NOTES

ON COLLAPSED NEUTRON STARS

ABSTRACT

Some consequences are discussed of the hypothesis that certain stars and cores of stars are composed mainly of neutrons. On the assumption that supernovae represent rapid transitions of ordinary stars into neutron stars, the large red shifts observed in the spectra of the recent bright supernovae are interpreted as gravitational red shifts. The neutron-star hypothesis, in conjunction with the general theory of relativity, leads to a theory of critical stellar masses.

In view of the rapid advances made recently in the observation of supernovae, it seems appropriate to give here a brief summary of some conclusions of a series of theoretical investigations concerning the properties of highly collapsed neutron stars, which it is hoped may be ready for publication in the near future.

The neutron-star hypothesis was first introduced by Baade and myself[1] in an effort to account for the tremendous liberation of energy in supernovae. We suggested the existence of stars and cores of stars the average density of which is comparable with the density of matter ordinarily encountered only inside of atomic nuclei. With the designation "neutron star" we do not wish to imply, however, that such a star is to be regarded as a giant nucleus composed of separate neutrons of precisely the same character as free neutrons. We only suggest, that, in contradistinction to ordinary stellar matter, in neutron stars already minute regions whose linear dimensions are larger than $\delta = e^2/m_e c^2 = 2.8 \times 10^{-13}$ cm are electrically neutral.

We here briefly describe some of the properties of neutron stars, as well as some new observations of supernovae which tend to support the neutron-star hypothesis.

a) Cold neutron stars, according to present knowledge, represent states of lowest energy that matter may assume without being completely transformed into radiation.

[1] W. Baade and F. Zwicky, *Proc. Nat. Acad. Sci.*, **20**, 259, 1934, and *Phys. Rev.* **45**, 138, 1934, and **46**, 67, 1934; F. Zwicky, *Scientific Monthly*, **40**, 461, 1935. More recently the neutron-star hypothesis has also been considered by G. Gamow, *Atomic Nuclei*, p. 234, Oxford, 1937; L. Landau, *Nature*, **141**, 334, 1938; and others.

b) According to the general theory of relativity, a *limiting mass* of stars exists for every given average density (Schwarzschild limit).[2] At this limit the energy liberated because of gravitational packing is

$$E = \left(1 - \frac{4}{3\pi}\right) Mc^2 = 0.58\, Mc^2 ,$$

where M is the proper mass of the star. For an average density $\rho = 10^{14}$ gm/cm^3 the limiting mass is $M_L = 6.4 \times 10^{34}$ gm. The derivation of these results which was obtained in discussion with Professor R. C. Tolman will be communicated in a joint paper with Professor Tolman.

A star which has reached the Schwarzschild limiting configuration must be regarded as an object between which and the rest of the universe practically no physical communication is possible. For instance, the velocity of light on such a star is infinitely small, so that it requires light from this star an infinitely long time to reach any external point. Also, the gravitational red shift is complete in the sense that light originating on the star arrives at any external point with the energy zero. It is, therefore, impossible to observe physical conditions in stellar bodies which have reached the Schwarzschild limit. It should, however, be possible to observe stellar bodies in stages intermediate between the ordinary configurations and the collapsed configurations of limiting mass just described, provided that such are accessible.

c) We may express the limiting mass M_L of collapsed neutron stars in terms of the universal gravitational constant

$$\Gamma = 6.66 \times 10^{-8}\ \text{gm}^{-1}\ \text{cm}^3\ \text{sec}^{-2} ,$$

the charge of the electron e and the masses m_e, m_p, and m_n of the electron, the proton, and the neutron, respectively. We obtain

$$M_L = aR^{3/2} m_n , \qquad (1)$$

where

$$R = \frac{e^2}{\Gamma m_p m_e} = 2.3 \times 10^{39} \qquad (2)$$

[2] See, e.g., R. C. Tolman, *Relativity, Thermodynamics and Cosmology*, p. 247, Oxford, 1934.

is the ratio of the electrical to the gravitational attraction between an electron and a proton and where α is a dimensionless number of the order 1. The number of neutrons in the mass M_L is $N = \alpha R^{3/2}$. According to an idea first discussed by H. Weyl,[3] the ratio R may play a role in the determination of large numbers, such as the total number of particles in the universe and the ratio between the "radius" of the universe and the radius of the proton. The fact that M_L is proportional to $R^{3/2}$ suggests possible observational tests of Weyl's idea, which will be discussed in another place.

d) If supernovae are transitions from ordinary stars into neutron stars, the observation of light-curves and spectra of supernovae should furnish us with direct evidence of the neutron-star hypothesis. For instance, the surface of the central star of a supernova should be exceedingly hot, the acceleration of gravity very high, and light coming from this surface should be subject to enormous gravitational red shifts. Now, it is a significant fact, first observed by Dr. R. Minkowski in the spectrum of the recent bright supernova in IC 4182, which was at its maximum brightness in August, 1937, that all of the permanent features of this spectrum have gradually shifted toward the red, until in June, 1938, a stage S was reached when this shift amounted to 100 angstroms.[4] On our hypothesis we may tentatively interpret this red shift as a gravitational red shift. Assuming that the central star has a mass $M_c = 2 \times 10^{33}$ gm, equal to that of the sun, the following characteristics for the central star in the stage S may be derived: radius $r = 74$ km; average density $\rho = 1.2 \times 10^{12}$ gm/cm^3. Since the supernova in the stage S was about one million times brighter than the sun, it follows that the effective surface temperature $T > 1.8 \times 10^7$ degrees absolute. For the limiting mass $M_L = 6.3 \times 10^{34}$ gm we obtain $r = 3700$ km, $\rho = 1.2 \times 10^9$ gm/cm^3, and $T > 3.1 \times 10^6$ degrees. The neutron-star hypothesis in conjunction with observations on supernovae may therefore lead to some new and far-reaching tests of the general

[3] H. Weyl, *Raum, Zeit, Materie*, 5th ed., p. 277, Springer, Berlin, 1923. See also *Naturwissenschaften*, **22**, 145, 1934.

[4] The spectra of the supernovae in NGC 1003 (1937) and NGC 4273 (1936) exhibit similar effects. I am indebted to Dr. Minkowski for the permission to make use here of these unpublished observational facts, which he will present in detail in a paper shortly to be published in this *Journal*.

theory of relativity. Also, the fascinating problem now presents itself of investigating how certain well-known physical processes, such as nuclear reactions, will be modified when they take place inside of highly collapsed stars in which the very properties of time and space are drastically altered.

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SPECTRAL TYPES AND RADIOMETRIC OBSERVATIONS OF STARS OF LARGE INFRARED INDEX

In a recent paper Hetzler[1] announced the discovery of a number of red stars with exceptionally large infrared indices, some of the values being as large as 10 mag. If one uses these indices as a basis for temperature determinations, on the assumption of black-body radiation, the large indices will yield temperatures of about 1000°. The objects of infrared magnitudes 4 to 6 having this temperature would be within easy reach of a vacuum thermocouple, the radiometric magnitudes being of the order of 0 to -2. For this reason it was considered worth while to study the stars radiometrically. At the same time a determination of their spectral types seemed desirable.

The radiometric measurements were made with a vacuum thermocouple[2] at the 24-inch reflector with a junction of bismuth against 95 per cent bismuth plus 5 per cent tin and with a highly sensitive galvanometer. Provisional results were obtained with the equipment not yet developed to its full sensitivity; at the time of the measurements a star of radiometric magnitude 3 gave a measurable deflection. The measurements consisted of a comparison of three of the more promising stars of large infrared index with α Orionis and α Tauri. The visual magnitudes of the chosen stars were 11.5, 12.5, and 14.0; the first two stars are included in Table 1. No deflection

[1] *Ap. J.*, **86**, 509, 1937.

[2] A more complete description of the radiometric equipment will be given later.