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The death of stars – What happens when stars run out of fuel?

The universe is filled with billions of stars that all function the same way during most of their lifetime. But what happens if they run out of their “burning” material? This work tries to outline the fundamental mechanisms at work in that last phase of every star and gives a glimpse of the immense forces involved. To achieve this, the basic physical laws at work will be explained at first. Then we will see how the shortage of the fuel of stars influences its inner machinery and how the size of a star plays the key role in that. Then we will see what will remain afterwards.

Stars consist at the beginning completely of hydrogen atoms that are, as a result of the immense heat inside, fused together in its core to form helium atoms. This hydrogen is what is described in the headline as the “fuel”. Stars of all sizes work this way. In this phase of its lifespan, the star is in equilibrium of two forces that keeps its form and size stable. On one hand its own gravitational force that is pointing inwards. On the other hand its radiation caused by the nuclear fusion that acts as a force on its matter pointing outwards, thus working against the gravitation. This force is called radiation pressure. Once the fuel begins to run out, the temperature and radiation pressure decrease. The gravitation is now the stronger force, which causes the star to densify and therefore increase in temperature again. The higher temperature in the core causes the outer layers of the star to expand drastically. In this stage the star is called a “Red giant” and has a size exceeding the earth orbit. Eventually the temperature in the core will increase so much, that it is sufficient to start a new nuclear reaction, which fuses the helium atoms in the core to carbon. One could say the star “changed” its fuel. This new source of radiation leads to a further expansion of the outer layers and turns the outer layers. Up to this point every star goes through these stages. Afterwards they go through one of mainly three different scenarios, depending solely on their mass. These three scenarios will be outlined now.

Stars with a mass of about 0,5-10 times the mass of the sun of our solar system will stay in the red giant state until also the helium fuel runs out. The outer layers will cool down and be ejected into space to form a nebula around the still slightly glowing carbon core. As there is again a lack of radiation pressure, this carbon core will densify again but without reaching temperatures that ignite another nuclear fusion into higher elements. The densification is stopped at the point that the electrons of the atoms generate a pressure against the gravitation, as the gravitation is not strong enough to press them into the atom cores. This pressure is called “electron degeneracy pressure”. The star has turned into a so called “white dwarf” as there is left only the small glowing carbon core. It will stay in this state for several billion years. It is yet not exactly known what happens after that stage, as the universe hasn’t existed long enough yet to make it observable.

Stars with a mass above 10 times the mass of our sun undergo another scenario after turning into a red giant. As described above, a lack of fusion material causes a densification and increase in temperature which eventually causes a new nuclear fusion into higher elements. While before the densification was stopped by electron degeneracy pressure before reaching temperature high enough to spark fusion of the carbon atoms, stars with a high mass generate enough temperature to go through several cycles of turning the fusion products of an reaction into a new fuel. So the carbon is fused to neon, which later can be fused together to oxygen. This goes on until the element iron-56 is the end product. This core element cannot be used as a new fuel, as the fusion requires more energy than it produces. As a result the radiation pressure comes to a final halt, which enables the immense gravitation of the star to cause an immense densification of the core. If the core is heavier than about 1,4 suns (Chandrasekhar limit), even the electron degeneracy pressure cannot support its weight against the gravitation. Electrons are pushed inside of the atom cores and react together with the protons through a quantum reaction into a neutron. This reaction turns the entire core in under a second into just neutrons, which causes the star to collapse in volume as neutrons can be tightly packed together. This quantum reaction and the collapsing outer layers onto the neutron core cause an immense shockwave which increase the temperature several million degrees, resulting in an explosion called “super nova”. These phenomena make the stars shortly shine brighter than whole galaxies and count as one of the most gigantic outbursts of energy known to man. What is left of the star is the core consisting of neutrons, called “neutron star”. It has the density of an atom core, which makes them the smallest and densest stars there exist. They have the mass of 1,4 - 3 solar suns, with a volume of just about 10 kilometers. A piece of the size of a matchbox weights about 13 million tons. The gravitation of the remaining neutron star is not strong enough to press the neutrons further together, which prevents a further collapse.

Stars so big, that the resulting neutron star would weigh more the approximately 3 suns, undergo even a more drastic scenario. The neutron core’s gravitational force is now big enough to cause even a further collapse, which is predicted by the general relativity theory. The gravitation of the resulting object is so big, that not even light and therefore no information can escape from it. It is now called a “black hole”. The physics of them are still not understood, as the center of the black hole would rip a “hole” into space, which is not possible with the current understanding of the laws of physics. As nothing can escape from its surface, an direct observation and measuring is yet impossible.