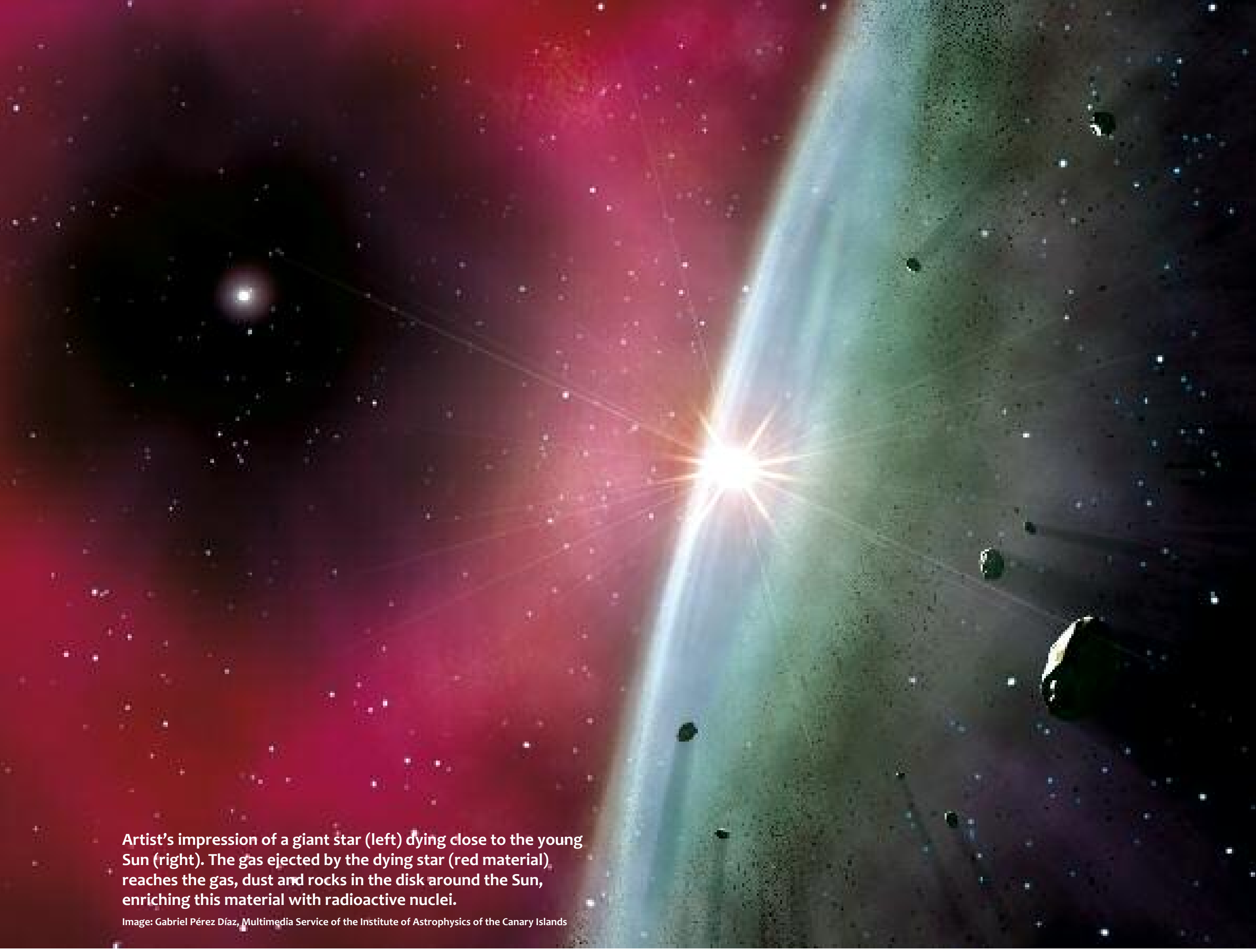

Artist's impression of a giant star (left) dying close to the young Sun (right). The gas ejected by the dying star (red material) reaches the gas, dust and rocks in the disk around the Sun, enriching this material with radioactive nuclei.

Image: Gabriel Pérez Díaz, Multimedia Service of the Institute of Astrophysics of the Canary Islands

The Birth of Our Solar System (and life as we know it)

BY MARIA LUGARO

When the Sun was born, the radioactivity pervading the material around it may have helped to create conditions for life in the rocks that formed the planets. Understanding the origin of this radioactivity could tell us how likely it is that life could exist elsewhere in the Universe.

Radioactivity is a natural phenomenon. Atomic nuclei that do not have the right numbers of protons and neutrons are unstable and "decay" into stable nuclei with the right numbers of protons and neutrons. This often happens via the conversion of a proton into a neutron, or vice versa, driven by the weak nuclear force inside a nucleus. During this process, energy is released in the form of neutrinos and photons of very high energy (gamma rays).

One example is aluminium-26, which has a nucleus comprising 13 protons and 13 neutrons. The protons inside this nucleus repulse each other because they are positive charged particles, but the strong nuclear force attracts all 26 protons and neutrons and manages to keep the nucleus "alive" for a relatively long time. But aluminium-26 is not completely stable, and after roughly a million years it decays into its so-called "daughter", magnesium-26, by converting one of its protons into a neutron. With one less proton, the strong nuclear force can overcome the electromagnetic repulsion and stabilise the daughter nucleus.

When our solar system was created 4.6 billion years ago, many radioactive decays were happening due to the presence of relatively large amounts of radioactive nuclei like aluminium-26. This ancient presence is revealed today in old meteoritic rocks that have unexpectedly high amounts of the daughters of radioactive nuclei like magnesium-26. However, we still do not know where these radioactive nuclei came from.

The presence of radioactive nuclei in the young solar system required nuclear reactions that were close in time and space to when and where the Sun was born. One theory is that these nuclear reactions occurred inside the solar system. While the Sun was young it was ejecting particles, such protons and helium nuclei, at relatively high speed. These particles struck the material around the Sun hard, triggering nuclear "spallation" reactions that led to the production of radioactive nuclei like aluminium-26. Another theory is that a nearby dying star produced the radioactive nuclei and injected them into the young solar system via its winds or via a supernova explosion.

Both theories are problematic. Spallation reactions around the young Sun cannot produce heavy radioactive nuclei that were present in the young solar system, such as iron-60.

However, stars can make all of the radioactive nuclei that were present in the young solar system, as stars have created most of the elements in the Universe. For example, models of nuclear reactions in supernovae have shown that a supernova can produce the necessary range of radioactivity observed in the young solar system as long as material from the inner regions of the star was not ejected in the stellar surroundings during the explosion. This condition is needed to ensure that levels of manganese-53, another radioactive nucleus present in the young solar system, are not greater than levels measured in meteorites.

In a study published in *Meteoritics & Planetary Science* in collaboration with Spanish and Dutch researchers, I have used models developed at Monash University and the Australian National University to show that nuclear reactions inside a red giant star of mass roughly six times the mass of the Sun can also produce all of the necessary radioactivity without producing too much manganese-53. The radioactive stellar material was expelled out of the star during the final stages of its life via strong stellar winds, and could have reached and impregnated the material around the Sun. However, it is difficult to find a plausible reason why a dying star should have been near the nascent Sun.

Within this "stellar theory", identification of the type of star near the Sun would help to locate where the Sun was born. For example, if the nearby star was a supernova then the Sun must have been born alongside thousands of stars. This stellar "cluster" would have then dispersed, leaving the Sun as an isolated star.

On the other hand, if the nearby star was a more common red giant star then we would not need to hypothesise that the Sun was born in a very large cluster, but it would still be unclear why such a star should have been nearby. In either case, the probability of having a dying star nearby the nascent Sun appears to be very dim.

There are several difficulties that hinder the solution of this long-standing puzzle. First, precise meteoritic measurements are very difficult to accomplish. While the abundance of aluminium-26 in the young solar system is known precisely to be 0.00005 times the abundance of the stable aluminium-27, the abundance of iron-60, for example, is currently uncertain by a factor 100.

Second, theoretical predictions of the production of radioactive nuclei around the young Sun and in dying stars are far

A portion of the Allende meteorite (cube = 1 cm). The visible white inclusions are among the first solids that condensed in the solar system. They are made of silicate and oxide minerals rich in calcium and aluminum with unexpectedly high amounts of magnesium-26, the daughter of the radioactive nucleus aluminium-26. Photo: Wikipedia

from accurate due to uncertainties in the models of stars and in the cross-sections of nuclear reactions.

There are fundamental reasons why we should pursue this quest by improving our measurements and models. A key question is whether the presence of radioactivity is common or rare around young stars. This would tell us whether the Sun was born in special conditions or in the same manner as most similar stars. It would also help us to determine whether the life that arose in our solar system is a special event in the Universe.

The presence of radioactivity in the young solar system can provide clues to where the Sun was born. Furthermore, it had important consequences for the evolution "planetesimals", the first large rocks (kilometres in size) that formed in the solar system and from which the planets subsequently formed.

The planets formed from these planetesimals less than a million years after the birth of the Sun. Radioactive nuclei like aluminium-26 were trapped inside them, and the high-energy photons released during their decay heated up the rocks.

This extra source of heat inevitably affected the evolution of these rocks, and in particular the presence of water inside them. This is because the presence of H_2O in the form of solid ice, liquid water or gaseous vapour depends on temperature.

The Earth grew from an accretion of planetesimals, and hence received its liquid water from them. Thus the initial presence of aluminum-26 could have affected the amount of water accreted by terrestrial planets.

Water is fundamental to make a planet habitable. Indeed NASA lists "extended regions of liquid water" as one of its principal criteria for habitability.

The presence of radioactivity as a heating source in the young solar system may have affected the habitability of our planet, and thus the opportunity for life in the solar system. If our solar system is unique in terms of the presence of radioactive nuclei at its birth, it may also be unique in its ability to harbour life. But if most stars are born with an amount of radioactivity that is similar to that of the young Sun, they may have a similar chance of harbouring life in the terrestrial planets orbiting them.

The origin of radioactivity in the young solar system is a question that we need to address by investigating this puzzle from the different point of views of planetary science, nuclear physics, astronomy and astrophysics. The effort is worth it, as this research represents a viable key to placing our solar system, our planet and ourselves in the cosmos.

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