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DYING STARS - NEUTRON STARS, BLACK HOLES, ETC.

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GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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It is nearly forty years ago that the existence of mysterious objects called neutron stars were first predicted by Landau, Oppenheimer, Volkoff and others. The study of these objects was somewhat neglected during World War II, and even when this problem was taken up again after the war the result was rather pessimistic that it is almost impossible to prove the existence of such stellar objects through observations even though it is quite possible that neutron stars exist according to theoretical physics of today.

However, as already reported in Shizen (May, 1969) by Dr. Morimoto, it has been concluded recently that the strange objects emitting pulsed radio waves, pulsars, which stirred up the interest of not only specialists but laymen as well, are indeed neutron stars which until then existed only in the minds of some theoreticians. Furthermore, it was proposed that neutron stars might be responsible for some other phenomena also, such as the strange behavior of the recently discovered new X-ray source (by Prof. Oda - Shizen, January, 1970), and it seems that suddenly more people have become interested in neutron stars. Therefore, in this paper we wish to try to explain such stellar objects mainly from the standpoint of "the fate of a star."

1. The Fate of a Star

It is generally believed today that, as it happens to a man, a star also is born, grows up and finally dies. In this country (Japan), the problem of stellar evolution has been studied mainly by Prof. Hayashi's group in Kyoto. It is difficult to explain in a simple way the fate of a star, for it is generally different in different cases (depending especially on the initial mass and composition of individual stars). But roughly speaking, the life of a typical star may be summarized as follows.

First interstellar matter condenses due to gravitational forces and gradually takes the form of a star. When the internal pressure due to the condensation reaches a certain point, equilibrium is achieved by the balance between gravity and internal pressure. However, heat is lost through radiation from the surface, and to make up for the lost energy the star keeps contracting. In this case, a half of the gravitational energy gained through contractions is lost from the surface and the other half is used to heat the interior.

In order for a star hundreds or thousands of light years away to shine on the earth for a period of time so long that it would seem like forever to us, it is clear that tremendous amounts of energy would have to be continuously supplied to the star for the same period of time. (One light year is the distance light travels in a year and is about 10^{18} cm.) But from where do they come? This is a problem which troubled astronomers for a long time. It was beyond any hope to try to explain it by such familiar energy sources as thermal reactions and chemical reactions. Even gravitational energy, the most powerful candidate of all, could not explain it, for a star can keep shining by its gravitational energy for only several million years, while a typical star lasts for more than several billion years. However, this problem was solved through the progress in nuclear physics. That is, when contractions of a star reach a certain point, the interior temperature becomes high enough to start a thermonuclear reaction in which hydrogen, a star's main composition, is converted to helium, and the accompanying release of large amounts of energy is sufficient to stop further contractions. Therefore, once this stage is reached, a star keeps shining as a stable star as long as the nuclear fuel, hydrogen, lasts near the center, for the energy balance is achieved by the nuclear energy. This is the longest period in a star's life, and most stars including the sun belong to this middle age group. It is about several billion years for stars of about a solar mass, but it is shorter for more massive stars. A star which is about 30 times heavier than the sun dies in several million years or so. There are still uncertainties yet as to what happens exactly when hydrogen in the central core is almost exhausted. But roughly it is considered as follows.

Generally in the case of massive stars, contractions due to gravity start again, and with the accompanying rise in temperatures, heavier elements are synthesized through thermonuclear reactions, while the hydrogen-helium conversion and other reactions involving lighter elements move to the outer layers with lower temperatures. This period is very short, and it generally takes a violent form such as a supernova explosion. Several possibilities are considered as the fate thereafter. The central core will collapse while the outer shell will explode away, the explosion will be strong enough to blow away the whole star, or the scale of the explosion is too small or the gravity is too large to eject the outer shell and nearly the whole star will collapse, and so forth. As to the collapsing core, it may settle down as a stable neutron star, or it may keep collapsing indefinitely and disappear as a black hole. Which of these possible fates will be waiting for a star depends on the mass, composition, temperature, rotational speed, etc., at the time of the explosion, but for the details we have to wait for future work.

Less massive stars will gradually age without following such violent courses even though thermonuclear reactions involving the conversion of helium to heavier elements may proceed to a certain degree, and finally they will silently wait for death as a stable white dwarf. This is due to degeneracy, the property which will be explained in the next section. As it will be explained later, the critical mass which determines which of these courses a star will follow is about 1.4 times the solar mass. Recently it was also proposed that a star near this critical mass will explode away as a whole, or lose the outer layers and settle down as a less massive white dwarf or a neutron star.

2. Properties of Dense Matter

As it is clear from the above descriptions, a star gets denser and hotter through the process of aging, which in turn accelerates the loss of stellar energy through neutrino emission and others. In this way a star near the end quickly becomes a relatively cold dense star. In a hot star, thermal pressure of gases and radiation pressure are the main forces to counterbalance gravitational forces in stellar interiors. In a cold, dense star, this balance with gravity is achieved by "degenerate pressure." "Degeneracy" is a unique property of particles called fermions, such as electrons, nucleons (protons and neutrons), hyperons, etc., when they are compressed. It is due to the "Pauli exclusion principle," according to which "more than two fermions of the same kind cannot occupy the same quantum energy level." Thus, even though fermions move freely in rarefied and hot gases, they start occupying the energy levels two at a time from the lowest as they become denser and colder. This is like a law which prevents a "pusher" to push more people into a train indefinitely, and it resists limitless compression of matter made of fermions of one kind. A gas in this state is called a "degenerate gas," and if we try to compress such a gas further the resistance (or the degenerate pressure) becomes enormous, and it will eventually cause transformations to other particles.

When we compress matter, first molecules decompose into atoms, then atoms decompose into nuclei and electrons, but when the density gets higher electrons are eventually absorbed in nuclei. A nucleus consists of protons and neutrons, but the absorbed electrons combine with protons to produce neutrons within a nucleus. Thus with increasing densities, more and more neutron-rich nuclei are produced, but finally when the density reaches a certain point nuclei cannot hold more neutrons and disintegrate into free neutrons and protons. With further increase in densities even free protons absorb electrons and become neutrons, and thus very quickly the main composition of matter becomes neutrons. All through these processes, the total number of protons and electrons including those both inside and outside nuclei are kept equal, and thus the matter as a whole is electrically neutral. With still further compression neutrons are converted to hyperons. This is due to the property that "matter is most stable when its total energy is minimum." With increasing densities, fermi energy of a neutron (the value of the top of the energy levels) increases, and when it becomes the rest mass of a hyperon (= mc^2, the minimum energy of a particle), a neutron-hyperon transformation takes place because it is more stable to exist as a low energy hyperon than as a high energy neutron.

In this manner, the kind of the particles which support gravity by their degenerate pressure is different at different densities. Exactly at what density the degenerate pressure is large enough to stop further stellar contractions, of course, depends on the amount of the applied gravitational forces. In general, less massive stars have less gravity, and when the stellar mass is up to about 1.4 $M_{\odot}$ ($M_{\odot}$ is a solar mass = 1.985×10^{33} gm.), the stellar contractions can be stopped before the density reaches the stage where electrons start being absorbed by nuclei. This is because the degenerate pressure of electrons is sufficient to support the given gravity. The central density of stars at this point is from about 10^4 to 10^9 gm/cm^3, and these stars correspond to white dwarfs. In more massive stars, the resistance by a degenerate electron gas is too small to counterbalance the given gravity, and stellar contractions continue while electrons are absorbed in nuclei, but when the main composition becomes neutrons, the pressure by a degenerate neutron gas can stop the gravitational contractions in certain cases. When this happens, the central density is from about 10^{14} to 10^{16} gm/cm^3, and such stars are called neutron stars. If the main composition is hyperons when contractions stop, such stars may be called hyperon stars. In the following section, we wish to explain these things more quantitatively.

3. Neutron Stars and White Dwarfs

For an assembly of matter to continue its existence as a star, various stability conditions must be satisfied. These restrictions generally determine the values of characteristic stellar parameters, such as mass and radius, which a stable star can take. The most importa.it of these fundamental equations deals with the balance of forces between gravity and pressure within stellar interiors. To solve these equations we need the equation of state which give the relation among pressure, temperature and density. To solve the equation of state the compositions in internal layers must be known. It was already mentioned briefly that the equilibrium composition of matter changes with density changes. We wish to describe this point more quantitatively below.

If we accept the theory that a neutron star is a remnant of a supernova explosion, quite high temperatures should be reached at the moment of the explosion (see the next section), and it can be assumed that the composition of a neutron star is the same as the composition of the central collapsing core for it should cool off very fast. Then the equilibrium composition at such high temperatures is as follows. If the density of the matter is less than or about 10^6 gm/cm ^{3}, the main composition is the ordinary iron group nuclei. For higher densities they are replaced by more neutron-rich heavy ions. The disintegration of these heavy nuclei into neutrons and protons begins to take place a little beyond 10^{11} gm/cm^3. When the density becomes about ten times higher than this value, the main composition becomes neutrons. Before the density becomes 10^{14} gm/cm^3 all heavy ions disappear but a few percentages in numbers of protons and electrons still remain. When the density is further increased, μ mesons and hyperons appear, but exactly where we do not know because of the uncertainties in the nature of strong interactions between these particles. If basically the same forces apply between hyperons as between nucleons, it seems that hyperons start to appear somewhere around $10^{14} \sim 10^{15}$ gm/cm^3, but it seems that it is not until the density becomes more than ten times higher than these values that hyperons become as abundant as neutrons.

For those who try to construct neutron star models, the greatest difficulty is the question of what happens when the distance between hyperons and nucleons becomes shorter than the size of these particles. This problem becomes very serious when the density exceeds about 10^{15} gm/cm^3. In fact, it is almost impossible to know the property of matter at such ultrahigh densities through elementary particle physics of today. In this sense also a miraculous breakthrough in this field is highly desirable.

On the other hand, due to the recent progress in nuclear physics, it is quite possible to predict what happens for densities up to about 10^{15} gm/cm^3 by using existing experimental data. The results of such calculations are summarized below. It was assumed that interaction forces between hyperons are basically similar to those between nucleons.

Figure 1 shows the relation between the central density and mass of dense stars. Density is in units of gm/cm^3 and mass is in units of a solar mass, $M_\odot$. In this figure we see major branches which ascend from left to right, one with central densities below about 10^9 gm/cm^3 and two with central densities of 10^{14} - 10^{16} gm/cm^3. The first represents white dwarfs and the last two represent neutron stars. That is, stars with a set of central density and mass values lying on these portions of the curves can theoretically exist. The branches which ascend from right to left (the major one found in the region of 10^9 to 10^{14} gm/cm^3) represent unstable models. (That is, a star with a set of central density and mass values lying on these portions of the curves cannot stay as it is, because even if it is formed it keeps expanding or keeps contracting with even minor perturbations in either direction.) The models V_β and V_γ represent two possible nuclear forces. It may be noted that there is a maximum mass a stable dense star can have. In this figure it is shown to be about 1 to 2 $M_\odot$ for neutron stars and about 1.2 $M_\odot$ for white dwarfs. The composition used in this figure is the equilibrium composition as described above, which is mainly heavy ions in white dwarf regions. The maximum mass of white dwarf stars is about

1.4 $M_\odot$ if they consist of lighter elements. In the absence of nuclear forces, the maximum mass of neutron stars is about 0.7 $M_\odot$. It may be noted that neutron stars have a minimum mass also which is about 0.1 $M_\odot$ where the central density is about 10^{14} gm/cm^3.

In Figure 2 the mass-radius relation is shown. White dwarfs lie on the branch marked (I) and neutron stars lie on the branches marked (III). According to this, the radius of white dwarfs is about several thousand km on the average, and the radius of neutron stars is around 5 to 20 km. In this figure the region between (I) and (III) represents unstable models.

In Figure 3 the internal distribution of matter is shown. For typical neutron stars with the density of about 10^{15} to 10^{16} gm/cm^3 (the models $V_\beta(2)$ and $V_\gamma(2)$), the internal density is practically constant. However, for lighter neutron stars (the models $V_\beta(1)$ and $V_\gamma(1)$), a star generally consists of the central core of mostly neutrons and the outer thick envelope of heavy ions, and the density is no longer constant. This outer envelope of heavy ions becomes negligibly thin as the central density of a star increases. The models $V_\beta(3)$ and $V_\gamma(3)$ show that, once the point of neutron star maximum mass is reached, further increase in central density fails to make the star denser as a whole due to the central singularity. Here again, the models V_β and V_γ represent two possible nuclear forces.

It was found that not only density but also temperature is practically constant in neutron star interiors. Thus, sharp decrease of density and temperature is expected within a very thin layer near the surface. The thickness of this layer is only about a meter or so for a neutron star of about 1 $M_\odot$ and 10 km. It is thicker at higher temperatures, but the above statement is valid when the surface temperature is from about 10^5 to 10^7 °K. The difference between the internal temperature and the surface temperature is also small for neutron stars. If the surface temperature is about 10^5 °K the internal temperature is only about 10 to 100 times the surface temperature. (For ordinary stars this ratio is about several thousands.)

The conclusion is that a neutron star is a strange star, with the density of about $10^{14} \sim 10^{16}$ gm/cm^3, mass of about 0.1 to 1 $\sim$ 2 $M_\odot$, and radius of about 5 to 20 km.

It may be argued that we should call these stars "hyperon stars" for hyperons are expected in these density regions. However, it seems that neutrons continue to be most abundant (even after the appearance of hyperons) until the density reaches about 10^{16} gm/cm^3, and even after that neutrons remain at least about 20 percent in abundance. Thus, it seems that we are justified to conveniently call all stars in the density region of about 10^{14} to 10^{16} gm/cm^3 "neutron stars." According to calculations done so far, the various properties described above are not seriously affected whether hyperons are included or not. In this sense it may be said that the effect of hyperons on neutron stars is small. However, it was recently reported that radial vibrations of neutron stars die out very quickly if hyperons are taken into account in calculations.

4. Gigantic Stellar Explosions, Gravitational Collapse, and Black Holes

As mentioned earlier, when hydrogen in the central region is nearly exhausted, a massive star begins to contract again rapidly. With the accompanying rise of temperatures up to several billion degrees, the synthesis of elements up to those in the iron group proceeds quickly. At this point, due to the iron-helium conversion (or the ever-increasing emission of neutrinos), sudden implosion of the central core occurs. The accompanying release of enormous amounts of gravitational energy results in the heating of the outer layers also up to about several billion degrees, triggering simultaneous thermonuclear reactions of various kinds in the outer envelopes where various nuclear fuels still remain. Any atomic or nuclear bombs a man can produce are nothing compared with the gigantic nuclear explosion produced in this manner. For a moment such an explosion is accompanied by surges of gravitational waves, neutrinos, cosmic rays, X-rays, etc. The expanding outer shells shine brilliantly for months, and even after thousands of years they decorate our night sky as a beautiful nebula. This is a very crude description of a supernova explosion. A phenomenon like this is expected at the rate of about once in 300 years per galaxy. (There is also a theory that it should be about once in several decades or so. I. S. Shklovsky: Cosmic Radio Waves, 1960.) The supernova which was reported in Japan and China in 1054 A.D. is a typical example, and we can see the beautiful remnant as the Crab Nebula even today, more than 900 years after the incident. In fact, it has already expanded into the wide region of several light years, but it is still very active, emitting strong X-rays, radio waves, etc., shining brightly, enjoying the gratitude of astronomers by offering various valuable data. (There are some other models of a supernova explosion, but the above is a typical example.)

What is the fate of the collapsing central core? If its mass is less than the maximum mass limit of neutron stars ($1 \sim 2\ M_{\odot}$ in the above calculations), the collapse will be halted when the density reaches about $10^{14} \sim 10^{16}$ gm/cm^3, and it will spend the rest of its life as a stable neutron star. However, if the mass is above this critical value, it is considered that it will now submit itself under the power of gravity and disappear into the central singularity. This phenomenon is called "gravitational collapse" and its grave (where it disappears) is called a "black hole."

In order to understand black holes, we have to depend on Einstein's theory of general relativity, not Newtonian mechanics, for we have to deal with strong gravitational forces. It was about thirty years ago that the problem of gravitational collapse was studied first by the Oppenheimer group. It was interrupted by wars and other things for a while, but the studies of this subject revived when quasi-stellar sources were discovered in the beginning of the 1960's. We want to summarize the result of these studies as simply as possible. At this point we wish to give the special acknowledgment that, for the description of this topic which follows below, we especially owe to the article in <u>A Science</u>

Year Report, 1968, p. 70, (Field Enterprise Educational Corp.) by Prof. K. S. Thorne of Caltech. Figures 4 and 5 were borrowed from that article, but figure captions and some other minor points have been changed to suit the present article.

According to Einstein's theory, a massive star (or central core) which collapses beyond the neutron star region will be absorbed in a hole called a black hole in an instant and keep contracting indefinitely. Light, man, rocket, or anything, which approaches this hole, will be absorbed into the hole and collapse by the enormous pull of gravity. The size of this hole as seen from the outside is about 3 km in radius if it is caused by the gravitational collaspe of a star of a solar mass. However, if it is due to the gravitational collapse of a quasar a billion times heavier than the sun, the circumference of the hole will be 0.002 light years. The radius of this hole as seen from the outside is called the "gravitational radius."

It will be impossible to see a star which has collapsed into this hole from the outside, for no light ever escapes from this hole. However, it may be possible to see a collapsing star. A star which contracts rapidly at first will appear to do so more slowly as it approaches the gravitational radius, stops when it shrinks to the size of the hole, and then quickly becomes black and disappears. Thus, this hole is called a black hole.

Why does it look like this from the outside, even though in fact the star collapses in a moment? This can be explained by the stretching of space in gravitational fields. As the gravitational radius is approached, rays of light bend more due to the stretching of space (Figure 4). Thus it takes longer for light to reach our eyes and the collapse appears to slow down as it approaches this hole. When the star has collapsed to the size of the gravitational radius, light from this star will turn 100 percent back due to this curvature of space, and thus it will never reach us. That is why the star looks black at this point. (See Figure 5.)

It was mentioned that anything which is absorbed into the hole shrinks indefinitely, but this is according to Einstein's theory of general relativity, which fails for densities beyond about 10^{79} times the density of a neutron star. Nobody knows what happens after that. However, the diameter at this point, if it is the collapsing of a star of a solar mass, is said to be one-millionth the diameter of a nucleus, so we may wonder if it can be said that the star has almost collapsed already. However, this is the result of calculations for a spherical collapse. For a non-spherical collapse, it is reported that the collapse into a black hole occurs but the singularity can be avoided. However, in this case it is said that the star cannot remain where it disappeared but it will pop out in some other universe. If we want to prove this strange theory, we should share the fate with the star and jump into the black hole. It was also proposed recently that there should be a black hole which is a remnant of an old quasar at the core of many galaxies.

It may be added that neutron stars and hyperon stars are somewhat larger than their black hole, with radius not less than about 1.6 times the gravitational radius.

5. On the Detectability of Dying Stars

Among the stars of the latest stages discussed so far, white dwarfs were already discovered by optical telescopes. They also have the longest life and their properties have been studied most (among these objects). Sirius B is a typical example.

Neutron stars are considered to cool down very fast, first by neutrino emission until the interior temperature becomes about 10^8 °K and thereafter by radiation from the surface. For the neutron star models given in section 3, it was found[*1] that it takes about one hour for least massive stars and about ten years for massive stars before the surface temperature becomes about 10^7 °K, it takes from about 10^4 to 10^6 years to cool down to about 10^6 °K, and it takes from several million years to ten times longer to cool down to about $10^4 \sim 10^5$ °K. If the radiation from the surface of a neutron star is approximated by a blackbody radiation, soft X-rays are expected when the surface temperature is about 10^6 °K, and visible light is expected when the surface is about 10^4 °K. When the surface temperature is about a million degrees, the luminosity of a

[*1] The effects of possible superfluidity and superconductivity in the interior and of strong magnetic fields both inside and on the surface of neutron stars were not included in these calculations. These effects are likely to change seriously the cooling times of neutron stars given in this paper, but we have to wait for future work to find these values.

neutron star is as strong as that of the sun, but it becomes less than one-millionth the solar luminosity when the surface has cooled down to emit visible light. That is, it is impossible to see a neutron star directly by an optical telescope if it lies outside of the solar system. At least theoretically, it seems possible to observe a neutron star by soft X-rays, and thus it was suggested for a while that X-ray stars might be neutron stars. However, the observed spectra of X-ray stars were inconsistent with those of blackbody radiation. Moreover, if a neutron star possesses strong magnetic fields, it will cool faster and even the X-ray observations become doubtful. It was also suggested that if π mesons exist in a neutron star it will cool down to about 10^5 °K within a few years. Thus, the prospect of observing neutron stars seemed to have become as remote as ever, and finally a distinguished physicist even offered to bet on the impossibility of discovering neutron stars. Then, most unexpectedly came the discovery of pulsars.

Details of pulsars, including the reason for why they must be neutron stars, have been already reported in this journal (Shizen) elsewhere. Therefore, only a most sketchy summary will be given below. It was when pulsars of very short period, 33 milliseconds and 89 milliseconds, were discovered that the hypothesis of "pulsars = neutron stars" began to be taken seriously, for it is impossible to produce such fast pulses (yet of such stable and precise period) by any tricks of a white dwarf star which was the only other feasible candidate. It is hard to explain the observed accuracy of pulsar periods except by motions in celestial mechanics. If we try to explain it by orbital motions of a binary system involving neutron stars, the result of observations becomes inconsistent with the theory of general relativity. Radial pulsations of a neutron star also fail in the sense that they cannot explain the typical pulsar period of about one second. On the other hand, the rotation hypothesis (that a pulsar is a rotating neutron star) is gaining more support as more observational data accumulate.

If a pulsar is a rotating neutron star, its period can take any value longer than about a millisecond, and the wide range of pulsar periods discovered so far, from 33 milliseconds to about 3.7 seconds, find a natural explanation. The gradual increase of periods detected for some pulsars also agree with the rotation hypothesis. If we assume that the increase of a pulsar period is due to the slowing down of the rotation of a neutron star, the rate of loss of the rotational energy of a neutron star calculated for the faster pulsar in the Crab Nebula (NP 0532) is numerically consistent with the total rate of energy dissipation by all electromagnetic waves, radio, visible, X-ray, etc., emitted from the nebula as a whole. Only two pulsars were found at the site of supernova explosions reported in the past, but this is quite understandable if we assume that pulsar sources rotate with a neutron star and that we can detect pulsars only when the emitted rays, like search light beams, enter the field of our view. So far slow pulsars were found in the place where we see nothing else. We can consider that these are old neutron stars which are remnants of supernova explosions occurred in pre-historic ages, and that the outer envelopes have already disappeared. There is no universally accepted theory yet which explains the cause of the beaming (the search light mechanism) to produce pulsed emissions, but it is most likely that the strong magnetic fields (expected to be as high as about 10^{12} gauss on the surface) are responsible for this.[*2] Figure 6 shows some of the models proposed so far. In the Crab Nebula which is playing a unique role in the problem of pulsars also, almost simultaneous pulsed emission of the same period was discovered for the faster pulsar (NP 0532) in the visible, infrared and X-ray regions as well. Other pulsars discovered so far are all in radio waves only. According to the rotation hypothesis, this is considered to be because the Crab pulsar is the youngest and the X-ray and light pulses become weaker at faster rates.

Black holes seem even more mysterious than neutron stars. To detect these objects, we can think about catching in some way the gravitational waves or neutrinos at the time of the gravitational collapse, or making use of the strong gravitational fields left behind. As an example of the latter, we can think of using the motion of the companion star if one of a binary system is a black hole. However, the above argument is valid if this is a neutron star instead of a black hole, and how can we distinguish one from the other?[*3] When it comes to practical problems, this and other difficulties are facing us. For nearly ten

[*2]Recently most quantitative work along this line has been done by Dr. Chiu's group.

[*3]In this connection, "the evidence for a collapsar in the binary system Epsilon Aurigae," recently reported by Prof. A. G. W. Cameron, is very interesting.

years Weber's group in the U. S. has concentrated their effort on the attempts to catch gravitational waves. Recently they reported in the APS annual meetings at Chicago that strong gravitational waves were detected in the direction of the center of our Galaxy. (New York Times, January 29, 1970). This report stirred up the interest of specialists, for this may be related to the hypothesis that there is a black hole in the central core of galaxies.

There were those who proposed that this has nothing to do with black holes and that this is due to phenomena which are beyond the knowledge of the present physical laws. However, let us think about the case of neutron stars. Even though it was thought to be impossible to observe neutron stars by the residual thermal energy of the fast cooling stars, it was in fact proposed in pre-pulsar days that rotational or vibrational energy as the residue of stellar explosions might be the energy source of the Crab Nebula and X-ray stars. But they could not go beyond speculations until the discovery of pulsars, for we had no means to prove or disprove these theories until then. Due to the unexpected device the Nature prepared in the form of pulsars, neutron stars, which were supposed to be dead, came out suddenly like ghosts. In recent conversations someone said that if you look at a glass half filled with water and say with a frown, "Only half filled," you are a pessimist, and that if you say with a smile, "Already half filled," you are an optimist. Which will you choose? We heard that Prof. Whipple, the Director of the Smithsonian Observatory, was asked ten years ago to bet on the prediction that men will go to the moon by 1970. He won, of course.

When we realize that it is the physics of particles and fields which hold one of the major keys to various problems of neutron stars and pulsars, will it be a mere daydream of a naive amateur, if one turns the problem around and hopes to get any hint from pulsar observations for the break-through in particle physics and other related fields?

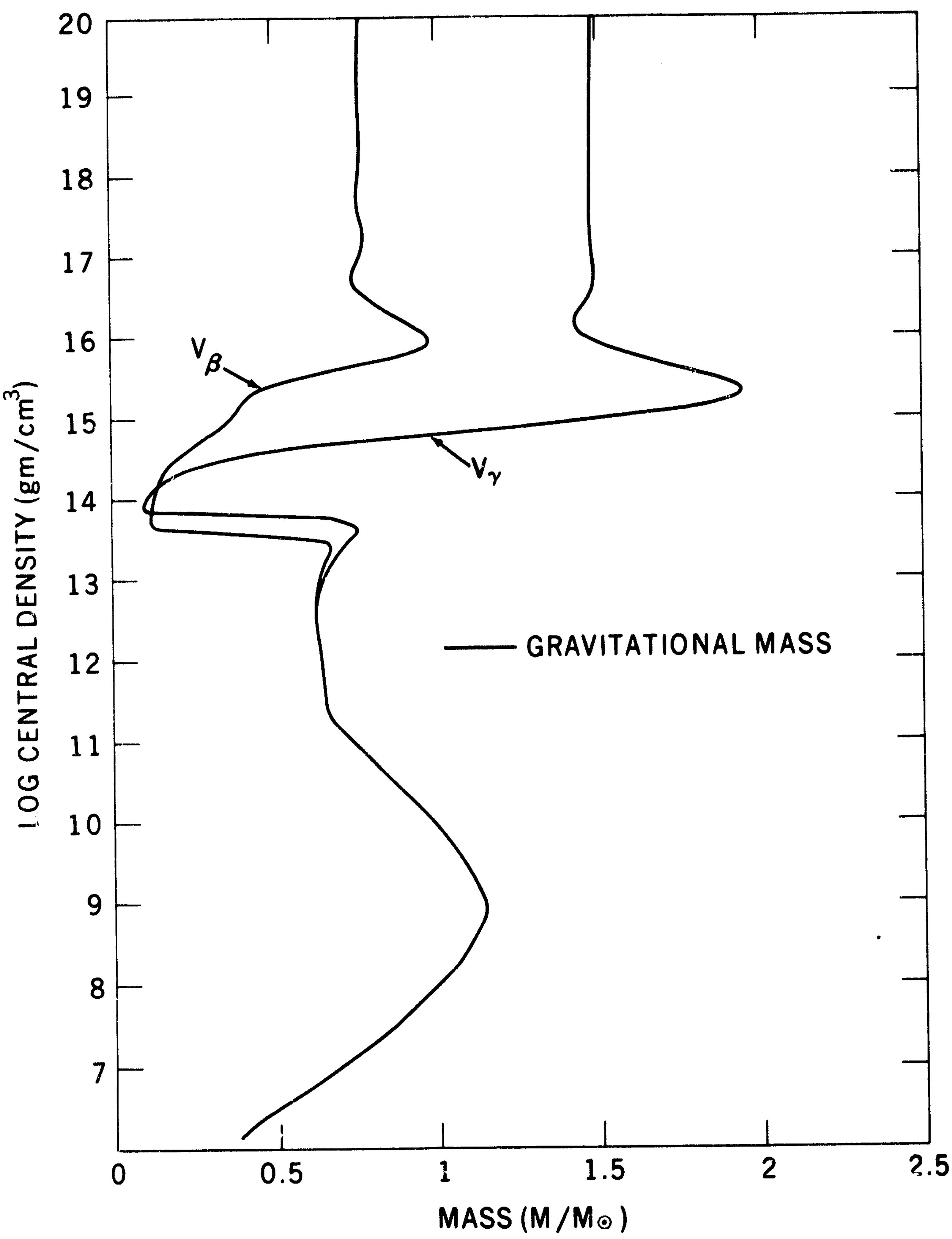

Figure 1. The central density-mass relation for dense stars. Different nuclear potentials are used for the V_β models and V_γ models.

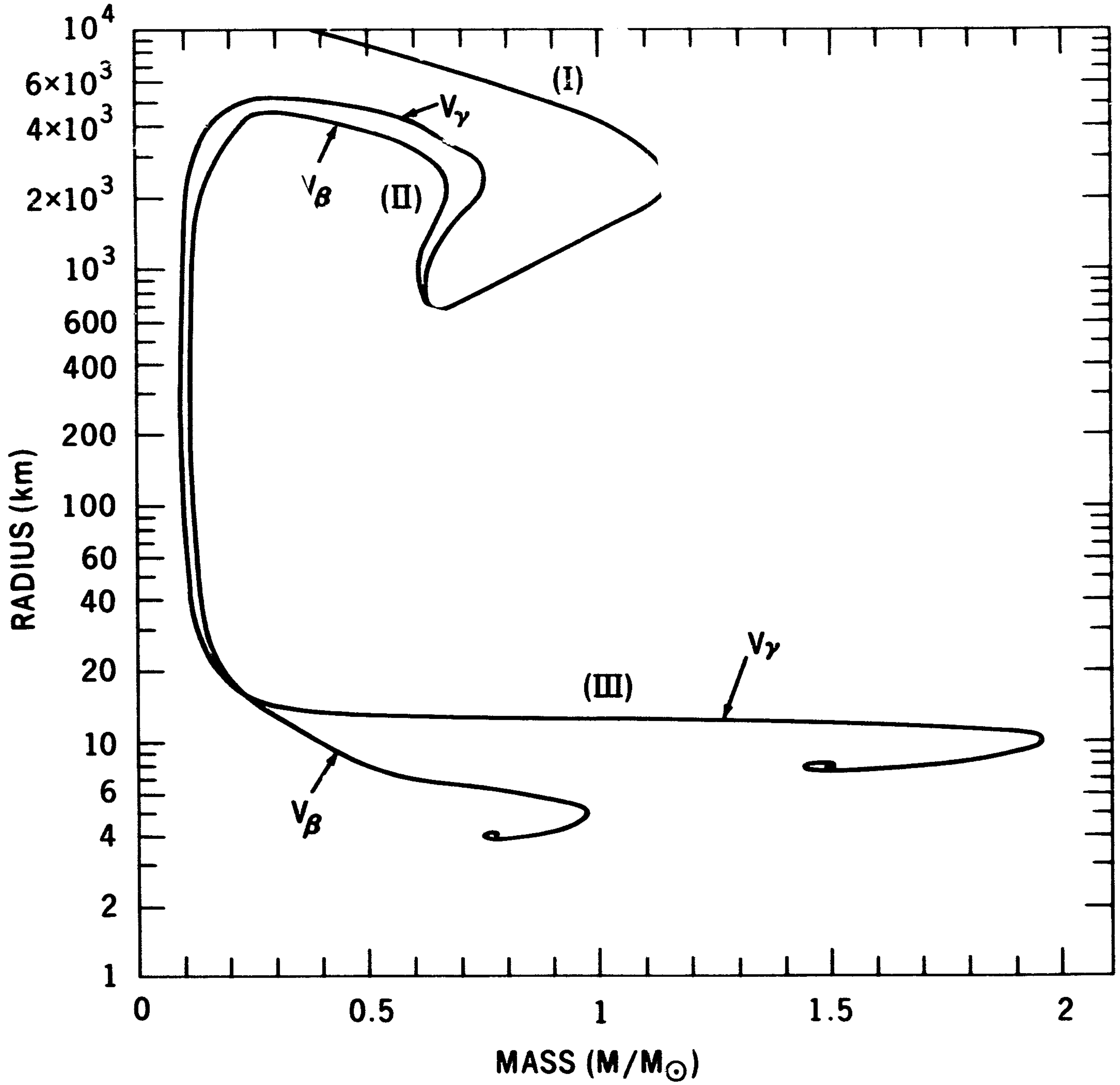

Figure 2. The radius-mass relation for dense stars.

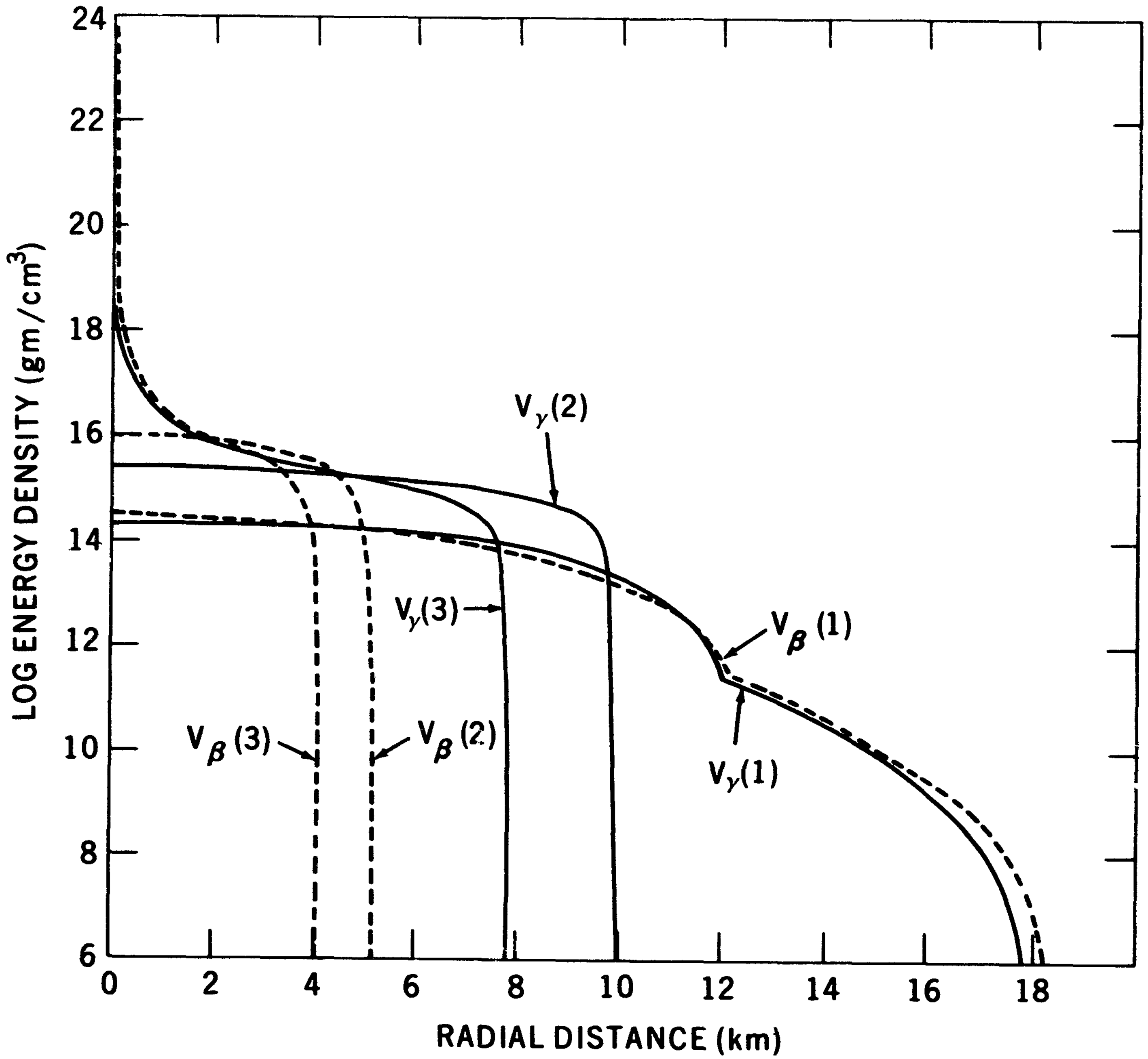

Figure 3. Density distributions in dense stars.

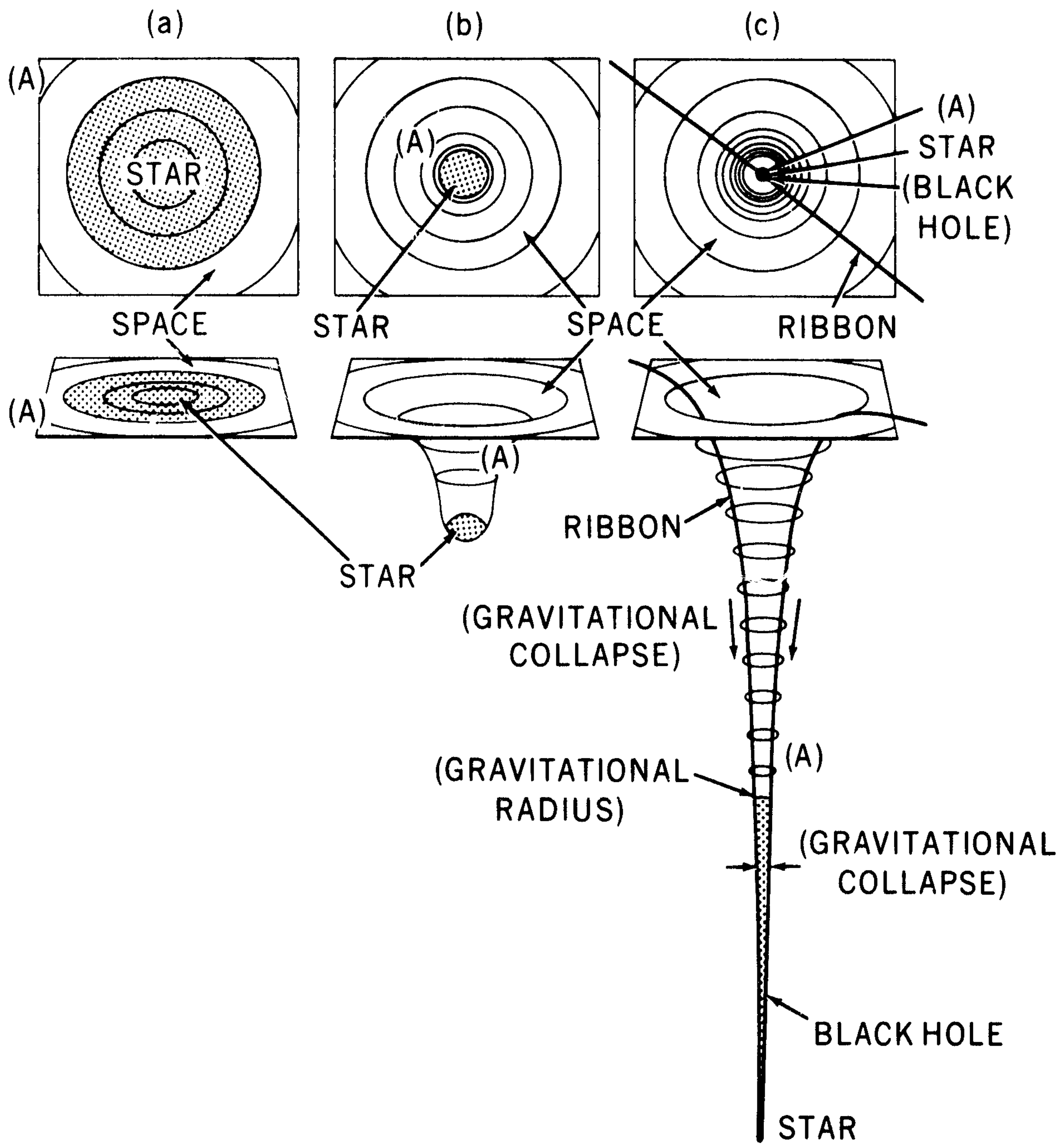

Figure 4. Gravitational collapse and the stretching of space. Shows how space swallows a star. Top row shows gravitational collapse as seen from the outside. Bottom row shows the stretching of space. (a) An ordinary star (the dark circle) and the surrounding space (marked by (A)), shown in two-dimensional space for simplicity. (The circle is actually a sphere.) Space is flat. (b) With increasing density of the star, the surrounding space (shown as (A)) stretches, together with the star. The curvature of of space is the largest at the center where gravitational fields are strongest. Due to the stretching of space, this simplified two-dimensional space appears three dimensional. (c) Shows a star collapsing under gravity. The collapse proceeds in the direction shown by the arrows. The surrounding space (A) stretches further. The ribbon in the bottom row shows that the distance to the star becomes longer as the gravitational radius is approached.

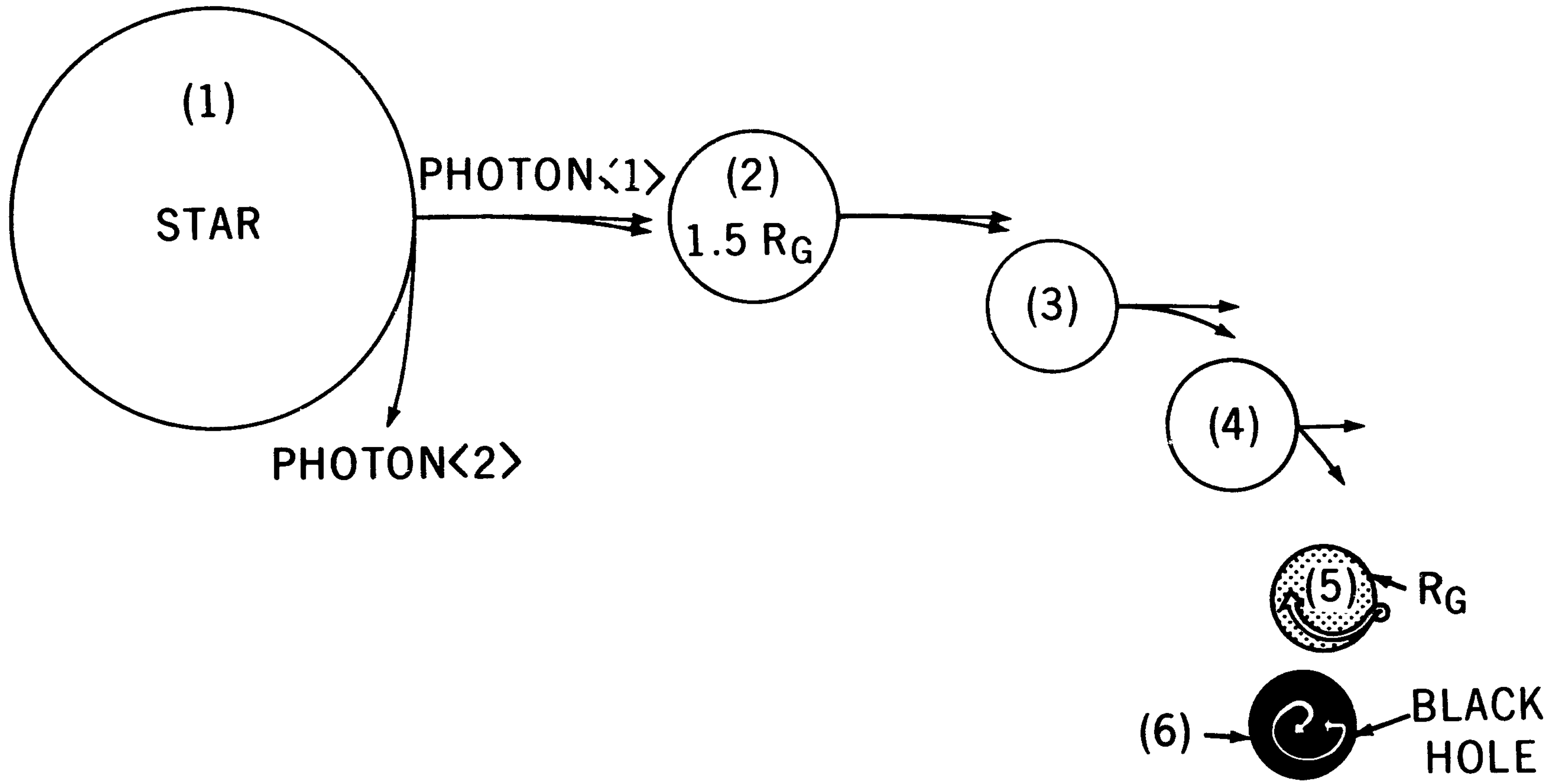

Figure 5. Shows why a star disappears under strong gravity. The birth of a black hole. As it proceeds from (1) to (6), a star becomes denser and gravity increases. At the stage (2) where the stellar radius is 1.5 R_G (where R_G is the gravitational radius), light emitted parallel to the surface (photon < 2 >) is absorbed by the star due to the curvature of space. As we proceed from (3) to (4), gravitational fields become stronger and even light emitted perpendicular (photon < 1 >) bends enormously, and it takes longer to reach us. Once inside the black hole, light emitted in any direction falls inward and is trapped (6).

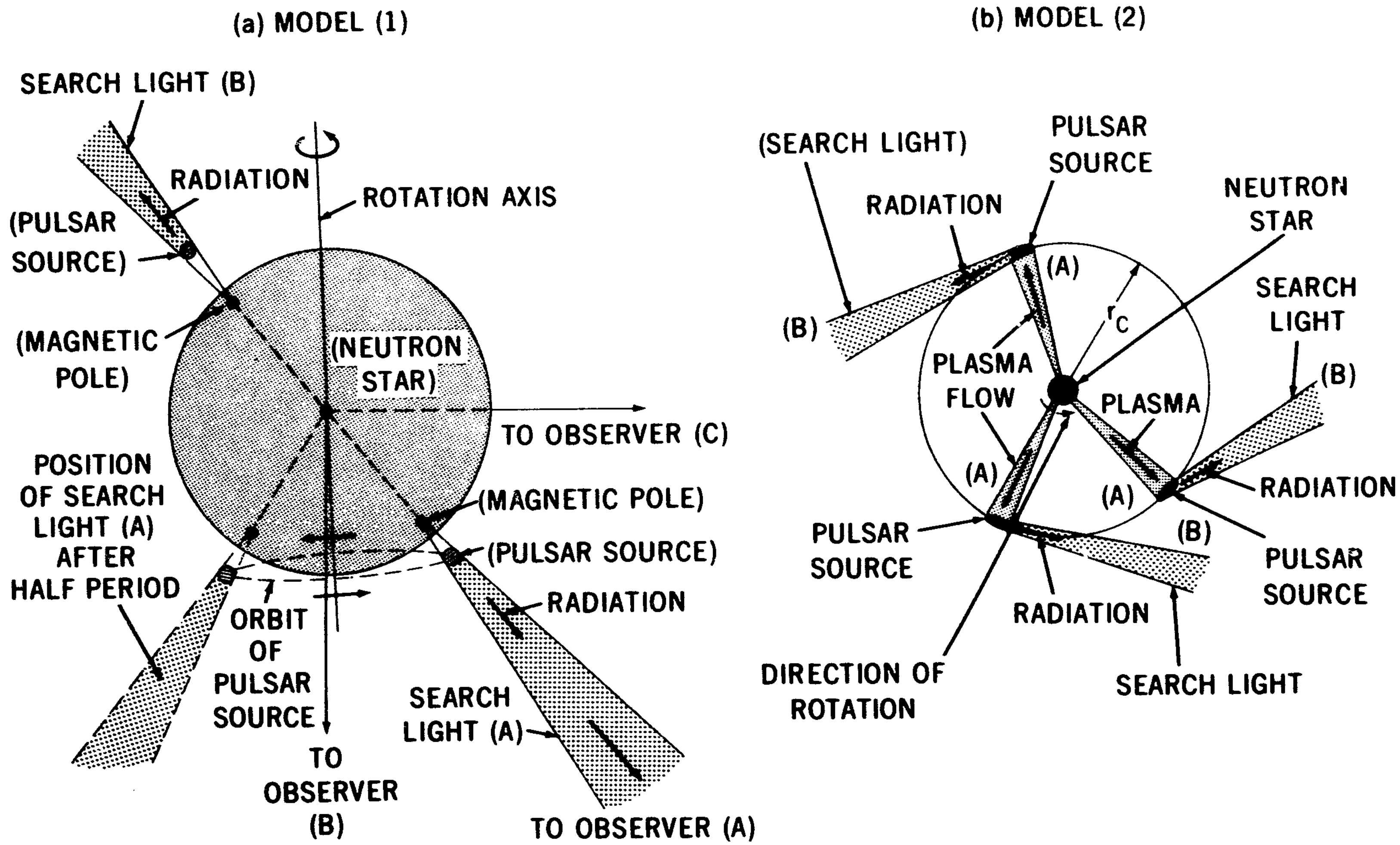

Figure 6. Pulsar models. Model (1): Radiation emitted radially from some regions near both magnetic poles, due to some complex mechanisms of plasma in strong magnetic fields. The search light produced in this way rotates with the star, which is observed as a pulsar when it enters the field of view (observer (A)). This pulsar will not be detected by observers (B) and (C). Model (2): Due to some mechanisms (like sunspots of the sun), plasma flows radially from the neutron star in the center. The surrounding magnetosphere also rotates with the star due to the strong magnetic fields. When the plasma flow reaches the velocity of light circle where the velocity along the circumference is equal to the velocity of light (with radius r_c), the plasma emits electromagnetic waves parallel to the circumference, producing search light like (B) A pulsar is detected when the search light enters our field of view. Prof. Gold's original model.

FIGURE CAPTIONS

Figure 1. The central density-mass relation for dense stars. Different nuclear potentials are used for the V_β models and V_γ models.

Figure 2. The radius-mass relation for dense stars.

Figure 3. Density distributions in dense stars.

Figure 4. Gravitational collapse and the stretching of space. Shows how space swallows a star. Top row shows gravitational collapse as seen from the outside. Bottom row shows the stretching of space. (a) An ordinary star (the dark circle) and the surrounding space (marked by (A)), shown in two-dimensional space for simplicity. (The circle is actually a sphere.) Space is flat. (b) With increasing density of the star, the surrounding space (shown as (A)) stretches, together with the star. The curvature of space is the largest at the center where gravitational fields are strongest. Due to the stretching of space, this simplified two-dimensional space appears three dimentional. (c) Shows a star collapsing under gravity. The collapse proceeds in the direction shown by the arrows. The surrounding space (A) stretches further. The ribbon in the bottom row shows that the distance to the star becomes longer as the gravitational radius is approached.

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1.5 R_G (where R_G is the gravitational radius), light emitted parallel to the surface (photon $< 2 >$) is absorbed by the star due to the curvature of space. As we proceed from (3) to (4), gravitational fields become stronger and even light emitted perpendicular (photon $< 1 >$) bends enormously, and it takes longer to reach us. Once inside the black hole, light emitted in any direction falls inward and is trapped (6).

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