THE ZOO OF NEUTRON STARS

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by

JURI POUTANEN

Stellar evolution, supernovae and formation of neutron stars

If you ask an ordinary person on the street what is hot? The answer will probably be that hot means anything above 40°C. In astronomy, hot means certainly many thousand degrees and for a high-energy astronomer like me – rather million or billion degrees. What is then large? A usual answer will be probably anything much bigger than a human. For astronomers, the sizes are usually measured in units of the radius of the Sun – our closest star – 700 000 km, so "large" means certainly millions of kilometres. What is far? A couple of hundred kilometres might be far enough. But astronomers will measure the distances between heavenly bodies in units of the distance between us and the Sun – one astronomical unit (AU) – 150 million km, and "far" means typically a distance of thousands of AU or even may correspond to the size of the visible Universe.

We see that astronomers have very different perception of the world around us. In this note I will review neutron stars – the objects that are almost incomprehensible for normal people. These stars form as a result of evolution of massive stars (i.e. those that are bigger, more massive than our Sun, $M_{\odot}=2\times10^{30}$ kg, by a factor of 10 or more). Our Sun is a small star for astronomical standards and for the purpose of today's discussion it lives almost forever – ten billion years, almost as long as the age of the Universe we know. Nearly nothing happens to the Sun for most of its life and only in the last billion year (i.e. about 5 billion years from now), when the hydrogen nuclear fuel inside it will be ending, one will see its dramatic expansion and transformation to the red giant star with the size of about 1 AU. In the end, the expanding outer layers will leave the star and the central hot core, which is a newborn white dwarf star, will remain. That core will then quietly cool for billions of years and nothing interesting will happen to it.

Larger stars live a much more exciting life. Such stars are much hotter inside and burn their fuel much faster. Only in tens of millions years (which is "tomorrow" in astronomical standards), all the hydrogen in the stellar core and then the helium and even heavy elements is burned in nuclear reactions and transformed mostly to iron, which has the most stable nucleus (because it has the highest binding energy per nucleon). At this stage, when all the fuel is exhausted, the stellar core cannot support anymore the weight of the surrounding material and will collapse under the action of gravity. When the material falls to the centre, the temperature grows and the matter is compressed. As a result, all the iron is transformed first to alpha-particles (helium-nuclei) and later even those dissociate into individual neutrons and protons, which capture electrons and also transform to neutrons. The stellar core will thus be made mostly of free neutrons. A neutron star is born.

Because neutrons are fermions and the density in that neutron star is very large, quantum effects do not allow neutrons to be packed too much, producing a repulsive force, that now counteracts the gravity. The same quantum effects will not allow neutrons to decay (in ordinary laboratories, free neutrons live only 15 minutes). Thus, once a neutron star is formed, the matter cannot be compressed anymore and the outer layers of the star will fall at the hard surface producing a shock wave that will heat the material and drive a powerful explosion known as a supernova. It will expel most of the stellar gas to large distances with the velocities that can be as high as 10% of speed of light. Some massive stars might have even larger cores, which cannot fight the gravity and therefore end their life as black holes (which is a different story).

Supernovae were known to the humans for thousands of years and only during the last century it was realized (Baade & Zwicky 1934) that they are connected to the formation of compact objects such as neutron stars (and black holes). And only during the last 50 years we know for sure that the neutron stars exists. The rest of the story tells about different types of neutron stars that we know now.

Neutron stars – laboratories to study the physics of extremes

A newborn neutron star is hot in the beginning (billions of degrees) and cools rapidly to millions of degrees. It is small, only 20–25 km across, smaller than Helsinki, but it is typically more massive than the Sun. Thus, it is very dense, with the density exceeding 10^{18} kg/m^3, i.e. about Everest mountain in a 1-liter milk package. Such a density is ten times higher than the density of atomic nuclei! Obviously, understanding what is happening inside the neutron stars is very difficult, because we cannot reach such densities in the laboratories. In addition to ordinary baryons (protons and neutrons), the neutron star cores may contain various exotic forms of matter such as hyperons and even free quarks. Different composition results in a different neutron star mass-size relation and thus from the accurate measurements of neutron star sizes and masses using astronomical methods we can learn about their interiors. Astronomical observations therefore can give us a clue how to construct a nuclear physics theory that would describe the physical phenomena under these extreme conditions.

The gravitation acceleration at the neutron star surface is about 10^{12} m/s^2, i.e. 100 billions times larger than that on Earth. The escape velocity from the neutron star surface is half the speed of light, meaning that gas falling onto a neutron star has such a velocity. The magnetic field of neutron stars can reach 10^8–10^{11} Tesla, which is million times larger than anything even achieved in terrestrial laboratories. Such huge fields affect all the microscopic processes and leave imprints on the observed radiation from the neutron stars. Astronomers then can decode that information to learn about the physics of processes in such high magnetic fields. Again this cannot be done in Earth laboratories.

Neutron stars represent one the most extreme forms of matter available in the Universe and they serve as laboratories to study physics under extreme conditions.

Radio pulsars

The first clear evidence for the existence of neutron stars came with the discovery of radio pulsars by a PhD student at Cambridge University Ms Jocelyn Bell in 1967 (Hewish et al. 1968), for which her supervisor got a Nobel Prize in 1974. Because of their small periods of about 1 sec, radio pulsars have been immediately associated with rotating neutron stars, which have their magnetic field dipole misaligned from the rotational axis, leading to the pulses of radiation when the magnetic pole points towards the observer. Among the best-known pulsars is the pulsar in the Crab nebulae that rotates 33 times a second. Nowadays pulsars are observed at nearly all wavelengths including gamma-rays. From the deceleration of the rotation one can measure the magnetic fields in these pulsars, which turns out to be typically in the range 10^8–10^9 Tesla.

The first binary pulsar with another neutron star as a companion, PSR 1913+16, was discovered in 1974 by Russell A. Hulse and Joseph H. Taylor. Because of a rather small orbital period of 7.75 hours, a number of relativistic effects were observed, including the decay of the orbit because of the emission of gravitational waves and relativistic precession of the orbit of 4 degrees per year (compare that to the anomalous Mercury's precession rate of 43 arcsec per century). These observations not only allowed to measure the neutron star masses to four digits accuracy, but also to show that the observations are consistent with the predictions of General Relativity at better than 1% accuracy.

Another exciting object, pulsar PSR J0737–3039, was discovered in 2003 by Marta Burgay. In spite of about 2000 pulsars discovered in the last 40 years, this object caused a lot of excitement, because this was the first double pulsar, i.e. a system containing two pulsars (with periods of 22.7 and 2.8 sec) on a 2.4-hour orbit. In such compact system, not only masses can be measured accurately (M_1= 1.337 $M_\odot$, M_2= 1.250 $M_\odot$), but even the moment of inertia of one of the pulsar could be measured within the next 20 years. This will allow to obtain the neutron star radius and to constrain the internal composition of the neutron star core, which is one of the largest mysteries in astrophysics.

Not all pulsars rotate so "slowly" as the first discovered ones. In 1982, Backer et al. discovered the first millisecond pulsar, PSR B1937+21, that rotates 641 times a second around its axis. This was the record holder for more than 30 years, and only in 2005 even faster pulsar, PSR J1748-2446ad, was discovered with the spin rate of 716 times a second (Hessels et al. 2006). Such rapidly rotating pulsars could not be formed during a supernovae explosion, but rather have been accelerated by the material accreting onto a neutron star surface from a companion star (Falanga et al. 2005). And indeed many millisecond radio pulsars are parts of the binary systems.

X-ray pulsars

For the confirmation of the theory of the origin of radio millisecond pulsars, we had to wait until 1998, when the first X-ray millisecond pulsar (with period of 2.5 ms), SAX J1808.4-3658, was discovered by Wijnands and van der Klis using the data from the Rossi X-ray Timing Explorer satellite (RXTE). In a compact binary system, stars can be so close to each other, that gas from an ordinary star may be stripped by the gravity of the neutron star (Figure 1). When the gas accretes onto the neutron star surface at half the speed of light, it is heated to millions of degrees and therefore emits in the X-ray band. X-ray satellites then can detect such systems. Fast rotation of the pulsar and its compact size allow to study different relativistic effects and to measure neutron star parameters to constrain its composition (Poutanen & Gierliński 2003).

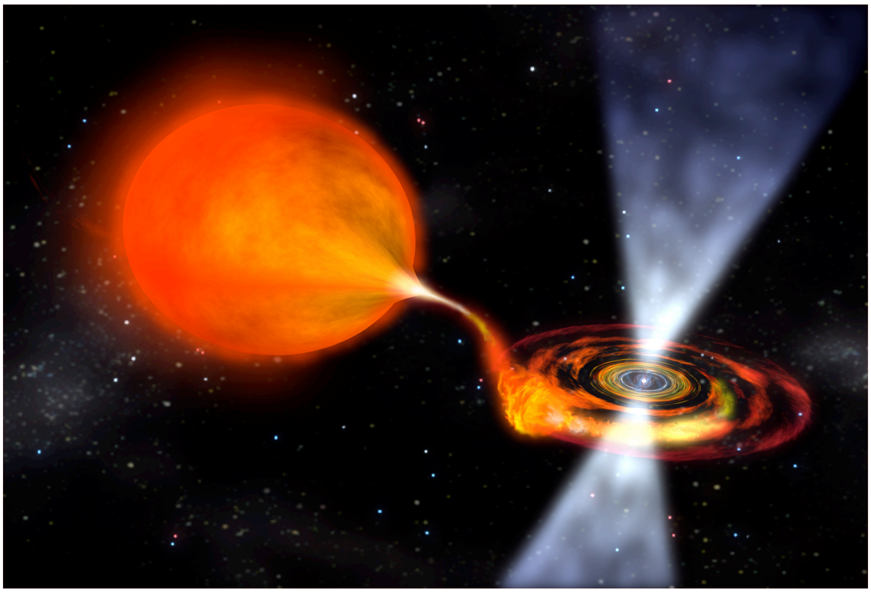

Figure 1: *A neutron star in a binary system. Gas from a companion star, stripped by the neutron star gravity, forms an accretion disc around the neutron star and accelerates its rotation to millisecond periods. ESA press-release for Falanga et al. (2005).*

RXTE made a number of important discoveries during the time of its operation 1995–2012. Thanks to its fast timing capabilities, now the class of X-ray millisecond pulsars contains more than a dozen of sources. In addition, it discovered highly coherent oscillations in the 200–600 Hz range from X-ray bursts – thermonuclear explosions at the neutron star surface – in 20 sources, showing that most neutron stars in old binary systems are rotating rapidly (typically more than 100 times a second). The energetics of these thermonuclear explosions is similar to that produced by 130 15-Megaton nuclear bombs exploding over every square centimetre of the neutron star! Studies of these explosions also can put limits on the neutron star composition (Poutanen et al. 2014).

Most of the X-ray pulsars, however, are much slower rotators. They are members of binary systems with young massive companion stars. In a couple of dozen of these sources, one observes absorption lines in their X-ray spectra, which are associated with the cyclotron harmonics, allowing to measure the magnetic field of 10^8–10^9 Tesla in these neutron stars (Walter et al. 2015). These fields are similar to those measured in radio pulsars.

Magnetars

Satellite observations in the gamma-ray energy range already in the 1960s discovered powerful flares of unknown origin. The most well-known are so called gamma-ray bursts, which emit their radiation at the megaelectronvolt energies. For some time they were though to be explosions at neutron stars in our Galaxy. In the end of 1990s it was realized that actually most these bursts happen outside of the Galaxy and are associated with supernovae explosions, leading to formation of a neutron star or a black hole, or with coalescence of two neutron stars. In addition to gamma-ray bursts, events at somewhat lower energies, but, what is important, repeating from the same direction were also observed. This phenomenon was called soft gamma-ray repeaters. These events were indeed associated with neutron stars. For many of them the period and its decay were measured from pulsations, which allowed to get their magnetic field of enormous strength of 10^{10}–10^{12} Tesla. Therefore, these objects were named magnetars.

It is the huge magnetic field of these objects that is responsible for the explosions called giant flares that emit at the 1-second peak 100 times more energy than all the stars in our Galaxy. A recent such event on 27 December 2004 from the object SGR 1806–20 situated at another side of the Galaxy has ionized the dark side of the Earth atmosphere to the level of the day-side and resulted in a break-up of communications all over the Earth, because of the failure of many satellites. Not many astronomical events can influence our life so dramatically!

In connection with the discovery of radio pulsars, the first observational appearance of neutron stars, one of the most brilliant Russian astrophysicist Iosif Shklovsky told to Jocelyn Bell in 1970 that she has made the greatest astronomical discovery of the twentieth century. Since then this phrase became even more true thanks to the discoveries of binary radio pulsars, millisecond radio pulsars, X-ray pulsars in binary systems, accreting millisecond pulsars, X-ray bursts, magnetars, isolated cooling neutrons stars, and recently even an ultra-luminous X-ray source containing an X-ray pulsar (Bachetti et al. 2014). Neutron stars became powerful space laboratories of the physics that we cannot possibly study at Earth. The discovery of neutron stars in 1967 has opened a completely new field of astronomy and physics and this field remains as exciting as it surely was nearly 50 years ago. New unexpected discoveries are expected in the future!

References

1. Baade W, Zwicky F, 1934, *Remarks on super-novae and cosmic rays*, Phys Rev, 46, 76
2. Bachetti M, Harrison FA, Walton DJ, et al., 2014, *An ultraluminous X-ray source powered by an accreting neutron star,* Nature, 514, 202
3. Backer DC, Kulkarni SR, Heiles C, Davis MM, Goss WM, 1982, *A millisecond pulsar*, Nature, 300, 615
4. Falanga, M., Kuiper, L., Poutanen, J., et al., 2005, *INTEGRAL and RXTE observations of accreting millisecond pulsar IGR J00291+5934 in outburst,* Astronomy and Astrophysics, 444, 15
5. Hessels JWT, Ransom SM, Stairs IH, et al., 2006, *Radio pulsar spinning at 716 Hz*, Science, 311, 1901
6. Hewish A, Bell SJ, Pilkington JDH, Scott PF, Collins RA, 1968, *Observation of a Rapidly Pulsating Radio Source*, Nature, 217, 709
7. Hulse RA, Taylor JH, 1974, *Discovery of a pulsar in a binary system*, Astrophys J Lett, 195, L51
8. Poutanen J, Gierliński M, 2003, *On the nature of the X-ray emission from the accreting millisecond pulsar SAX J1808.4–3658*, MNRAS, 343, 1301
9. Poutanen J, Nättilä J, Kajava JJE, et al., 2014*, The effect of accretion on the measurement of neutron star mass and radius in the low-mass X-ray binary 4U 1608–52,* MNRAS, 442, 3777
10. Walter R, Lutovinov AA, Bozzo E, Tsygankov S, 2015, *High-Mass X-ray Binaries in the Milky Way: A closer look with INTEGRAL*, arXiv:1505.03651
11. Wijnands R, van der Klis M, 1998, *A millisecond pulsar in an X-ray binary system*, Nature, 394, 344