Explosions in the cosmos: core-collapse supernovae

Our familiarity with the stars begins with the Sun.

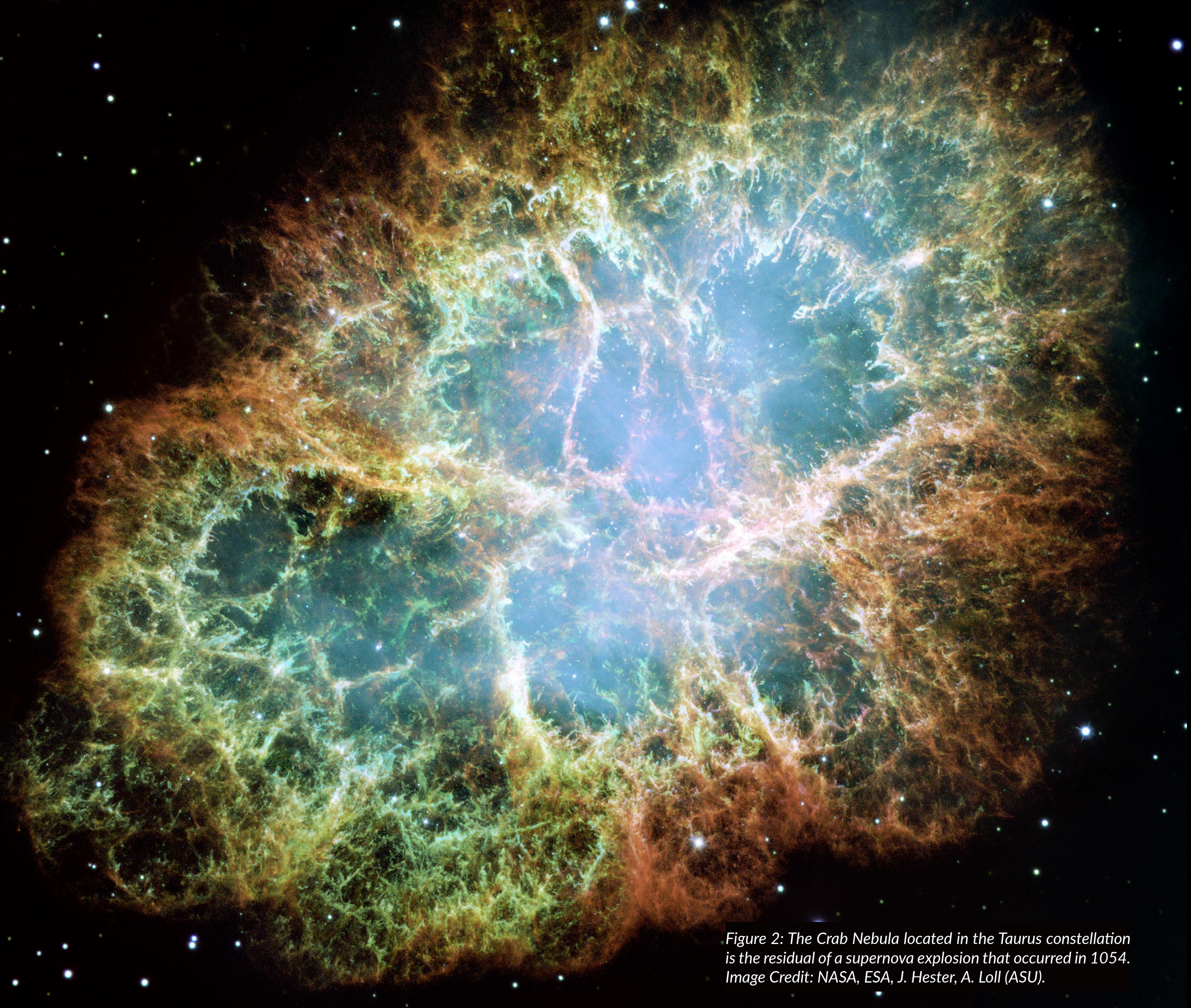

Figure 2: The Crab Nebula located in the Taurus constellation is the residual of a supernova explosion that occurred in 1054. Image Credit: NASA, ESA, J. Hester, A. Loll (ASU).

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 at night. 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 and contract under the weight of their own mass. This contraction heats 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 fuels 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 nuclear burning occurs in a smaller region located inside the core of the star and

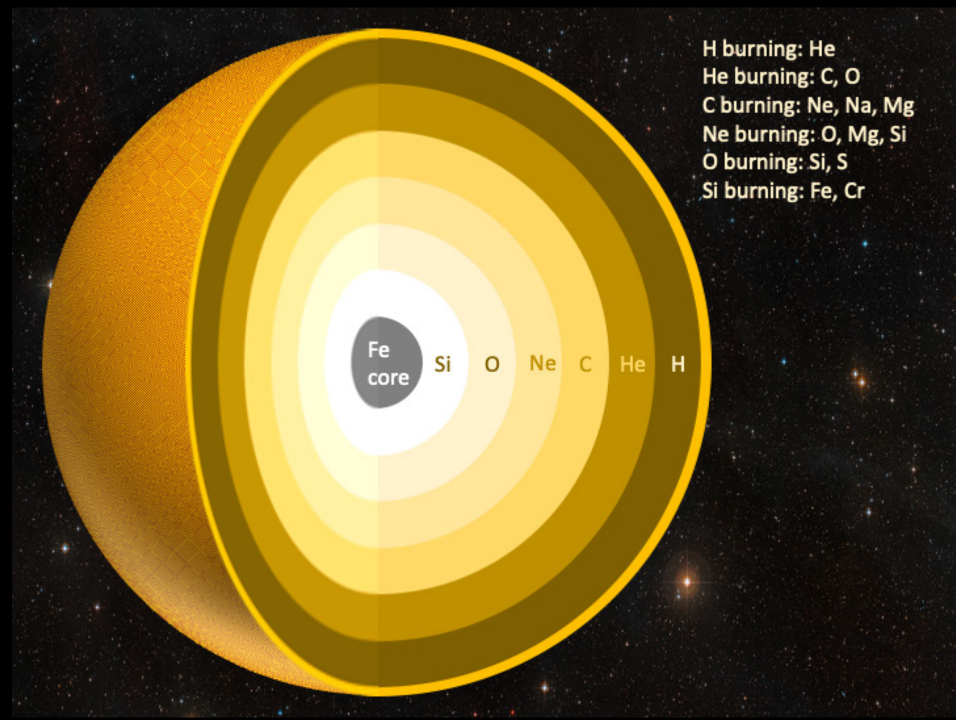

Figure 1: The final structure of a massive star just before it explodes as a supernova. The different chemical composition of the layers reflects the burning stage that each of them experienced. Note that the size of the layers is not to scale. Background image credit: ESO/Digitised Sky Survey 2.

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 1 foe (= 10^{51} erg), which is an acronym for ten to the power of 'fiftyone erg'. To make a comparison with our familiar orders of magnitude, the typical energy release of the most powerful thermonuclear bomb (the so-called H bomb) is 10^{24} erg, which is a billion of billions of billions of times lower than the average energy of a supernova explosion. The final result of the explosion is that a part of the envelope is ejected into the surrounding interstellar medium, while the innermost regions of the star fall back onto the Fe core and form a neutron star or a black hole (Burrows and Vartanyan, 2021).

Explosive nucleosynthesis: are we made of stars?

The supernova shock wave crosses the stellar matter 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 becomes weaker and weaker by moving away from the Fe core, and it is almost negligible when the wavefront reaches the outer layers. In the star's internal zones, however, the temperature may even increase up to 10 billion Kelvin and triggers 'explosive nucleosynthesis', i.e. the activation of nuclear processes similar to what happened during the evolution before the explosion, but on a much shorter timescale. The explosive nucleosynthesis, therefore, reprocesses the material synthesised during millions of years of the evolution of the star in a few seconds and defines the final chemical composition of the ejected material. The most produced elements are those belonging to the iron group, plus Si, S, Ar, K and Ca (Figure 3). Among the iron group nuclei that are synthesised in a supernova, ^{56}Ni has peculiar importance. It is radioactive, which means that it is an unstable nucleus that decays first into ^{56}Co and then into ^{56}Fe. ^{56}Ni is produced close to 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 us to have polluted the Earth with the radioactive nuclei currently discovered in sea sediments (Wallner *et al.*, 2020). They are even thought to be related to mass extinction events (Melott, Marinho and Paolucci, 2019; Fields *et al.*, 2020), but, luckily, 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 decays: 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' (Burbidge *et al.*, 1957). However, neutron captures can not 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'. The γ-process, i.e. a chain of photodisintegrations starting on heavy nuclei, is recognised and generally accepted as a feasible process for the synthesis of p-nuclei in O and Ne-rich regions of core-collapse supernovae (Pignatari *et al.*, 2016). Despite being known for many decades, the gamma-process in stars is still affected by many uncertainties, and the abundance pattern of the p-isotopes measured in the solar system is still not well explained by stellar simulations (Travaglio *et al.*, 2018). With the goal to solve this mystery, the γ-process in core-collapse supernovae is one of the new research topics studied at the Konkoly Observatory, in collaboration with scientists at the ATOMKI nuclear facility in Debrecen and with an international research team of nuclear astrophysics experts, within the framework of the OTKA project 138031 and the ERC project RADIOSTAR 724560.

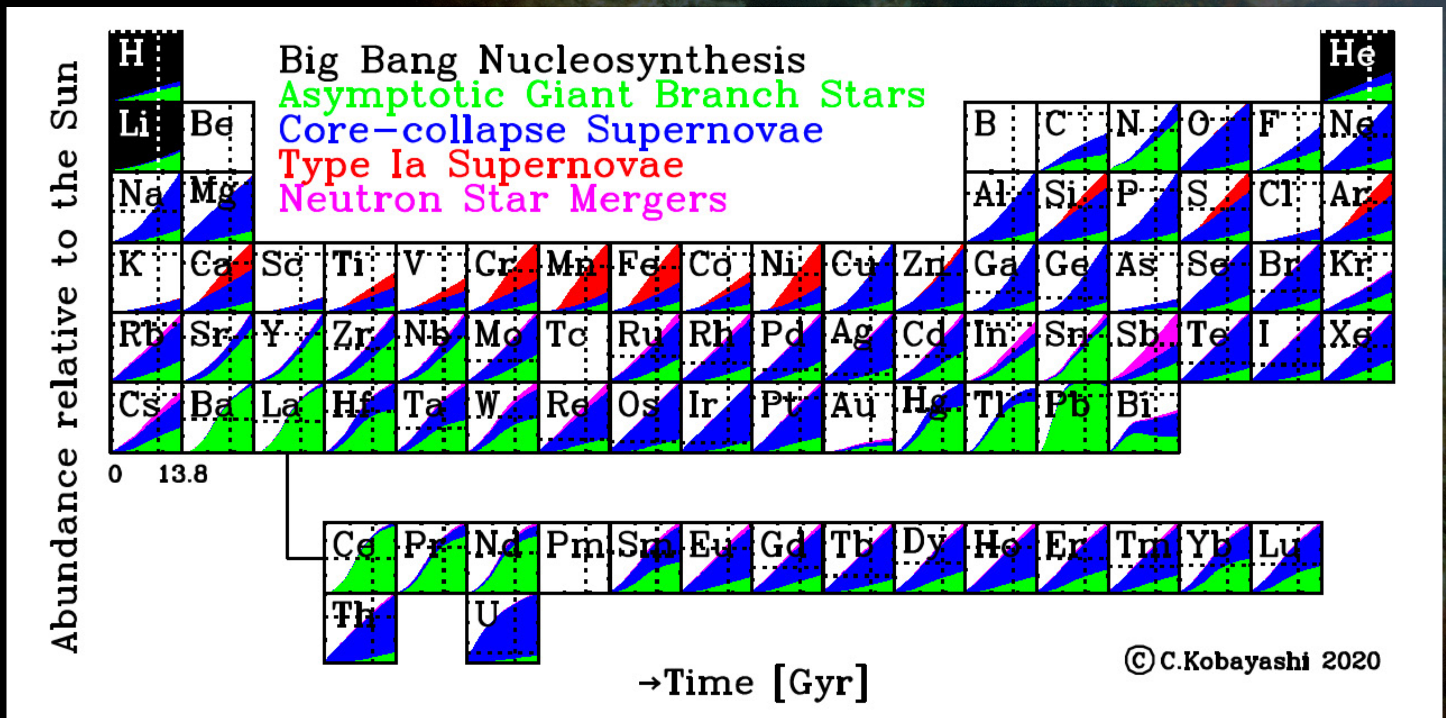

Figure 3: Periodic table of the elements with their origin. A large number of the elements found on Earth were made in core-collapse supernovae. Photo credit: Kobayashi, Karakas & Lugaro, 2020.

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PROJECT NAME

The gamma-process nucleosynthesis in core-collapse supernovae

PROJECT SUMMARY

This is a project supported by OTKA and by the ERC Consolidator Grant project RADIOSTAR. The aim is to shed light on the production of proton-rich heavy nuclei that are measured in the solar system abundance pattern, using different sets of core-collapse supernova models and the latest nuclear reaction rates.

PROJECT PARTNERS

The gamma-process and RADIOSTAR projects are both based at the Konkoly Observatory in Budapest, part of the multidisciplinary Research Centre for Astronomy and Earth Sciences of the Hungarian ELKH research network.

PROJECT LEAD PROFILE

Lorenzo Roberti was born in Rome, Italy, where he obtained his PhD at the 'Sapienza' University of Rome in 2022, with a thesis on the neutron capture nucleosynthesis in rotating massive stars at very low metallicity. He recently joined the Konkoly Observatory as a postdoc, working on gamma-process nucleosynthesis and massive star evolution and explosion.

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