The question of the origin of the elements has been studied at the interface between nuclear physics and astrophysics since the 1950s.

Elements heavier than helium are synthesised inside and then ejected by dying stars. The next generation of stars forms from gas clouds that include heavy elements from the previous stellar generations. Therefore, stars in the present-day galaxy are like fossils that retain the information on the properties of stars from the past.

From the elemental abundances of the present-day stars, it is possible to disentangle the star formation history of the galaxy. This approach is called Galactic Archaeology and can be applied not only to our Milky Way but also to other galaxies.

(Chiaki Kobayashi *et al* 2020 *ApJ* **900** 179)

Kobayashi, C., Karakas, A. I. & Lugaro, M. (2020). The origin of elements from carbon to uranium. *The Astrophysics Journal* **900** 179-212. **DOI** 10.3847/1538-4357/abae65

This research aimed to reach a deeper understanding of the origin of elements in the periodic table. The authors examined the processes that make elements inside stars (stellar nucleosynthesis) of different masses. These were then included in a model that tracks how the abundances of each element change with time inside a galaxy like our own Milky Way. Their work brings together nuclear physics and astrophysics.

Image L to R:
A/Professor Amanda Karakas
Monash University

Dr Maria Lugaro
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University of Hertfordshire

ASTRO 3D, the Australian Research Council's Centre of Excellence For All Sky Astrophysics in 3 Dimensions aims to understand the evolution of matter, elements and light in the Universe from the Big Bang to the present day by combining Australian and international expertise in radio, optical and theoretical astronomy.

ASTRO 3D

BIG BANG NUCLEOSYNTHESIS

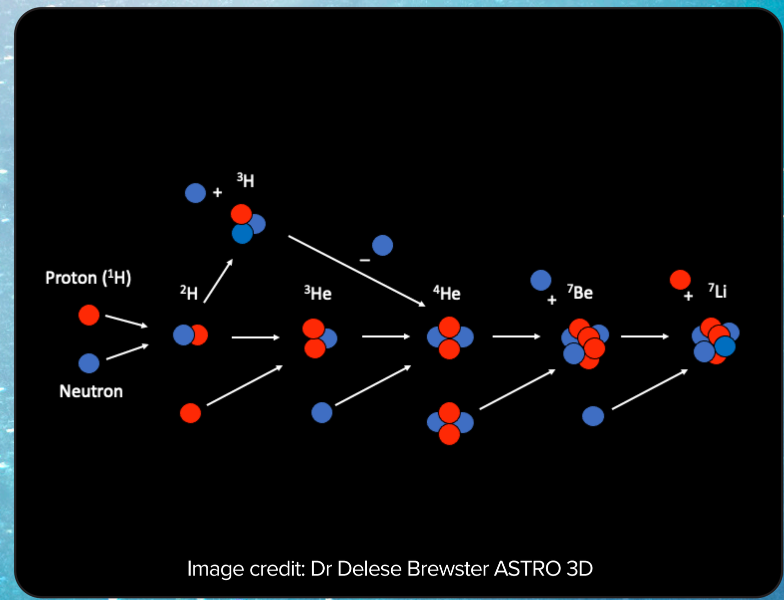

Image credit: Dr Delese Brewster ASTRO 3D

The Big Bang Nucleosynthesis produced the lightest elements. A few minutes after the Big Bang, when the expanding and cooling Universe reached 1 billion Kelvin, neutrons fused with protons to form the hydrogen isotope deuterium (2H), then helium (3He, 4He) and some lithium (7Li). The Universe cooled to 10 million Kelvin and fusion stopped. Mostly hydrogen (75%) and helium (25%) were available to form the first stars.

OBSERVATIONAL METHOD

Theoretical models are in agreement with the abundances of H and He in the Universe, however, the prediction for Li does not match the observations of this trace element in the oldest stars, which are supposed to have recorded its Big Bang production. This yet unsolved puzzle is called the 'cosmological Li problem'.

SYNTHESIS METHOD

The nuclei of these elements (i.e., H, He, Li) were created within minutes of the Big Bang. These combined with electrons to form atoms around 380,000 years after the Big Bang. We now see the photons emitted at that time as the Cosmic Microwave Background.

EXPLODING MASSIVE STARS

Image credit: X-ray: NASA/CXC/GSFC/B. J. Williams et al; Optical: NASA/ESA/STScI

A massive star can be 8x to 50x the mass of our Sun—the greater the mass, the shorter the star's life. After a few million years, a massive star's core will collapse, resulting in a violent supernova (Type II) explosion. Some become neutron stars and some become black holes.

OBSERVATIONAL METHOD

It is possible to see nearby supernovae with the naked eye. In 1987, people in Australia could see the supernova 1987A in the Large Magellanic Cloud for a whole month. Supernova remnants, like the Crab Nebula, can also be 'seen' with radio waves and x-rays.

SYNTHESIS METHOD

Some elements like C, O, Mg, Fe, N, Si, S, Ca are produced inside the star before its death. Others are created by fusing lighter elements into heavier ones like Ni, Zn, Cr, Mn, Cu during the supernova explosion.

EXPLODING WHITE DWARFS

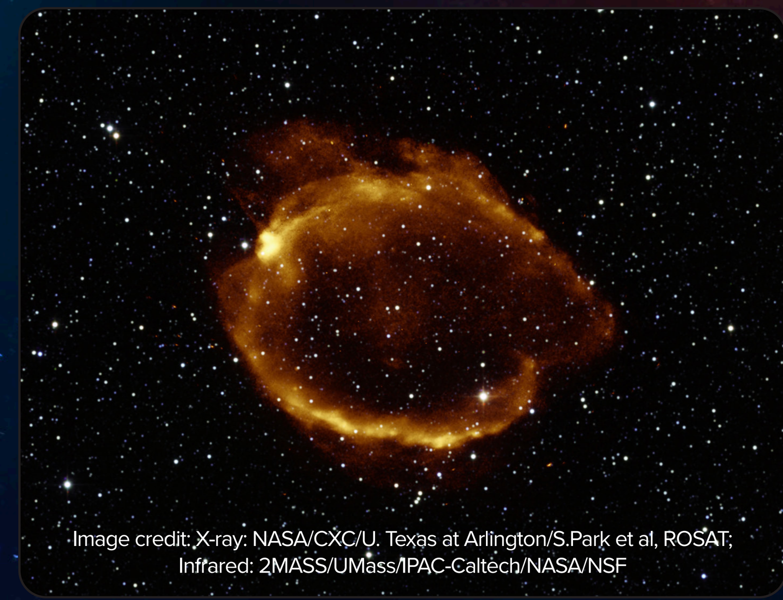

Image credit: X-ray: NASA/CXC/U. Texas at Arlington/S.Park et al, ROSAT; Infrared: 2MASS/UMass/IPAC-Caltech/NASA/NSF

White dwarfs are incredibly dense stars that have run out of easy-burning fuel and are cooling down. A white dwarf in a binary system 'steals' gas from its neighbouring star. If a sufficient amount is collected, the increase in mass, pressure and temperature in the core of the white dwarf reignites nuclear fusion. This results in a supernova (Type Ia).

OBSERVATIONAL METHOD

Space telescopes, such as the Chandra X-ray Observatory, can observe supernovae for weeks after the initial explosion and see the concentration of elements increasing over time. This increase tells scientists that it was the explosion that created the elements. Supernovae emit intense optical (i.e., visible light) from newly-created elements. The elements produced by this type of supernova differ from those produced by exploding massive stars.

SYNTHESIS METHOD

Nuclear fusion within the explosion mostly creates the elements close to iron.

MERGING NEUTRON STARS

Image credit: University of Warwick/Mark Garlick,CC BY 4.0

A neutron star is the ultra-dense remains of a massive star. If two neutron stars are in close orbit, they may crash together due to the pull of gravity. This merger results in the formation of elements heavier than iron.

OBSERVATIONAL METHOD

The theory for this process was established in 1957[1], but not observed until the 2020s in groundbreaking science. Instrumentation was ready to observe gravitational waves predicted to be produced by events such as the merging of neutron stars. On 14 August 2017, the LIGO and Virgo detectors sensed the first-ever gravitational wave signal from a neutron star—neutron star merger. It also produced light. Optical telescopes were focused on the signal, collecting data for weeks afterward. Astronomers identified some elements, such as Sr, by analysing this light with spectrometers on telescopes.

SYNTHESIS METHOD

Neutron capture into the nucleus rapidly produces heavier elements.

DYING LOW-MASS STARS

Image credit: NASA, ESA, CSA, STScI

A low-mass star is up to 8x heavier than our Sun. These stars die when as red giants, they eject all the material from their outer layers leaving behind a white dwarf. Most of the aging low-mass stars in our galaxy fall into this category.

OBSERVATIONAL METHOD

As with merging neutron stars, the theory for how low-mass stars produce elements was established in a 1957[1] paper. The authors were able to calculate which elements would be made in low-mass stars. One of these elements was technetium (Tc).

Spectroscopy of dying low-mass stars shows the signature of Tc. This observation supports the calculations, and since the half-life of Tc is very short, it could only be observed if it was synthesised within the star.

SYNTHESIS METHOD

Neutrons are slowly captured by iron (from previous generations of stars) to produce heavier elements.

1) Burbidge, E. Margaret., Burbidge, G. R., Fowler, William A. & Hoyle, F. (1957) Synthesis of the Elements in Stars. *Rev. Mod. Phys.* **29**, 547-650.