The 68th Compton Lecture Series

Stars: Their Life and Afterlife

Lecture 7: Life In, On, and Near Neutron Stars

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http://kicp.uchicago.edu/~humensky/ComptonLectures.htm
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Introduction

This week we go back to the site of the crime, where we left a proto-neutron star several weeks ago and traveled outwards with the expanding blast wave. So this week we are going to talk about

- Neutron stars – and the degenerate neutron gas that supports them
- Pulsars
- Pulsar Wind Nebulae

Part 1. Degenerate gas redux

Earlier in the lecture series we saw that white dwars are supported against gravity by the pressure provided by a gas of degenerate electrons. Neutron stars are similarly supported by a degenerate gas – this time made of neutrons.

For comparison, a few words first about ideal gases. An ideal gas is one in which the particles are assumed to be point-like and to interact only by bouncing off of one another. There are no long-range forces between them. Qualitatively – and quantitatively – most of the gases we are familiar with, from the atmosphere to the insides of the Sun, are well described by the ideal gas law. This law states that the pressure "P" of a gas is proportional to the product of its density "n" and temperature "T", divided by its volume "V":

$$P = n * k * T / V$$

where "k" is Boltzmann's constant, $k = 1.381 \cdot 10^{-23}$ Joules/Kelvin, a proportionality constant that works for all ideal gases. The pressure in an ideal gas is supplied by the kinetic energy of the particles in it, and that kinetic energy is proportional to the gas's temperature. Thus, one of the key properties of an ideal gas (from our perspective) is that the pressure is proportional to the temperature.

The ideal gas law breaks down at low temperatures or high densities, situations in which we can no longer ignore long-range interactions between the particles in the gas. Degenerate gases are an extreme example of this breakdown that occur at the lowest temperatures (eg, Bose-Einstein condensates), highest densities (white dwarfs and neutron stars), and in between (conduction-band electrons in metals).

Whereas ideal gases can be described in terms of classical physics, degenerate gases rely on two key features of quantum physics: Heisenberg's uncertainty principle and Fermi's exclusion principle.

Fermi's exclusion principle says that no two electrons (or neutrons or protons) can exist in the same state at the same time.

Heisenberg's uncertainty principle says that the position and momentum of a particle cannot both be known to arbitrary precision at the same time: the product of their uncertainties has a minimum value.

What this means in practice (for us) is that if you pack a very large number of identical particles into a very small space, they will fill all of the available states and at least some of them will have very large momenta. Just like for an ideal gas, the pressure is provided by the momentum of the particles in a degenerate gas. The difference is that in a degenerate gas, the distribution of the momenta is dictated solely by the density of the gas, and is independent of temperature – and this means that the pressure in a degenerate gas is also independent of temperature. Strictly speaking, that is only true at a temperature of absolute zero; at the temperatures inside stars, some small amount of pressure is still provided by the temperature of the gas, but it is negligible compared to the pressure provided by degeneracy.

For a white dwarf, if the temperature rises high enough to ignite a new round of fusion inside the star, the energy released via fusion will cause the temperature to rise further. *If* a white dwarf were an ideal gas, an increase in temperature would increase the pressure, throwing the star out of hydrostatic equilibrium – in which the star rests at a pressure that just balances the force of gravity. In response, the white dwarf would expand, lowering its density and cooling until its pressure were back in equilibrium with gravity. In this way, a star behaving as an ideal gas can self-regulate is temperature to maintain a rate of fusion that provides just enough pressure to balance gravity.

However, a white dwarf is supported by a degenerate-electron gas instead of an ideal gas. Thus, there is no link between temperature and pressure, so when the temperature rises the star has no built-in mechanism with which to control the temperature. Fusion rates increase with temperature, and a runaway nuclear reaction spreads throughout the star, eventually disrupting the star.

Neutron stars are also supported by a degenerate gas, but in their case it is made of neutrons rather than electrons. Since neutrons are 2000 times more massive than electrons, the density of a neutron star must be correspondingly higher.

Part 2. Neutron stars

As density increases, the degenerate electron gas becomes relativistic. Eventually, some of the electrons have an energy exceeding the mass difference between a proton and a neutron, 1.29 MeV. At this point, electrons and protons can react via inverse β-decay to form neutrons. As electrons become even more energetic, they are able to react with the protons bound into heavier nuclei, converting them to neutrons as well. As heavy nuclei become too neutron-rich, they begin to fragment. This process starts at a density around $4 \cdot 10^{11}$ g/cm^3 and destabilizes the interior of the star. The star will not find a stable state again until it reaches a density of ~ 10^{14} g/cm^3, at which point nearly all the matter has been converted to neutrons and the neutrons have formed a degenerate gas.

As with white dwarfs, it is the degenerate-neutron pressure that supports the star against gravity rather than the random thermal motions of the neutrons.

Figure 1 shows a schematic of the internal structure of a neutron star. The star has a radius of ~ 10 – 15 km and a mass in the range ~ 1.4 – 2.1 $M_\odot$. The mass has to be large enough to overcome electron degeneracy pressure, but not so large as to overcome neutron degeneracy pressure.

The outer crust of a neutron star is similar in structure to a white dwarf, made of heavy nuclei and a degenerate-electron gas. The inner crust is made of neutron-rich nuclei, free degenerate neutrons, and a relativistic degenerate-electron gas. The bulk of the interior of the neutron star is made of a neutron fluid in which the degenerate neutrons are superfluid. A small number of protons and electrons are also present. The densities at the core of a neutron star get so high that there is a lot of uncertainty about how nuclear matter behaves under those conditions. It is possible that even more exotic states of matter exist in the cores of neutron stars.

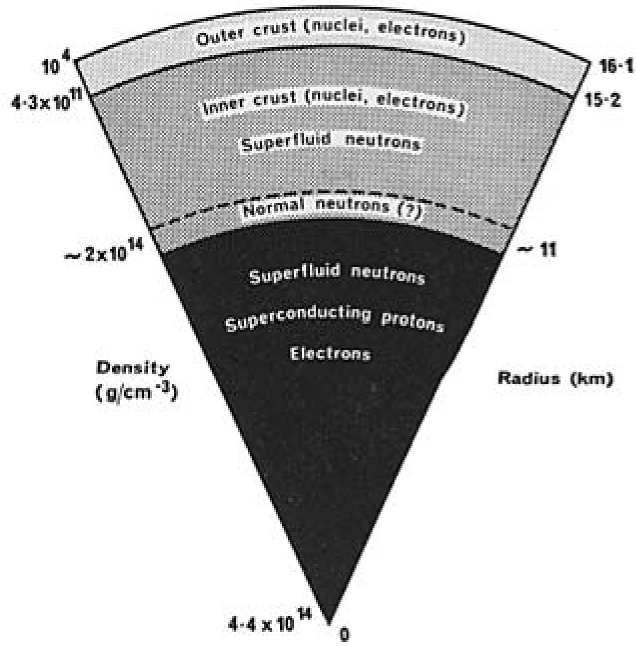

Figure 1. Internal structure of a neutron star.

Part 3. Pulsars

When a star's core collapses to form a neutron star, the star's magnetic field is tied to the ionized plasma that makes up the star. As that plasma contracts, the magnetic field lines contract with it, and the strength of the magnetic field grows as $B \propto 1/r^2$. Because of this, neutron stars naturally have very high magnetic fields, typically 10^6 – 10^9 Tesla (and sometimes higher), compared to the 10^{-2} Tesla of a star like our Sun.

Figure 2 shows the structure of the magnetic fields around a neutron star. In general, a neutron star will be spinning very fast. Again, this is related to how it forms: just like an ice skater spins faster as she pulls her arms in close to her body due to conservation of angular momentum, a neutron star will spin much more rapidly than its progenitor star. Typical rotation periods range from ~ 1 ms up to several seconds (much below 1 ms, centrifugal forces would become so strong that the neutron star would be torn apart!). For example, the Crab pulsar, at the heart of the Crab Nebula, has a period of ~ 33 ms.

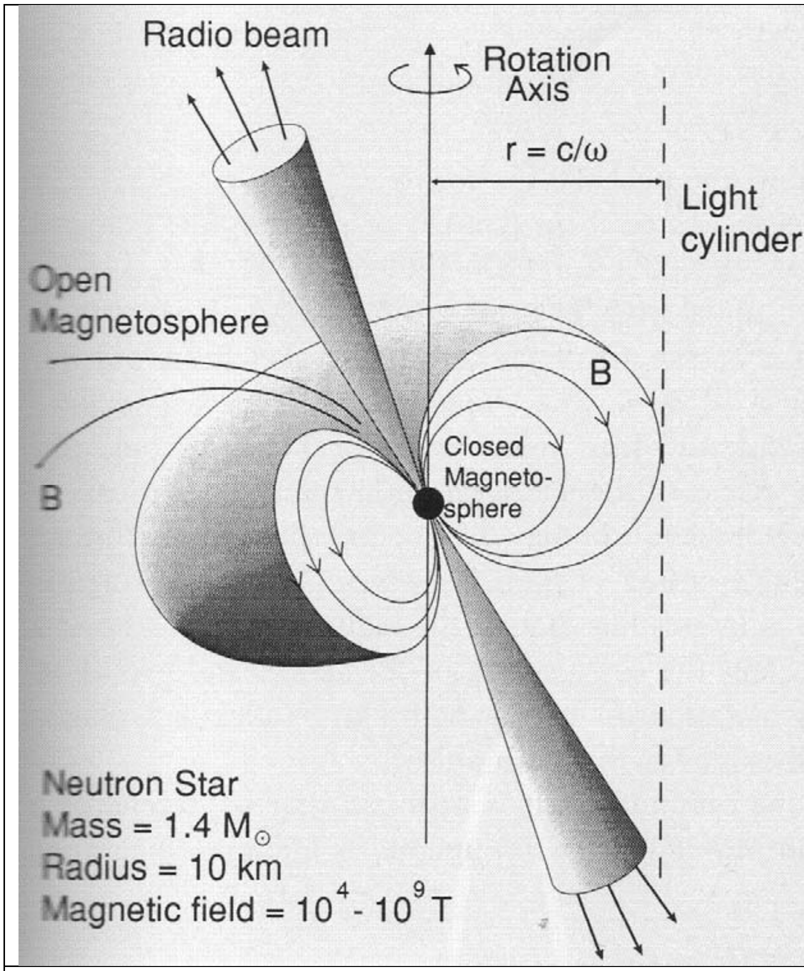

Figure 2. Structure of a pulsar and its magnetic fields.

The atmosphere of a neutron star is called its magnetosphere because of the strong magnetic and electric fields that are present – electromagnetic forces dominate over gravity in this area, and the atmosphere is completely ionized.

In general, the magnetic poles of the neutron star are not aligned with its rotation axis. It is thought that electrons are pulled off the surface of the neutron star near the poles and accelerated by the ambient electric fields to high energies. As they move away from the neutron star along the curved magnetic field lines, they do two things:

- interact with ambient photons to create additional electron-positron pairs.
- Radiate because they are accelerating (by moving along curved trajectories, since they are bound to the magnetic field lines)

It is the coherent radiation of these clusters of electrons and positrons that we see as radio pulses coming from pulsars. This radiation is emitted as a beam that is only seen when the magnetic poles sweep past the direction of the earth. The emission itself is steady, but we see it as pulsed because of the rotation of the pulsar. This leads to several possibilities:

- The magnetic poles and rotation axis are misaligned, and rotation causes the magnetic poles to sweep past the earth: this produces objects that we detect as radio pulsars.
- The magnetic poles and rotation axis are aligned, and pointing directly at us: this would produce steady emission that is otherwise similar to a pulsar's emission. As far as I know, no such objects have been found.
- The magnetic poles and rotation axis are misaligned, but the magnetic poles never sweep past the earth: these are still pulsars, but we cannot detect the pulsed emission from them. Quite a few objects like these have been found, such as the neutron star associated with the supernova remnant IC 443.

Pulsars are also seen to pulse at other wavelengths, and the Crab pulsar's pulsed emission extends all the way from the radio to gamma rays! It is not yet clear where the higher-energy (optical, X-ray, and gamma-ray) pulsed emission is produced, whether it is also produced in close to the neutron star's polar caps or perhaps further out from the star. Interestingly, *where* the radiation is produced is connected to how broad the resulting beam of pulsed emission is, so different models predict that we would see pulsed emission from a larger or smaller fraction of neutron stars. One of the most anticipated results from the Fermi Gamma-ray Space Telescope is a population study of how many gamma-ray pulsars they see, compared to the number of radio pulsars: this information will go a long way towards telling us how pulsars pulse!

Part 4. Pulsar Wind Nebulae

The high-energy electrons and positrons streaming away from a pulsar form a wind – a "pulsar wind." Eventually, this wind encounters the interior of the supernova remnant that gave birth to the pulsar. The collision between this wind and the SNR's interior produces a shock front. Similar to the shocks at the edges of a supernova remnant, this shock front accelerates particles. Most likely, it accelerated predominantly electrons and positrons, since there are already a large number of energetic electrons and positrons available. This region of energetic particles surrounding a pulsar forms a "pulsar wind nebula," of which the Crab Nebula is probably the most famous example. Figure 3 shows a schematic of a pulsar wind nebula. These nebulae shine brightly in synchrotron radiation, as the electrons and positrons interact with the ambient magnetic field (much weaker here – 10's of microgauss – than near the pulsar).

The synchrotron radiation makes pulsar wind nebulae fascinating objects to study in X-rays. In addition, inverse Compton scattering can produce TeV gamma rays, and a large population of very-high-energy pulsar wind nebulae have been discovered in the last five years. The combination of X-ray and TeV gamma-ray measurements is teaching us a lot about the structure and physics of pulsar wind nebulae.

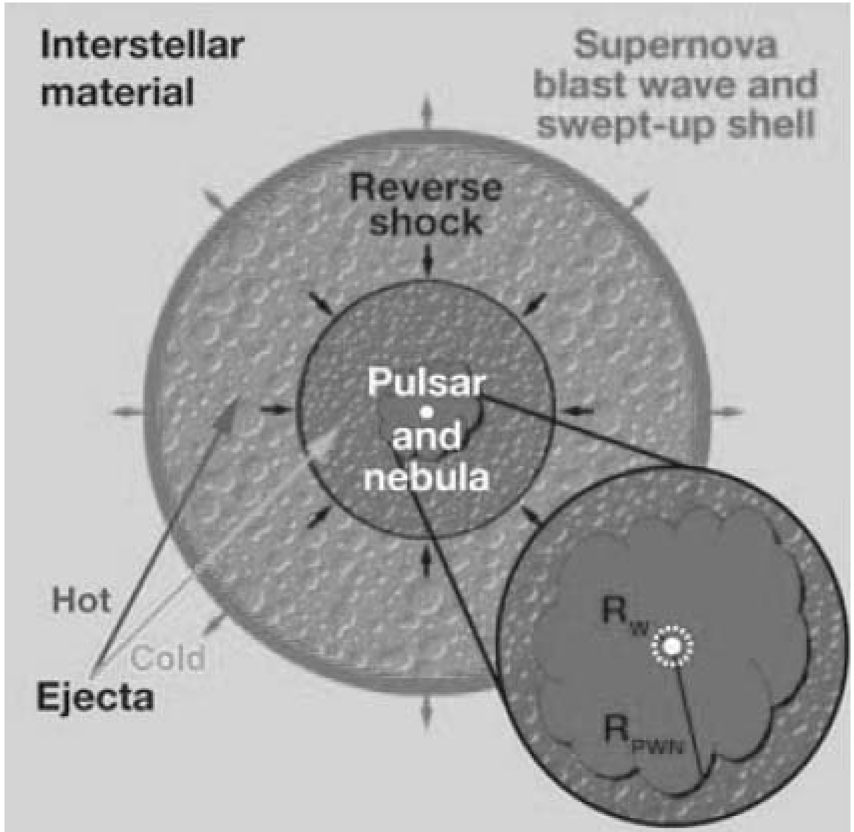

Figure 3. Schematic of a supernova remnant with a pulsar and its wind nebula.

Coming Up Next Week: Fade to Black

Next week we'll take a "look" at black holes and X-ray binary systems.

References

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