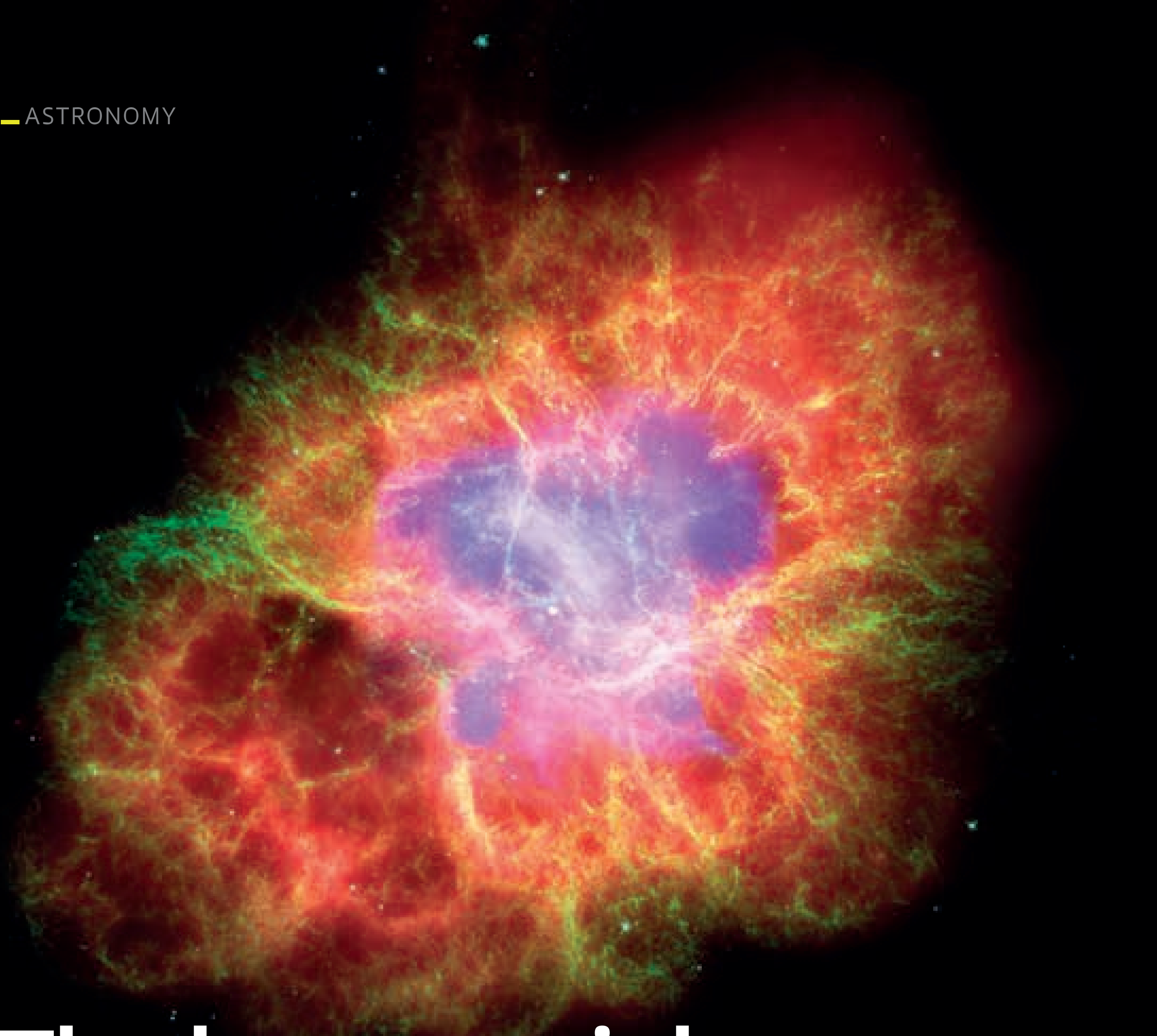

The heavyweights of the Universe

Alternative mechanism may explain the formation of neutron stars that are more massive than normal

Salvador Nogueira

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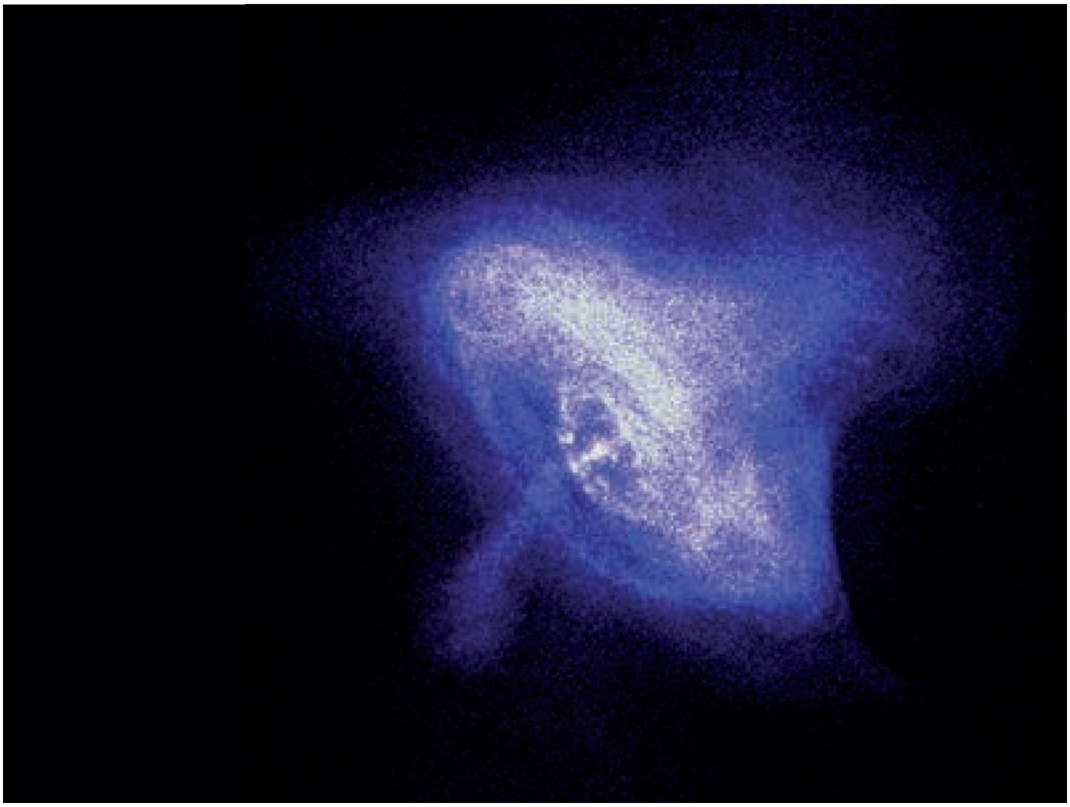
The Crab nebula is bathed in particles emitted....



... by a neutron star (right) at its central region

NASA / JPL

Imagine compacting the Sun until it is the same size as a city. Is that radical thinking? It might be, but nature performs the same experiment when it creates the so-called neutron stars, which are among the smallest and densest objects in the Universe. Astronomers know basically how this process happens, but there are few who admit that a great deal of work remains before science can explain what is out there. One of the mysteries is how neutron stars appear that have a greater mass than that forecast by the theory of stellar formation and evolution. A group of researchers in Brazil is attempting to illuminate the subject by reviving a controversial hypothesis. In general terms, they are suggesting that there must be more than one way of creating neutron stars.

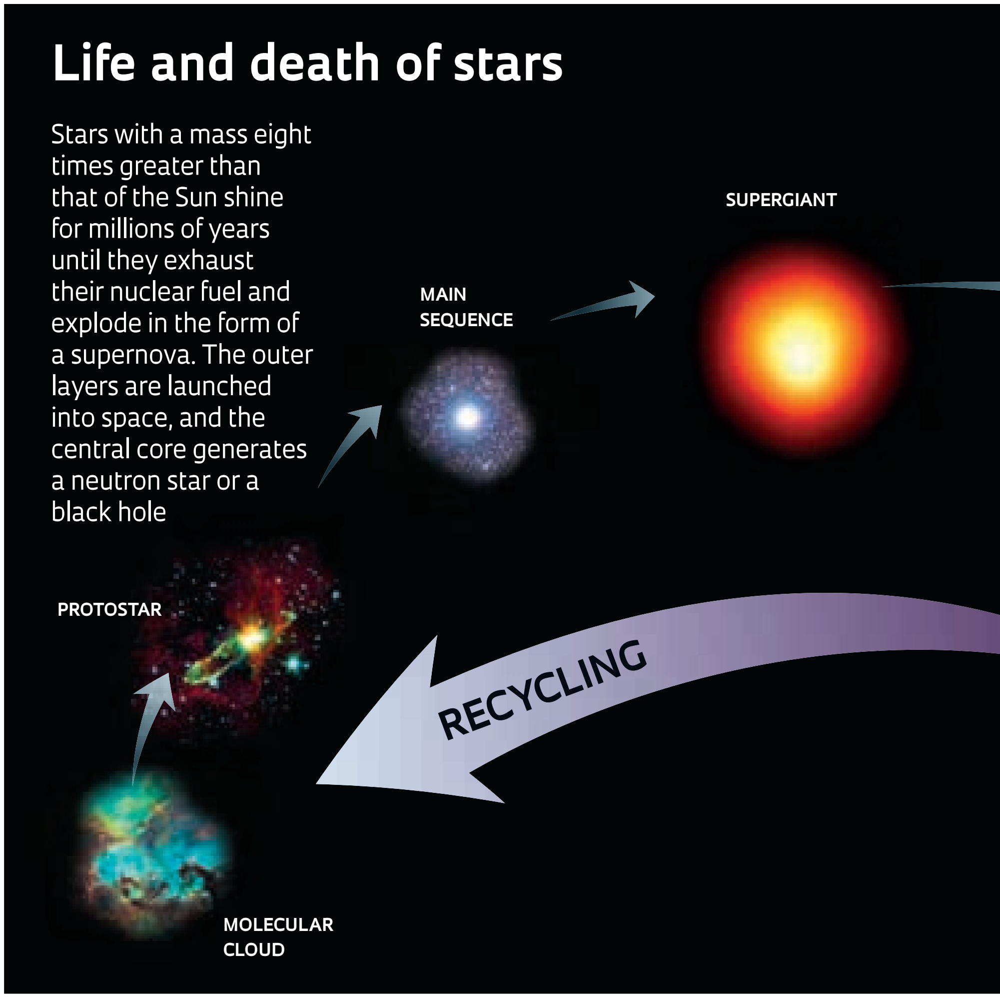
Neutron stars appear because of the death of stars that have very large mass, at least eight times greater than the Sun's mass. To understand what happens, it is necessary to first consider what astronomers know about how stars live and die. Made from concentrated gas (mostly hydrogen) and dust, stars begin to shine when the concentration of material makes the atoms in the central region of these heavenly bodies join together, a process known as nuclear fusion (*see text on page 60*). The transformation of two hydrogen nuclei, each with one proton, into a helium nucleus, which has two protons, is accompanied by a subtle reduction in the total mass. Part of the mass is converted into energy and escapes from the star. This escaped energy is the source of a star's power, which can bathe an entire planetary system in radiation. This energy generated inside the star offsets its gravitational force, which acts in the opposite direction. Because of this equilibrium, the star remains approximately the same size throughout most of its life.

Over millions of years, however, the fuel available for nuclear fusion gradually runs out. Without hydrogen, heavier elements, such as helium, carbon, and oxygen, are used until a limit is reached: iron. This is the final frontier: the fusion of iron nuclei consumes more energy than the energy released at the end of the process. At this stage, the production of energy in the central region is interrupted, and gravity begins working unimpeded without any force to offset it.

COSMIC BOMB

At this point, the star collapses, triggering a complex sequence of events. The result is the explosion of the outermost layers of the star, when 90%

of its mass is launched into space. What remains after this violent episode, known as a supernova, is a very compact stellar core. If the mass of the core is relatively small, this compression produces what is normally called a neutron star. If the mass is larger and the compression continues, a black hole is formed, an object so dense that nothing escapes its attraction, not even light.



According to the currently accepted theory, neutron stars (so called because they have high proportions of uncharged particles (neutrons) inside them) should all have the same dimensions: a mass almost 40% greater than that of the Sun compressed into a sphere less than 20 km in diameter.

"But no one knows exactly what mass a star needs to have during its life to die and leave a neutron star or a black hole," says astronomer Jorge Horvath from the Institute of Astronomy, Geophysics and Atmospheric Sciences (IAG) at the University of São Paulo, coordinator of a group that is investigating the characteristics of neutron stars.

"Until recently, it was believed that all neutron stars had this pattern," says João Steiner, another astronomer from the IAG. "But last year, a case was discovered that is clearly bigger."

The name of the object is PSR J1614-223, a neutron star located 3,000 light years away from Earth that was discovered by a group from the National Radio-astronomy Observatory (NRAO) in the United States. Presented in an article published in *Nature*, this star appears to have two solar masses – it is mammoth, in terms of objects of this type.

This finding obliged the astronomical community to accept the fact that there is significant variation in the size of neutron stars. This realization fits well with the forecasts made recently by Horvath's group, which were published in the June issue of the journal *Monthly Notices of the Royal Astronomical Society*. In this work, Horvath, Eraldo Rangel and Rodolfo Valentim conducted a statistical analysis of the mass of 55 heavily studied neutron stars and found there are two common patterns: one is formed by stars with a smaller mass (approximately 1.37 times that of the Sun) and with little variation, as expected; the other is a more variable type with a larger mass that is approximately 1.73 times the solar mass.

Why do these two different groups exist? "The results point to more than one mechanism for neutron star formation," says Horvath.

This idea seems compatible with the distribution of neutron stars in places like globular clusters, which are inhabited principally by very old stars with a smaller mass than the mass that would be necessary to give rise to neutron stars, according to the star formation theory. Recent observations by astronomers from various countries have shown there are many more neutron stars in these regions than would be expected if they were the exclusive product of the explosion of large-mass stars.

Stars that originally have a mass that is less than eight times that of the Sun do not generate neutron stars when they collapse. Instead, they generate another class of object: white dwarves, with the mass of a sun compressed to a volume such as that of the Earth.

THE PROJECTS

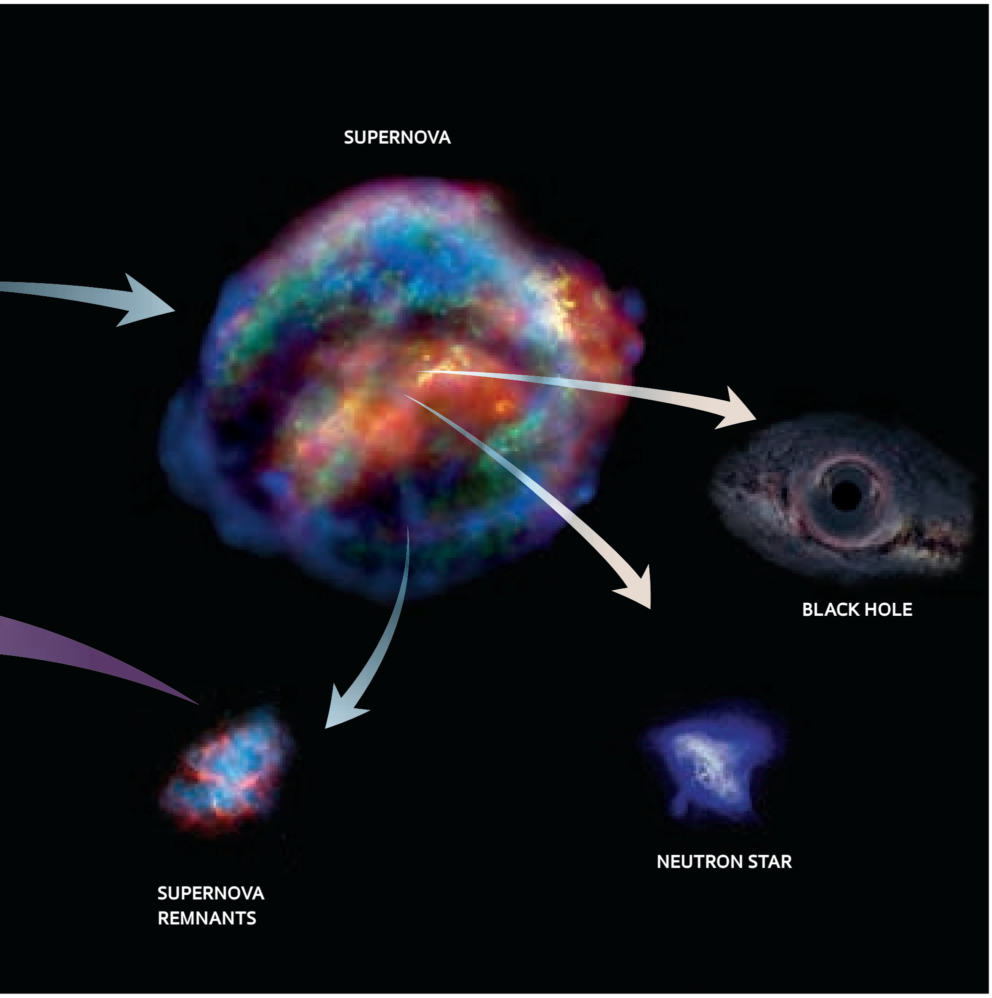
1. Hadronic matter and QCD in astrophysics: supernovas, grbs and compact stars – nº 2007/03633-3

2. Investigation of high energy and high density astrophysical phenomena - nº 2008/09136-4

TYPE
1. Thematic Project
2. Young Investigators Awards Program

COORDINATORS
1. Jorge Horvath – IAG/USP
2. German Lugones - UFABC

INVESTMENT
1. R$ 154,250.00 (FAPESP)
2. R$ 91,207.65 (FAPESP)



This is how the Sun will likely end its days. In some binary systems, the white dwarf uses gravity to rob mass from its companion star until it reaches a limit that induces a new collapse. This event is explosive and produces a specific type of supernova, called Ia, in which the entire mass of the star is violently launched into space.

However, some astronomers suggest a different process can occur. Instead of resulting in a supernova, the rapid growth in mass of a white dwarf might cause it to become a neutron star. "This is an idea that has been around for 20 years, and there are those who hate it," says Horvath. "But there are also those who say that it works. It's difficult to imagine a better alternative to explain how certain neutron stars end up where they do."

Recent data complicate the situation by indicating there are neutron stars with a mass smaller than that of the Sun that were not formed by collapse.

The definitive answer is yet to emerge, but it is almost certain that future research will involve reformulations in the theories of how neutron stars arise and behave.

INSIDE AND OUT

If there is mystery regarding the size and mass of neutron stars, it is no simpler when the subject is their composition. The level of compacting of these objects is so high – the density of a neutron star is greater than that of the nucleus of atoms and 100 trillion times that of water – that the matter may appear in forms that are not found in any other place in the Universe.

At densities greater than that of the atomic nucleus, particles such as protons and neutrons break down into their fundamental units: quarks, which are generally never seen alone. It is difficult to reconcile these predictions with observations, but it is believed that these conditions exist in certain neutron stars that presumably harbor a soup of quarks at their core.

At the Federal University of ABC in Santo André, in the Greater São Paulo Metropolitan Region, Germán Lugones' group has been performing calculations and simulations of how different internal compositions of these stars would affect their mass, radius, evolution and other properties. One of the team's results is that certain phenomena that arise when matter is found in the form of quarks – such as the transition to a superconductor state – naturally explain the existence of stars with masses much greater than the classic 1.4 times the solar mass. This is why the discovery of PSR J1614-223 was an important sign that researchers may be on the right path. Lugones believes that a more radical version of quark stars – the strange star, or auto-linked quark star, in which the entire star is composed of these particles – should be considered a candidate if stars with a mass even greater than that of PSR J1614-223 are observed.

"According to theoretical studies carried out over the last few years by our group, the density necessary for particles of matter to break down into quarks is 5 to10 times greater than the density of the inside of an atomic nucleus," says Lugones, emphasizing that this density may be reached quite easily in the center of neutron stars with greater mass.

No one knows if this occurs. There are gaps in understanding of both the physics behind these processes and the observable properties of neutron stars. Manuel Malheiro, a researcher at the Aerospace Technological Institute and a collaborator with Horvath and Lugones, has been at the University of Rome since 2010, where he is investigating the composition and other characteristics of another type of neutron star: magnetars, which have a high magnetic field.

Advances in theory and observations will be necessary to arrive at a more cohesive picture. The only certainty is that there are interesting problems regarding these stars that are, accidentally, ideal laboratories for studying the most extreme properties of matter. ■

Scientific article

VALENTIM, R. *et al*. On the mass distribution of neutron stars. **Monthly Notices of the Royal Astronomical Society**. v. 414 (2), p. 1.427-31. June 2011.