play an important part in the evolution of the orbits of a binary pair that originated by fission. In the absence of the foregoing mechanisms a star on division would form simply a very close spectroscopic binary of very low eccentricity, and if the mass ratios approached unity they probably would disintegrate.

The fundamental equation describing the relative orbit of a binary system is

$$1 - \epsilon^2 = \frac{-\,2Eh^2}{\gamma^2(M + m)Mm} \tag{14}$$

where ϵ is the eccentricity of the relative orbit, M and m the masses of the two components, h the areal velocity, and E the energy of the system defined by

$$E = \frac{-\,\gamma Mm}{2a_1} \tag{15}$$

in which a_1 is the semi-major axis. Logarithmic differentiation of Eq. (14) yields

$$\frac{1}{1 - \epsilon^2}\,\frac{d(1 - \epsilon^2)}{dt} = \frac{2}{h}\,\frac{dh}{dt} + \frac{1}{E}\,\frac{dE}{dt}\,. \tag{16}$$

The radiation reaction forces necessarily add kinetic energy to the system and thus by Eq. (16), the eccentricity of the orbit increases. An increase in the areal velocity h, on the other hand, which corresponds to the normal tidal angle δ, decreases the eccentricity. Thus, it appears that almost any shape or size of orbit can result from this process, for the relative values of the angular momentum and energy added by the mechanism will evidently depend on the magnitude of the angle δ and on the relation of the instantaneous surface temperatures to the instantaneous positions of the component stars. Evidently either close or visual pairs can result from one and the same mechanism. Moreover, if the surface temperatures actually approach the values assumed it seems not only possible, but quite probable, that certain pairs born of an energetic parent will be completely separated and spend the remainder of their life as isolated stars.

Curtailed Evolution and Cepheid Variables

In the foregoing we have assumed that the radiation or the atmosphere thrown off by the star receded to infinity. It seems probable that certain stars will break up and have such a surface temperature that an atmospheric atom will have sufficient energy to get well away from the parent star but not enough to remove it to infinity, and the atom will describe gravitational orbits about the pair of stars. Thus under some conditions we might expect a recently formed pair to be surrounded by a close fitting veil or high density nebula. The presence of the veil which may be thought of as completely surrounding the binary pair, acts in a degree at least, as an absorber and reradiator of the radiant energy inside. Thus radiant energy from the hot surface no longer completely lost but a certain large fraction of it is returned and the radiation reaction forces are curtailed. Such a system will evolve into a true binary very slowly, the two components gradually separating while the pair rotates hot face to hot face with an outside protecting veil.

Such a rotating close pair may be thought of as a Cepheid Variable according to Jeans[3] who has shown that such systems fit in well with the mechanical properties of Cepheids. Jeans has apparently failed to note, however, that a surrounding radiating veil, light pressure and gravitational forces will account for the shape and phase relations of the luminosity-velocity curve, and will also account for the hitherto puzzling fact that the velocities of recession and approach are different for different elements. Reflection will show that the close binary pair at the center and the gravitational rotation of the veil will give rise to a rotation and a superposed radial pulsation having a period of one-half that of the close pair. An atom in the veil, if it were at rest, would be exposed to the hot faces of the pair twice a revolution and at such times would be blown outward by radiation pressure, the maximum outward velocity corresponding closely (but slightly later) to the maximum density of radiation. On the removal of the high temperature radiation the particles fall inward under gravity. The return of the particles under gravitational forces can be thought of as a relatively slower process than the outward blast due to radiation pressure. Since the outward motion is dependent on radiation pressure the velocity of different elements would be expected to differ. Qualitatively this type of star is almost equivalent to Shapley's pulsating model except that a definite mechanism is provided to account for the regular variation of the radiated energy.

Novae

The division of an energetic star exposes high temperature surfaces with a consequent loss of radiation and momentum. Such a cataclysm will certainly produce observable effects of the type we usually associate with Novae. Several Novae have increased in intensity 40,000 times, indicating that their surface temperatures must have increased tremendously, for, be it remembered, all radiation shorter than about 2900A is absorbed by our atmosphere and the maximum radiation for even 50,000 degrees falls in the extreme ultraviolet at 580A. Thus an observed increase in radiation by a factor of 40,000 certainly corresponds to a much larger true increase in radiation.

In spite of the comparatively small amount of light received from a Novae by an observer at the bottom of the atmosphere, the star might conceivably deliver sufficient radiation to the high atmosphere in the extreme ultraviolet and soft x-ray region to ionize highly the earth's high atmosphere. The possibility that such a mechanism might produce effects on radio transmission or cause a magnetic storm has been examined by determining the correlation between magnetic storms of relatively long duration and the appearance of Novae. The correlation is no better (nor worse) than the agreement of magnetic storms with other supposedly related physical quantities and no definite conclusion can be drawn from available data.

Remarks

The addition of a mechanism which is capable of adding angular momentum and kinetic energy to a newly born binary components removes several of the most fundamental objections to the fission theory. The reaction forces readily account for the observed differences in the orbits of binary stars, wide pairs with moderate eccentricities being as readily produced as close pairs with zero eccentricity. Moreover, the restriction as to mass ratio is now removed, and Darwin's calculations for liquid stars apply, in a degree at least to actual stars which are probably largely gaseous. The requirement of an initial surface temperature approximating 10^7 degrees is by no means necessary for lower temperatures result only in a slowing up of the evolutionary process. A systematic asymmetric loss of mass amounting only to a few hundredths of a percent of the total mass is all that is required to account for the evolution of any type of binary system and such a loss not only seems possible but quite probable.

No attempt has been made to follow the variation of the orbit in great detail because the evolution depends, in an important manner, on the tidal angle δ and the manner in which this quantity changes with the separation of the components cannot now be calculated.

Close examination may show that radiation reaction forces are important in the evolution of spiral nebula, particularly if the arms of these systems are formed by any sort of a fission process.

Perhaps the most important result of our calculations, however, is the probability that certain very energetic parent stars will endow their offspring with sufficient energy by the process described to separate completely the two companions. Thus our own sun may well have had a companion star which was lost sometime immediately after the parent sun divided. This conclusion has a very important bearing on the origin of the solar system, for it has led to a consistent fission theory of the origin of the solar system. This matter will form the subject of a subsequent paper.