Radioactive isotopes: astrophysics answers in abundance

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How were the elements which we are made of formed?

How can meteorites and deep-sea sediments help us better understand nuclear processes and propagation phenomena in the galaxy?

How can they help us understand if our solar system is unique or if it has many siblings?

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Shortly after the Big Bang, the first nuclei were formed: hydrogen, helium, and some traces of lithium. These elements were abundant in gas clouds. After a while, the first stars formed out of this gas. Stars are basically giant gas balls. The gravity of such a gas ball increases the pressure in its centre, which becomes so high that nuclear hydrogen fusion is ignited. This nuclear hydrogen fusion then releases heat which counteracts the further gravitational collapse of the star. The fusion in the star fuses the hydrogen to helium until enough helium has been produced in the star to ignite the nuclear helium as well.

For intermediate-mass stars like our Sun, this is the last burning stage before they eject their outer envelopes into the galaxy and their cores cool down as white dwarfs. However, massive stars can ignite further nuclear burning stages until they produce nickel and iron. Beyond nickel and iron, nuclear fusion **requires** energy, so the nuclear burning in the centre of a massive star cannot contribute to withstanding the gravitational collapse of the star anymore. The massive star collapses under its weight and explodes in a supernova, ejecting its outer shells while leaving a neutron star behind.

If we look at a binary massive star system, both stars might undergo a supernova explosion leaving two neutron stars behind. If their distance and initial momentum are suitable, they can orbit each other and slowly spiral inwards towards their common centre of mass under the emission of gravitational waves. When they collide in a so-called neutron star merger, some of the material of the two neutron stars will experience a strong neutron density, which will force the nuclei to become very neutron rich. Some of these very neutron-rich nuclei can be ejected from the neutron star merger and decay towards stability. This decay is actually a ß-decay, which means that the excess neutrons are converted into protons. More protons in a nucleus mean that, in general, a heavier element is created. Since the collision of two neutron stars takes only a couple of seconds, this nuclear process is called the 'rapid neutron capture process' and is responsible for the production of about 50 per cent of all elements heavier than iron.

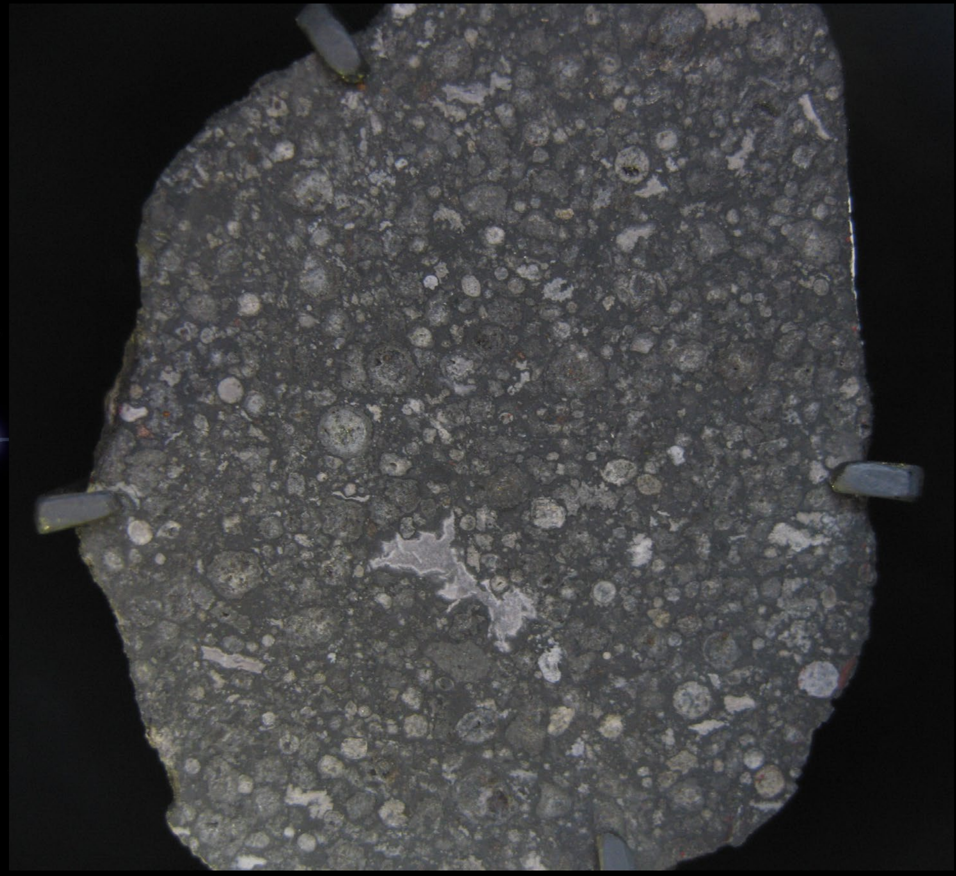

Figure 1: A slice from the Allende meteorite, which was found in Mexico in 1969. The long grey features are some of the oldest solids in our Solar system and can be used to study the nuclear abundances at the time of the formation of the Sun.

Inside meteorites

Not all of the very neutron-enriched nuclei from the last nearby neutron star merger event decay towards stability at the same speed, though. Some decay chains starting from some neutron-rich nuclei proceed through short-lived isotopes and some through longer-lived ones. And this is where meteorites come into play: since some of them were created before the birth of our Sun, they 'lock' the nuclear composition of the solar neighbourhood 'pre-Sun' within them. Thus, they can serve us with important information about the solar nursery's conditions and the last nucleosynthesis processes that occurred in the solar neighbourhood shortly before the birth of our Sun. A set of about twenty special isotopes has been identified to carry very high informational content. These can be extracted from meteorites (see detailed review by Lugaro *et al.*, 2018).

Early days of our solar system

For instance, the early solar system ratio of the abundance of the isotope iodine-129 to its stable reference isotope iodine-127, and the ratio of the isotope curium-247 to its longer-lived reference isotope uranium-235, have been determined. This gives us important information about the last time the rapid neutron capture process contributed to the solar nursery. From these two ratios, we can calculate the

Figure 2: Deep-sea crust sample. Samples like this are used to determine the influx of live cosmic radioactive isotopes to Earth in the last millions of years. This Figure was taken at TU Munich by Klaus Knie, and has been previously published in Nature Communications, Wallner et al., (2015).

abundance ratio of iodine-129 and curium-247 in the early solar system, two isotopes that can be directly produced in neutron star mergers. Since the two isotopes have very similar half-lives, their nuclear abundance ratio in the early solar system allows us to draw conclusions about their ratio at the time of their production in the last neutron star merger that contributed to the solar nursery. This can help us directly determine at which astrophysical conditions the last neutron star merger occurred (Côté *et al.*, 2021). This result is also very important for both the nuclear physics and the high energy physics community. Since they now know the ratio at which these two distinct isotopes were produced the last time before the formation of our Sun, they can use that information to benchmark their modelling and their simulations to that ratio. For instance, if a simulation of the rapid neutron capture process in a neutron star merger yields an excess of the much lighter iodine-129 in comparison to the heavier curium-247, maybe the nucleosynthesis period during the neutron star merger was too short, or maybe the model assumed too much fission of heavier isotopes causing an excess in lighter ones.

Back on Earth

Another very interesting insight radioactive nuclei can provide comes from their ongoing deposition on Earth. Wallner *et al.* (2021) have selected multiple areas in the ocean and excavated samples from the sea-floor. They discovered multiple radioactive iron-60 and plutonium-244 isotopes at different depths in the samples. With their modelling of the accretion rate of sediments to the deep-sea floor and a prescription for the influx of these two isotopes into the solar system and onto Earth, they were able to derive the atomic density of these two isotopes in the solar neighbourhood over the last ten million years. These two isotopes are so interesting because iron-60 is thought to be produced in supernovae, and plutonium-244 is thought to be exclusively produced in neutron star mergers. Suppose we combine that information with the data about these two isotopes, which we already have from meteorites. In that case, we can conclude that the solar neighbourhood atomic density of plutonium-244, as derived from meteoritic data at the time of the birth of our Sun, was much higher than what can be expected from analysing the deep-sea samples, which rather represent present-day conditions. This allows us to study two solutions: how often are these elements ejected from their nucleosynthesis sites (supernova or neutron star merger), and how do they propagate in our galaxy? For the former, if any nucleosynthesis site occurs too often, the radioactive products of that site do not have enough time to decay between consecutive events, which would be inconsistent with the large differences between the time of the formation of the Sun and the current day. For the latter, maybe dispersion effects have brought these isotopes closer to the Sun, or maybe nearby supernovae have carried them away from the solar system location.

The Milky Way

A third lesson to be learned from using radioactive isotopes for astrophysics is how prevalent they are throughout the galaxy and if they are evenly distributed. We use sophisticated computer programs to simulate the formation of the Milky Way galaxy in great detail, (e.g. Vincenzo and Kobayashi, 2020). Among many other features, we give birth to stars and let them die, let them produce elements and explode them, so they distribute some of the elements that they produced during their lifetime into their surroundings. We monitor the gas in the galaxy and its nuclear composition. Once the galaxy has evolved for 9 billion years (4.5 billion years ago—the time of the solar system's birth), we analyse its contents. We can see exactly where in the galaxy which density of the isotopes of interest is present.

Chances of life

The simulations allow us to determine whether the amounts of those isotopes in meteorites represent normal atomic densities of these isotopes or, as in the majority of space in the galaxy, if the density of these isotopes was higher or lower. Since some of the isotopes we focus on are also highly relevant for the heating of planetesimals (Lichtenberg *et al.*, 2019), they are also important for the development of those planetesimals and for later maintaining a temperature that permits liquid water. Thus, some of the isotopes in question are also relevant for any form of life in any stellar system. If the meteoritic data are an outlier in the results of the galaxy simulation, we can speculate whether we are the only stellar system capable of hosting life in the galaxy. If the data fall in the bulk of the results of the galaxy simulation, many solar-like systems can be expected in our galaxy.

The simulation snapshots provide us with precise information on where exactly in the galaxy to expect such isotope densities. This allows us to further constrain which regions of our galaxy could potentially host life. Follow-up observations could then be carried out and checked to see whether these isotopices are actually abundant in these regions. If, for instance, it is found in our simulations that solar system-like isotope densities are to be found in the centre of our galaxy's spiral arms, telescopes could be pointed in those directions to seek other signs of extraterrestrial life.

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PROJECT SUMMARY

The ERC Consolidator Grant project "RADIOSTAR: Radioactivities form Stars to Solar Systems" uses radioactive nuclei produced by nuclear reactions inside stars and supernovae to understand the history of the chemical matter that builds up our Sun, our planet and ourselves, generating a new understanding of our solar system and the life within it.

PROJECT LEAD

This sub-project of RADIOSTAR is led by **Dr Benjamin Wehmeyer**. Born in Westerland/Sylt (Germany), he received his PhD from the University of Basel (Switzerland) in 2016. He then moved to North Carolina State University (USA) for a postdoctoral research position, during which he received a prestigious research fellowship of the Swiss National Science Foundation.

In 2019, he joined the RADIOSTAR project to work with **Dr Lugaro** at the Konkoly Observatory in Budapest (Hungary) and **Prof Dr Kobayashi** at the University of Hertfordshire, UK.

PROJECT PARTNERS

The RADIOSTAR project (PI Dr Maria Lugaro) is based at the Konkoly Observatory in Budapest, part of the multidisciplinary Research Centre for Astronomy and Earth Sciences of the Hungarian ELKH research network. This sub-project is developed in collaboration with Prof. Dr Chiaki Kobayashi at the University of Hertfordshire, UK.

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