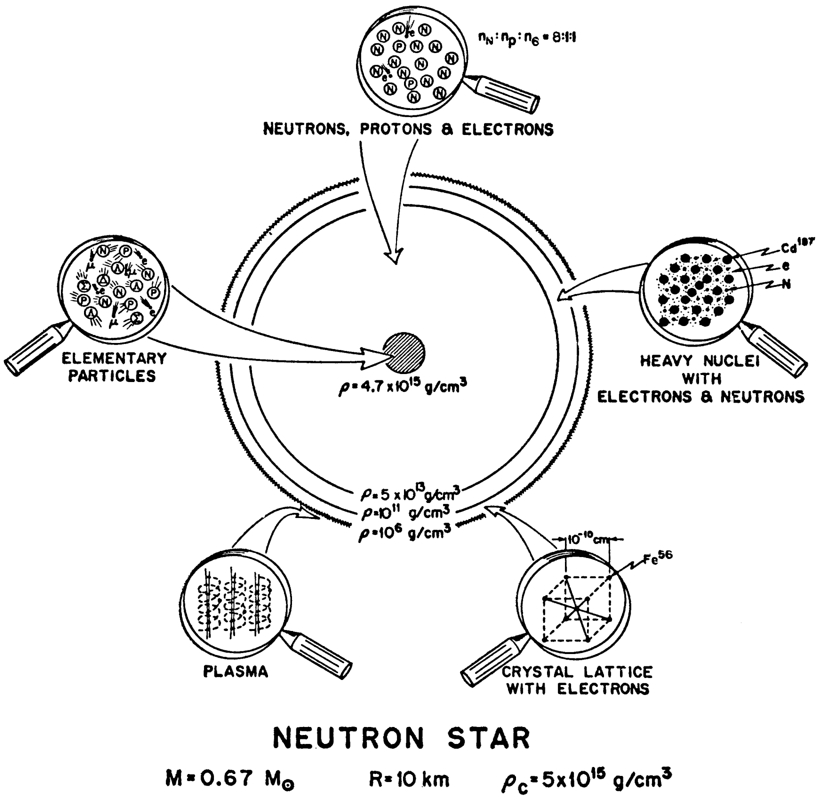
ASTROPHYSICS

Neutron stars vs. black holes

Can collapsing stars form enough neutron stars to account for the pulsars?



Rhoades and Ruffini

Anatomy of a neutron star: Each level is stranger than the one before.

by Dietrick E. Thomsen

After 30 years as an astrophysicists' hypothesis, neutron stars have become real. Or at least there is a good deal of evidence and argument that neutron stars are embodied in the pulsars that astronomers have been studying since 1968.

Because neutron stars may really be there, theorists have been working lately to provide a detailed theoretical description of a neutron star, one that will not only tell qualitatively what it looks like but also provide accurate enough numerical values so that it can be compared with observations. In this way the answers can be found to such questions as whether neutron stars can exist and whether pulsars can be neutron stars.

Clifford E. Rhoades Jr. of Princeton University and Dr. Remo Ruffini of the Institute for Advanced Study and Princeton University have surveyed the work they and others have done in this line. The picture of a neutron star that emerged was of a fairly complicated body. Their description and conclusions about the probable existence of neutron stars were presented at the meeting of the American Physical Society in New York this month.

Neutron stars are supposed to be the result of the collapse of ordinary stars. They are a sort of dead end to the chain of stellar evolution.

When a star burns out all its nuclear fuel, it loses its equilibrium. While the thermonuclear burning is going on, it generates motion and expansive forces that counterbalance the tendency of the star to collapse under the influence of its own gravitation. When the burning stops, collapse occurs in a complicated series of events that includes implosion at the center and explosion at the edges. This is the theorists' explanation of the events known to observers as supernovas.

The imploding core of the supernova can become either a neutron star or a black hole, a body in which gravitational collapse continues without stopping until the body has such a strong gravitational field that neither matter nor light can escape, and it is cut off from the rest of the universe (SN: 12/26/70, p. 480).

The questions to be answered are: Under what conditions will a supernova's gravitational collapse stop at the relatively stable neutron star instead of running away down a black hole, and, if those conditions can be met, do they yield a body that approximates the known data for pulsars?

One of the critical factors is the mass of the collapsing star. If the mass necessary to cause runaway collapse is more than 50 times the sun's mass, black holes should not form as a result of stellar evolution since stars are not usually that heavy. On the other hand, if the critical mass is much less than one solar mass, black holes should form almost exclusively. The 50-50 point is a critical mass of 1.5 solar masses, says Dr. Ruffini.

Another crucial consideration is the equation of state for a neutron star. An equation of state is a mathematical expression representing the total physical state of an object, a gas cloud for instance. It deals with such qualities as density, temperature, pressure and rigidity. As the Princeton researchers put it: "Give me an equation of state and a value for the central density and I will show you what a neutron star looks like."

An equation of state for neutron stars has in fact been worked out by Dr. Rolf Hagedorn of the CERN laboratory in Geneva, and Rhoades and Dr. Ruffini have set out to see whether its application changes the picture enough to make neutron stars impossible.

A typical neutron star, they say, is a body with a mass 0.6 to 0.7 that of the sun, a radius of 10 to 15 kilometers and a central density of about 10^{15} or 10^{16} grams per cubic centimeter. (These values coincide more or less with those inferred from observation of pulsars.) By contrast, the earth has a density of only 5.5 grams per cubic centimeter; the sun, only 1.4 grams per cubic centimeter.

Like Dante's Inferno, the neutron star has a succession of levels, each denser than the last. The outermost circle is a magnetosphere consisting of a tenuous plasma of ions and electrons bound to the star's magnetic field. This region is the origin of pulsar radio signals according to most theories.

. . . neutron stars

Under the magnetosphere is a region of supersolid. Here the matter of the star forms a crystal composed of nuclei with atomic numbers between 26 and 39 and atomic weights between 58 and 133 (SN: 6/27/70, p. 626).

After the density passes 10^{12} grams per cubic centimeter comes the third level, a collection of heavy nuclei that are exceedingly rich in neutrons, and are perhaps found nowhere else in nature.

The fourth circle comes at a density of 10^{14} grams per cubic centimeter. At this point the heavy nuclei begin to break apart because of so-called neutron drip; they have too many neutrons. The matter here can be regarded as a gas of neutrons, protons and electrons interacting by nuclear forces and according to the laws of nuclear physics. The whole region, Rhoades and Dr. Ruffini remark, can be regarded as a single giant nucleus containing approximately 10^{57} particles.

Finally, the fifth circle, the innermost core, is the domain of particle physics. Here the density is above 5×10^{15} grams per cubic centimeter. The kinetic energy of neutrons, protons and electrons is so high here that collisions among them continually create new particles. All the 1,432 known particles and resonances will be here, plus others as yet unknown to the laboratory. Dr. Hagedorn's equation of state applies particularly to this region, and to derive it he had to take into account the probabilities of producing all these particles out of all the others.

Study of the model of the neutron star in the light of this new equation of state indicates to the researchers that the innermost level is surprisingly soft. Physicists had expected that as the density increased, the matter would get more rigid. However, it does not. The softness is attributed to the activity involved in continually changing particles into different particles.

Rhoades and Dr. Ruffini find that the new equation of state does not significantly affect the critical mass that separates neutron stars from black holes. Even if they assume extreme values of temperature or rigidity, it does not change the value very much.

Current estimates of the critical mass depend on the mathematics used by different theorists. They range from 0.34 solar mass to 2 solar masses. If the lower figure is correct, there would be little chance of forming neutron stars. But any figure in the neighborhood of one or higher would allow a significant number to appear. Rhoades and Dr. Ruffini see no way of pushing the value above two so that even in the most favorable case for neutron stars many black holes would also form. ☐

films OF THE WEEK

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