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Neutron Stars: An Extraterrestrial Laboratory

Introduction

[1] Humans appreciate the importance of the laws of nature, because they can be applied to improve the reality of daily life. However, modern physics is fascinating not only because it is responsible for the technological progress on the Earth, but also because it helps understand the fundamental principles in the Universe as well as discover and describe what is invisible to the naked eye. One of the most interesting objects in space, whose characteristics could only be explained thanks to contemporary physics, is the neutron star. Its unique genesis, structure, and conditions it generates are the subject matter of this paper.

Formation

[2] Neutron stars are called "the final products of stellar evolution."[1] Stars are defined as large masses of gas, in which hydrogen is fused into helium, producing light and heat. The fusion is conditioned by the star's strong gravity, which determines high pressure inside it. At the same time, the energy released as a result of the fusion acts as a counterforce to the gravitational force, and the forces maintain an equilibrium that can last for billions of years. In case of bigger stars, the lifespan can be only a several to about a hundred million years, due to their higher temperature and thus burning rate.

[1] https://arxiv.org/pdf/astro-ph/9801235.pdf

[3] After some time, in the bigger stars, helium becomes the new fuel that fuses into carbon and oxygen. From that point, various fusion reactions occur so that elements such as neon, magnesium, silicon, sulfur, and nickel form. The nickel's unstable isotope undergoes positive beta decay, and cobalt forms. Cobalt also decays, forming iron. Then, iron can decay into heavier elements, up to bismuth-209. As a result, the produced elements form layers within the star. The denser an element is, the deeper inside the star its layer is located.

[4] Then, the core of the star is mostly composed of iron-56. The isotope accumulates inside the star, because it is impossible to burn iron-56 at this pressure. With its accumulation, the star runs out of fuel for further fusion. As the energy released in fusion gets small enough, the gravitational force prevails, and the equilibrium state of the star is upset. This causes the star to collapse as quickly as a thousandth of a second. As a result, the star shrinks a thousand times, and its new radius is only a few kilometers. The collapse is finally stopped by the repulsive mutual interaction of nucleons inside the iron core, which has reached an extremely high density and a mass of about 1.4 that of the Sun (the Chandrasekhar mass). The pressure of the star collapse causes protons and electrons inside the core to combine to form neutrons and neutrinos. The release of gravitational potential energy results in a huge and spectacular explosion called the supernova, which emits visible light (sometimes visible even to a naked eye from thousands of light years away) as well as ultraviolet light, x-rays, gamma rays, and neutrinos. It also "blows out into space a nebula of debris containing a mix of all of the naturally-occurring elements, in proportions which agree closely with those calculated to exist on earth."[2] What remains in the same place after the explosion is a big cluster of neutrons. Thus, a neutron star is formed.

[2] https://www.physicsoftheuniverse.com/topics_blackholes_stars.html

Structure

[5] The exact composition of the center of a neutron star is not known; due to its density higher than in a nucleus, it probably consists of hyperons, kaons, and/or pions (surmised examples include pion condensates, lambda hyperons, delta isobars, and quark-gluon plasmas). The outer layer of the core is mainly composed of neutrons. These neutrons are believed to be in the superfluid state, which is defined as "the frictionless flow and other exotic behaviour observed in liquid helium at temperatures near absolute zero"[3] The outer one-kilometer layer, the crust, is solid, even though its temperature is very high: about 1,000,000 K. The crust is mainly composed of nuclei (containing mostly neutrons in its deeper layer). Its outmost layer consists of dense, crystalline iron-56. The iron atoms are polymerized and "become compressed and elongated in the direction of the magnetic field and can bind together end-to-end."[4] Apart from iron, there are also lighter elements closer to the surface, and heavier elements closer to the center. The surface of a neutron star is very flat: extremely high gravitation allows a very low elevation of only about 5 millimeters. Above the surface, there are a few micrometers of a hot plasma atmosphere.

[6] A peculiar transition from the inner crust composed of neutron-rich nuclei to the outer core composed of super-dense matter, called the neutron superfluid, is referred to as the "nuclear pasta," which consists of the following phases: "meatballs," "spaghetti," "lasagna," respectively, and the "nuclear anti-pasta,", which consists of the following phases: "anti-lasagna," "anti-spaghetti," "anti-meatballs," respectively. This means that the deeper inside the star, single and separated nuclei (the meatballs) immersed in the neutron liquid merge to form strands of nucleons (the spaghetti), and then sheets of nucleons (lasagna). As the nucleons start to prevail over the neutron liquid, the structure follows the "anti-pasta"

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[3] https://www.britannica.com/science/superfluidity
[4] https://www.britannica.com/science/neutron-star

sequence. In the final “anti-meatball” layer, neutron liquid fills holes left by the uniform nuclear matter, a structure called also the “Swiss cheese.” For a 1.4-solar-mass star, the transition layers are 100-meter-thick and 0.01-solar-mass total.

Characteristics

[7] Neutron stars are very small in the celestial scale. Their diameters are about twenty thousand meters—comparable to the diameter of a city. The highest mass a neutron star can have is about 2.16 solar masses; most often, a neutron star’s mass is approximately one and a half solar masses. These two factors combined result in neutron stars being the densest objects in the universe except for the black holes—the stars are about 1014 times denser than water and are of similar density to atomic nuclei. Therefore, one spoon of a neutron star would weight as much as a large mountain on Earth.

[8] Because of high masses and densities, neutron stars have a very strong gravity—two billion times stronger than that on Earth. This results in a sufficiently high gravitational lensing so that radiation from the star is bended, and one could observe part of the back of the neutron star when “looking” at it. Due to the high gravities, time on a neutron stars flies 10-20% slower than on Earth. The gravities also implies a very high escape velocities—about 100,000 km/s, compared to Earth’s 11.3 km/s. Therefore, for an object to escape from the surface of a neutron star, the speed of about a half of the speed of light is needed. An object falling from one meter above a neutron star would reach the surface in one microsecond and gain the final speed of 7,200,000 million km/h.

[9] Neutron stars rotate extremely quickly, with the initial spin frequencies of 60 to 700 times per second. Two factors can explain it. The neutron stars retain the angular momentums from their maternal stars but are much smaller than them. In addition, their spins are enhanced by the power of the supernovas that give birth to them. Their spins’ speeds can also increase if they are parts of binary systems and accrete material from the other stars.

Over time, though, they loose energy through radiative processes, through magnetic fields, and/or are broken by winds in X-ray systems. Therefore, their rotating speeds decrease so that normal pulsars spin from 0.1 to 60 times per second.

[10] Neutron stars exhibit very powerful magnetic (10^8 tesla) and electric fields, trillions of times stronger than those of Earth ($3*10^{-5}$-$6*10^{-5}$ tesla). They have a very large impact on the surrounding matter. Using very high energy, they can accelerate particles to a speed close to that of light, causing the synchrotron radiation. Their magnetic poles are usually aligned with their poles of rotation. Neutron stars with this feature are called pulsars. They sweep regular pulses of radio waves in opposite directions across the universe, which can be detected from many light years away: they are often compared to lighthouses. About one in ten neutron stars have exceptionally strong magnetic fields (10^8 to 10^{11} tesla) and high rotating times (below one second). They are called magnetars. Magnetars are bright X-ray and gamma-ray sources. Their active life is relatively short—about 10 000 years.

Conclusion

[11] Neutron stars have proved very useful for modern science. Because of their unique characteristics, they are referred to as the universe's physics laboratories. They help scientists examine various ideas, including the current understanding of stellar evolution or the General Relativity theory. Thanks to the regular radio waves emission, pulsars are very precise natural clocks. Their cyclical pulsation also allows the detection of extrasolar planets as well as investigation of the interstellar medium and gravitational waves. Pulsars are used to measure distances in the universe. They were used even to write down directions to Earth on a plaque sent to an advanced extraterrestrial civilization that could find the Pioneer 10 probe in the distant future. Finally, collisions of neutron stars explain the existence of half of the heavy elements in the universe, including gold and platinum known on Earth. Since the first neutron star detection in 1968, about 2000 others have been discovered.

Sources

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