STRANGE MYSTERY: STRANGE STARS

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Abstract

Imagine a class of star that is entirely made up of quarks, the most stable form of matter known. These "Strange Stars" would be very peculiar and could be the source behind soft gamma ray repeaters, pulsars, gamma-ray bursts, and may be confused with neutron stars and black holes. Intriguing as it may sound, empirical evidence for these stars is slim. The interesting characteristics of these theoretical stars is discussed along with pros and cons about their existence.

1. Filling a gap

Very massive stars die in supernova explosions that leave behind either a rapidly spinning neutron star or a black hole. A neutron star is a small star (tens of kilometers in diameter) so dense that it consists almost exclusively of degenerate neutrons, meaning they literally cannot be squeezed any closer together without breaking the strong force which binds them. According to popular theory, if the star becomes even denser then it becomes a black hole, a place where our understanding of space and time breaks down.

However, some scientists have theorized that a particular class of star could exist in this gap between neutron stars and black holes (Anand *et al.* 1997). Quantum Chromodynamics (QCD), which is the leading theory explaining the forces at work at the nucleon level, predicts that nuclear matter can be broken apart into deconfined quark matter, or quarks freely running about the place (Morel and Piekarewicz 1999). These stars are so dense that the neutrons have done just that, broken apart into up, down, and strange quarks. Quarks, along with leptons, are the most fundamental forms of matter known to exist. In an atom, the protons and neutrons in the nucleus are made up of quarks. These stars made of quarks are aptly called "Strange Stars" because the strange quark is more numerous. The strange quark is the third lightest quark, behind the up and down quarks. In a quark-gluon plasma, strange quarks should exist with gluons, which are the particles that carry the strong force that has been broken. The Pauli Exclusion Principle prevents two identical fermions (such as quarks) from being in the same state, so strange quarks must exist in the plasma since they can occupy lower-energy states which are already packed with as many ups and downs as possible.

2. A strange birth

How a Strange Star is formed is open to debate. To get deconfinement of quarks at low pressure would require a temperature of 2 trillion K! One possibility is that a Strange Star is formed after a neutron star spins down a few days following the supernova explosion that created it (Zhang *et al.* 2000). As the rotational energy of the neutron star diminishes, leftover ejecta from the supernova fall back onto the neutron star (Chatterjee *et al.* 2000) and the neutrons collapse further, eventually fragmenting into a soup of strange, up, and down quarks. Another theory suggests that a Strange Star can only form in a binary system in which one star has gone supernova. The second star still left in the system could either combine with the neutron star or else the neutron star could accrete (gravitationally pull) mass from the other star. The weight of the added mass tears apart the neutrons. Blurring the line even further, some feel that even regular neutron stars have a “strange core.” This opens the door for numerous models explaining how this strange core takes over the star. One involves the use of “strangelets,” which are groups of strange quarks (Anand *et al.* 1997). As they interact with another atom, the negatively charged strangelet is attracted to the nucleus because it is more massive than the negatively charged electrons which remain in orbit around the nucleus. As the quarks enter the nucleus they break apart the protons and neutrons into even more quarks which are released as new strangelets. This initiates a chain reaction that eventually turns everything into a quark-gluon plasma. *Voila*, you have a strange star.

The composition of a Strange Star is as poorly understood as the creation of Strange Stars. It is a popular belief that Strange Stars are probably surrounded by an accretion disk of matter left over from the supernova explosion. The distance of the innermost stable circular orbit (ISCO) of matter to the surface of the star is likely a function of the angular momentum of the star (Bhattacharyya *et al.* 2001). This is not the case in regular neutron stars. As a whole, Strange Stars are rotating very quickly just like neutron stars. In fact, some pulsars—which are believed to be neutron stars emitting pulses of light—may, in fact, also be Strange Stars! If so, then Strange Stars will probably be more unstable than neutron stars and have different sized accretion disks as they age and lose angular momentum (Phukon 2000). On the surface, Strange Stars probably have a crust made up of only neutrons, the material found inside regular neutron stars. It is most likely a very thin crust because an intense magnetic field interferes with the ability of neutrons to collect around the sphere (Madsen 1998). Also, over time these neutrons may slowly settle down into the quark core of the star as its rotation rate spins down. The neutrons will be broken apart into quarks and in the process release thermal radiation. It is theorized that because of this effect, for as long as ten years after a Strange Star is created, it will actually heat up instead of cool down (Yuan and Zhang 1999)! Otherwise, Strange Stars are expected to be cooler than neutron stars because of a higher loss of energy in the form of neutrinos during their creation (Cheng 1999).

Most of the mass in a Strange Star is made up of a large core of quarks in a superconducting liquid (Cheng 1999). The dominant theory of core mechanics is called the "MIT Cloudy Bag Model" (Miller *et al.* 1981). In this model a meson cloud is coupled to the quarks to maintain chiral symmetry, which QCD requires for a collection of deconfined quarks to be stable. Mesons are made of a quark/antiquark pair (although not necessarily identical quarks and antiquarks) and bosons, which are exempt from the Pauli Exclusion Principle (PEP), thus allowing a density higher than the neutron star, which must obey the PEP since by definition neutrons are fermions. The Cloudy Bag model is only a start, however, and has limitations. One is that it leads to wave functions that break down at the boundary of the bag (Landau 1996), leaving a hole in our understanding of how a core made up of quarks and mesons interacts with the outside Universe.

3. Burden of proof

Theory is just one step in the process of science. Theory doesn't mean much without experiment to prove or disprove it. For astronomy, experiment means observation. But how do you observe something so small, dark, and far away? Since Strange Stars are so similar to neutron stars, it is difficult to predict what would distinguish the two in terms of observation. The most popular strategy for detecting Strange Stars was first published by Vladimir Usov of the Weizmann Institute. According to Usov, there are three characteristics that distinguish Strange Stars from neutron stars. First, a Strange Star will emit 10-100 times as many x-rays as a neutron star of the same size (Usov 1997). Secondly, the x-rays will be emitted in pulses lasting about 1 millisecond each. Finally, Strange Stars will emit gamma radiation. He predicts that a small amount of electrons exist in the core and as they escape, they create an electric field on its surface. This field ignites spontaneous pair production of electrons and their oppositely charged cousins, positrons. When these two meet, the particles and their specific antiparticles annihilate each other, as oppositely charged particles tend to do, emitting gamma radiation in the process (Weizmann Institute 1998). Usov predicts that one percent of all known neutron stars could be Strange Stars, as well as some black hole candidates.

One particularly strong black hole candidate, 1E1740.7-2942, also happens to be a strong Strange Star candidate. 1E1740.7-2942 is an enigmatic x-ray source about 1 degree away from the center of our galaxy as seen from Earth. It exhibits all three properties of Usov's hypothesis. However, none of those properties specifically exclude it as a black hole either. The interstellar medium (ISM) at that distance from the core of the galaxy is so thick that direct observation is difficult and, also, any emissions of the object could be contaminated by the thick ISM. Recent observations by the Chandra telescope has provided more information on this object by discovering x-ray jets (Cui *et al.* 2001), but even these observations are not sensitive enough to peer through the thick ISM to positively identify the nature of 1E1740.7-2942. If a multi-billion dollar space telescope run by the top minds in the industry cannot solve the debate, what can?

Another Strange Star candidate is SAX J1808.4-3658, a pulsar that emits x-ray bursts 400 times per second. It was detected by the Italian-Dutch satellite BeppoSax in 1996 and observed in 1999 by NASA's Rossi X-Ray Timing Explorer (RXTE). Observations from both satellites suggest that the object is only 17km across, too small to be a neutron star but just right for a Strange Star (Li *et al.* 1999). However, the models used to determine the star's size are under scrutiny and the jury is still out. Indeed, a recently published article modeled the star's diameter to be at least 9.73km with a mass of 2.27 times that of the Sun, a very massive and small neutron star to be sure (Bhattacharyya 2001).

Another possible method of detecting Strange Stars relies on their properties of thermal radiation. If the aforementioned model is correct about a Strange Star heating up in its first years after birth, one way of detecting a Strange Star will be to monitor all young pulsars for increased thermal radiation over time. Ten years is a short time in the world of astronomical phenomena, so the odds are slim that this can be observed. Detection of a galactic supernova would provide ample opportunity to test this hypothesis, as would the detection of the source of thermal radiation from a compact remnant of SN 1987A (Page 1992). If a Strange Star has a weak magnetic field, then this thermal heating phase may not occur and instead the star may simply cool off slower than a neutron star (Yuan and Zhang 1999). So, observational evidence of neutron stars too warm for current neutron star models to explain would support the existence of a Strange Star. Such evidence doesn't exist yet, but perhaps the launch of the infrared observatory SIRTF in 2002 will help shed light on this possibility. A second burst of neutrinos detected after a supernova would also support the theory of a neutron star turning into a Strange Star a few days after the supernova.

A final possible method of detection focuses on the gamma radiation created by the annihilation of electrons and positrons on the surface of the Strange Star. Both gamma-ray bursts (GRBs) and soft gamma-ray repeaters (SGRs) are intense gamma-ray energy sources with unexplained source phenomena. Other more popular theories abound for explaining GRBs and SGRs, but some scientists think they could also be the children of Strange Stars. GRBs may begin a few days following a supernova, when a neutron star has spun down enough to turn into a Strange Star. At this point, the energy released can be sped up to ultra-relativistic velocities thanks to the low baryonic content of the Strange Star (Wang *et al.* 2000). The afterglows are caused by the impact this jet has on the ISM surrounding the Strange Star. SGRs could be the result of Strange Stars that do not have a thin nuclear crust. The exposed quark core could emit pulses of gamma rays, thanks to thermal emission from pair production created when matter, such as comets and other debris left over from the formation of the stellar system (similar to the Oort cloud surrounding our Sun), impacts the surface of the star. The models of such systems produce light curves that match light curves which fairly well match light curves of known SGRs (Zhang *et al.* 2000).

4. Conclusion

The existence of Strange Stars has not been proven. The problem with all of these models is that none of them have been conclusively backed up by observation. Some observations support them, but those same observations also support other more popular theories which have been more rigorously tested by the research community. However, each of the new Strange Star theories can be tested as new equipment improves our view of the cosmos. Better glimpses of neutron stars, long term cooling trends of pulsars, remnants of new supernovae, neutrino detections—these are all areas of observation just waiting for more data in the not-too-distant future. High quality data in each area will be able to prove or disprove a theory concerning Strange Stars.

It took three decades for neutron stars to be discovered after they were initially theorized. It took even longer for black holes to be considered "a sure bet." Prof. Edward Witten of the Institute for Advanced Study in Princeton made the first suggestion that stars made up of quark matter may exist in 1984. If history is any guide, evidence for or against the existence of Strange Stars may be just around the corner. And even if a Strange Star is never found, the search itself will be enlightening.

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