Explosions in the cosmos: core-collapse supernovae

Our familiarity with the stars begins with the Sun.

From our perspective, the Sun is a huge source of energy, and it is responsible for life on our planet. Still, at least once in their life, every human being looked up and admired the stars populating the sky. By observing them, we have found that a number of them are much more massive than our warm and reassuring Sun. For example, in the summer, we observe Deneb, located in the Cygnus constellation and one of the Summer Triangle stars. And on winter nights, we can see the stars that compose the indistinguishable figure of the Orion constellation. These are just a few examples of stars that are at least ten times more massive than our Sun. What makes these objects special and different from our favourite star?

What is a ‘massive’ star?

Stars are gaseous spheres in which the energy released by nuclear fusion counterbalances gravity. Their life is characterised by different phases during which they convert lighter elements into heavier elements, and phases during which they exhaust one type of nuclear fuel. In contrast, under the weight of their own mass. This contraction treats the innermost regions of the stars until the temperature is high enough to burn again, this time using the products of the previous burning stage as new fuel. There are six major burning stages as the star progressively ignites hydrogen (H), helium (He), carbon (C), neon (Ne), oxygen (O) and silicon (Si). We define a ‘massive’ star as an object which is able to undergo all of these six phases. To be able to do so, a mass roughly eight times larger than the Sun is needed. Stars like our Sun are instead so-called ‘low mass stars’. During their evolution, they can not reach a temperature high enough to start the C burning, and they end their life losing all the H and He rich envelope and cooling down as ‘white dwarfs’.

All the nuclear fusion reactions that involve the major furs are processes that release energy. Increasing the weight of the fuel, it becomes more and more difficult to fuse the nuclei; therefore, the energy released decreases, and the mass of the outer region located inside the core of the star and on a shorter timescale. The result of the complete evolution of a massive star leads to the onion structure shown in Figure 1, in which each layer contains some unburnt fuel down to a very dense core rich in nuclei such as Fe and Cr. In this so-called ‘iron (Fe) core’, no further nuclear energy can be produced because Fe fusion requires energy. Hence, after the formation of a Fe core, the energy release due to nuclear reactions in the centre of the star stops, and the core begins to contract. Once the star has formed a Fe core, the gravitational collapse cannot be stopped by any nuclear energy release anymore.

The death of massive stars: core-collapse and supernova explosion

During the core-collapse, the centre of the star becomes more and more compact until, in the innermost regions, it reaches the characteristic density of an atomic nucleus, which is of the order of 2x10^{14} g/cm^3. To give a rough idea of the meaning of this number, we could imagine confining 200 million trucks in a (game) die, which would correspond to a density close to the atomic density. When the innermost regions of the Fe core of a massive star reach such a huge density, the matter becomes incompressible, the collapse halts and the matter falling from above bounces back, generating a shock wave that propagates outward in mass. But this is not enough to trigger the explosion of the star; the shock wave still has to cross the external layers of the Fe core, and in this zone, it loses an enormous amount of energy through the heating of the stellar matter and the emissions of neutrinos. This leads to a stall in the propagation of the shock front. The mechanism that is likely responsible for the final explosion is called the neutrino-driven delayed explosion, and it was first studied by Bethe and Wilson (1985). In this theory, the emitted neutrinos accumulate behind the stalling shock and re-power it since the density is high enough to prevent them from escaping. Once the energy of the shock is high enough, it propagates outward in mass, and the star finally explodes, giving birth to one of the most spectacular and energetic phenomena in the Universe: a supernova (Figure 2). The energy involved in a supernova explosion is of the order of 10^{50} erg, which is an acronym for ten to the power of ‘fifty-

Figure 1. The final structure of a massive star just before it explodes as a supernova. The different chemical composition of the layers reflects the burning stage that each of them experienced. Note that the size of the layers is not to scale. Background image credit: ESO/Digitised Sky Survey 2.

Figure 2. The Crab Nebula located in the Taurus constellation is the residual of a supernova explosion that occurred in 1054. Image Credit: NASA, ESA, J. Hester, A. Loll (ASU).
Explosive nucleosynthesis: are we made of stars?

The supernova shock wave crosses the star's outer layers in a timescale of a few seconds, inducing compression and heating on the layers of the star. The increase in temperature due to the passage of the shock wave may even increase up to 10 billion Kelvin by moving away from the Fe core, and its decay emits high-energy photons responsible for powering the supernova's light after the explosion.

No doubt massive stars are fascinating objects; their explosions are some of the most spectacular and energetic events in our Universe, and they synthesised many of the elements we are made of. A few million years ago, some of them were close enough to have polluted the Earth with the radioactive nuclei that are currently harvested by our laboratories (Mellot et al., 2020). They are even thought to be related to mass extinction events (Mellot, Marinho and Paulucci, 2019; Fields et al., 2000). But, oddly, they were not close enough to completely wipe out life on Earth.

The p-rich nuclei

Among the nuclei populating our solar system's chemical composition, there are several nuclear species whose origin is still debated. In particular, 35-proton rich stable isotopes of elements heavier than Fe belong to this category. The usual process to produce heavy elements in stars is through sequences of neutron captures and radioactive decay. Neutrons are easily captured by heavy nuclei to form more massive nuclear species, and depending on the characteristic timescale of these nuclear captures, this synthesis is defined as 'slow' or 'rapid' (Burbridge et al., 1957). However, neutron captures cannot account for the production of p-isotopes. During the explosive nucleosynthesis, energetic photons are released, and their interaction with the stellar matter produces the splitting of heavy nuclei into less massive atoms and lighter particles, such as p, n and He nuclei. This process is called photodisintegration (Kamionkowski et al., 2002). They even thought to be related to mass extinction events (Mellot, Marinho and Paulucci, 2019; Fields et al., 2000). But, oddly, they were not close enough to completely wipe out life on Earth.

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