International Particle Physics Outreach Group

PASSPORT TO THE INFINITE

The Origin of Atoms in the Universe

Atoms that constitute the material essence of everything – including ourselves – are the products of countless generations of stars, which have driven the evolution of matter throughout the Universe.

Planetary nebula NGC 6543

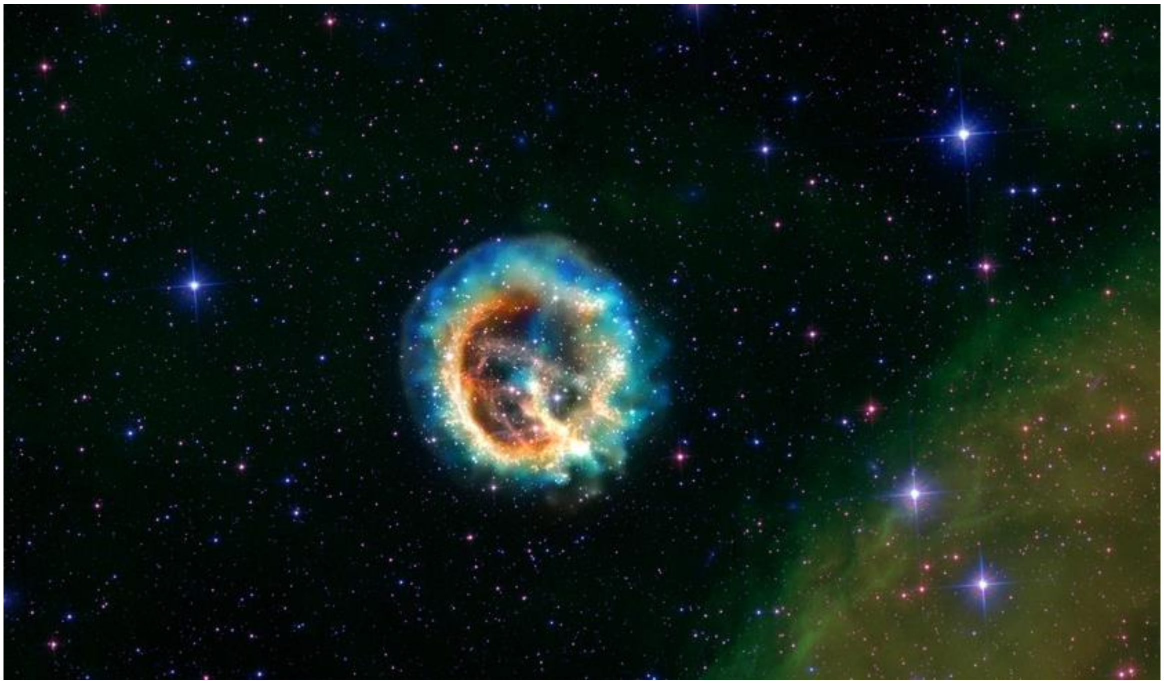
In this image recorded by the Hubble Space Telescope in 2004, the nebula consists of at least eleven concentric shells of ejected matter.

The first atom nuclei to emerge from the Big Bang – hydrogen and helium – served as fuel for the nuclear reactors that stars are. The extreme conditions prevailing in stellar cores – temperatures and pressures – facilitate the formation of complex nuclei. Depending on their initial mass and stage of evolution, stars undergo nucleosynthesis, a process by which new atomic nuclei are created, a phenomenon that has been studied by nuclear physicists since the 1950s.

Once synthesised and ejected into the surrounding space, these nuclei capture electrons to become atoms, which then combine into molecules. After 13.8 billion years of evolution, atomic matter is now predominantly composed of hydrogen (90% by number of atoms), a small amount of helium (around 10%), and a pinch of all the other elements. However, it is the trace amounts of more complex atoms that have enabled the formation of planetary systems and, at least on Earth, the emergence of life and consciousness.

Credit: NASA/ESA/HEIC & the Hubble Heritage Team (STScI/AURA)

Stars engage in various nuclear processes, such as hydrogen and helium fusion, to create more complex nuclei. At the end of their evolution (duration: 10^{10} years), stars with a mass similar to that of the Sun shed their outer layers. A planetary nebula then forms that contains some of the nuclei produced in their cores. After approximately 25 thousand years, the



Credit: X-ray image, X NASA/CXC/MIT/D. Dewey & NASA/CXC/SAO/J. DePasquale; optical image, NASA/NSTcI

nebula has completely dispersed, scattering the newly synthesised nuclei into the interstellar medium.

Supernova remnant E0102-72.3

Composite view combining an optical image recorded by the Hubble Space Telescope and an X-ray image recorded by the Chandra Space Telescope.

In stars with masses greater than 8–10 $M_\odot$, the conditions at the core (temperature: 10^8–10^9 K) enable the nuclear fusion of heavier nuclei, such as carbon, oxygen, neon, and silicon. At the end of their shorter life cycle (ten million years), these stars explode into supernovae. Outer layers are violently expelled. The shock wave generated by the explosion triggers a series of new nuclear reactions in the medium that release vast quantities of neutrons. These neutrons combine with existing nuclei to create the entire range of heavy elements, up to uranium.

By obliterating most of the stellar crucibles, supernovae disperse the nuclei synthesised during earlier phases of nuclear fusion and in the initial moments of the explosion across vast distances. All the newly-formed nuclei end up in the interstellar medium, where they will seed future generations of stars. As factories for atomic nuclei – up to the heaviest elements – and highly efficient agents of their widespread distribution, massive stars are the main contributors to the enrichment of the Universe with increasingly complex nuclei, including those of atoms essential for life, such as carbon, nitrogen and oxygen.

Translated from 'L'origine des atomes dans l'Univers', **Passeport pour les deux infinis,** *IN2P3/Dunod, https://pass2i.ijclab.in2p3.fr/ (French); updated with ICHEP2024 conference (https://ichep2024.org) for IPPOG*