AstroTalk: Behind the news headlines of March 2016

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A stellar treasure chest of gold and other heavy elements

Stars that are quite a lot more massive than our Sun end their lives in spectacular explosions known as supernovae. For the first time, the orbiting *Kepler* space telescope has now captured the brilliant flash of an exploding star's shock wave—what astronomers usually refer to as the "shock breakout"—in visible light. An international science team analysed light captured by *Kepler* every 30 minutes over a three-year period, searching some 50 trillion stars spread across 500 distant galaxies.

In 2011, two massive stars, so-called "red supergiants", exploded while in *Kepler*'s view. The first of these, known by its catalogue number KSN 2011a, is nearly 300 times the size of our Sun and located 700 million light years from Earth. The second, KSN 2011d, is roughly 500 times the size of our Sun and about 1.2 billion light years away.

> "*To put their size into perspective, Earth's orbit about our Sun would fit comfortably within these colossal stars*," said Peter Garnavich, an astrophysics professor at the University of Notre Dame (USA), who led the analysis.

Whether it's a plane crash, a car wreck or a supernova, capturing images of sudden, catastrophic events is extremely difficult but tremendously helpful for understanding the event's root cause. The steady gaze of *Kepler* allowed astronomers to see, at last, a supernova shock wave as it reached the surface of a star. Catching this flash of energy is an investigative milestone for astronomers, because the shock breakout only lasts about 20 minutes.

> "*Like police getting surveillance footage of a crime after the event, we can study brightness histories from* Kepler *to find out what was happening in the exact hour that the shock wave from the stellar core reached the surface of the star*," said Edward Shaya, an associate research scientist at the University of Maryland (also in the USA) and a co-author of the study. "*These events are bright enough that they change the brightness of the whole galaxy by a measurable amount.*"

Supernovae like these—known as Type II—begin when the internal furnace of a star runs out of nuclear fuel, causing its core to collapse as gravity takes over. As the core of a supernova collapses to form a neutron star, energy bounces back from the core in the form of a shockwave that travels at 30,000 to 40,000 km s^{-1}, and causes the nuclear fusion that creates heavy elements such as gold, silver and uranium.

> "*It's like the shockwave from a nuclear bomb, only much bigger, and no one gets hurt*," said Brad Tucker, from the Australian National University's Research School of Astronomy and Astrophysics.

The two supernovae the team observed with *Kepler* matched up well with mathematical models of Type II explosions, thus reinforcing some existing theories. But the supernovae also revealed an unexpected variety in these devastating stellar events. While both explosions delivered a similar energetic punch, no shock breakout was seen in the smaller of the two supergiants. Scientists think that this is likely due to the smaller star being surrounded by gas—perhaps enough to mask the shock wave when it reached the star's surface.

> "*That is the puzzle of these results*," said Garnavich. "*You look at two supernovae and see two different things. That's maximum diversity*."

The team from the Australian National University, the University of Notre Dame, the Space Telescope Science Institute, the University of California Berkeley and the University of Maryland saw a shockwave only in the smaller star with a radius 270 times that of the Sun, shown as a peak in the light emitted from the explosion in the first few days. In the second star, a large supergiant with a radius 460 times that of the Sun, a shockwave could not be detected, although it must have existed, said Brad Tucker.

> "*The star was so large that the shockwave did not travel all the way to the surface*," he said.

Studying the physics of these violent events allows scientists to better understand how the seeds of chemical complexity and life itself have been scattered in space and time in our Milky Way galaxy.

> "*All heavy elements in the Universe come from supernova explosions. For example, all the silver, nickel, and copper in the Earth and even in our bodies came from the explosive death throes of stars*," said Steve Howell, project scientist for the *Kepler* mission and its follow-up *K2* operation, based at NASA's Ames Research Center in California's Silicon Valley. "*Life exists because of supernovae*."

> "*We are really probing the process of blowing up*," Brad Tucker said. "*Supernovae made the heavy elements we need to survive, such as iron, zinc and iodine, so we are really learning about how we are created*."

Garnavich, Shaya and their co-authors are part of a research team known as the *Kepler* Extragalactic Survey (KEGS). The team is nearly finished mining data from *Kepler*'s primary mission, which ended in 2013. However, with the reboot of the *Kepler* spacecraft as the *K2* mission, the team is now hunting for supernova events in other, distant galaxies.

> "*It is a thrill to be a part of theoretical predictions becoming an observed and tested phenomenon,*" Shaya said. *"We now have more than just theory*

> *to explain what happens when a supernova shock wave reaches the surface of a star as that star is totally torn apart*."

The origin of the heavy elements was a popular research theme last month, in fact, at least as reported by the news media. Michigan State University (MSU) researchers, working with colleagues from the Technical University Darmstadt in Germany, were also reported to be zeroing in on the answer to the question as to where heavy elements, such as gold, uranium and plutonium, originate. Currently, there are two candidates, supernovae or neutron-star mergers, in which two of these small yet incredibly massive stars come together and spew out huge amounts of stellar debris.

In a recently published paper in the journal *Physical Review Letters*, the researchers detail how they used computer models to come closer to an answer.

> "*At this time, no one knows the answer*," said Witold Nazarewicz, a professor at the MSU-based Facility for Rare Isotope Beams (FRIB) and one of the co-authors of the paper. "*But this work will help guide future experiments and theoretical developments*."

By using existing data, often obtained by means of high-performance computing, the researchers were able to simulate production of heavy elements in both supernovae and neutron-star mergers.

> "*Our work shows regions of elements where the models provide a good prediction*," said Nazarewicz. "*What we can do is identify the critical areas where future experiments will work to reduce uncertainties of nuclear models*."

Meanwhile, in a letter published in the prestigious journal *Nature Physics*, a team of scientists from the Hebrew University of Jerusalem (Israel) recently suggested a closely related solution to the Galactic radioactive plutonium puzzle. All of the plutonium used on Earth is artificially produced in nuclear reactors. Still, it turns out that it is also produced in nature.

> "*The origin of heavy elements produced in nature through rapid neutron capture ('r-process') by seed nuclei is one of the current nucleosynthesis mysteries*," Kenta Hotokezaka, Tsvi Piran and Michael Paul from the Racah Institute of Physics at the Hebrew University of Jerusalem wrote in their letter.

Plutonium is a radioactive element. Its longest-lived isotope is plutonium-244, with a lifetime of 120 million years. Detection of plutonium-244 in nature would imply that the element was synthesized in astrophysical phenomena not so long ago—at least on Galactic time-scales—and hence its origin cannot be too far away from us. Several years ago it was discovered that the early Solar system contained a significant amount of plutonium-244. Considering its short-lived cycle, plutonium-244 that existed over four billion years ago when Earth formed has long since decayed, but its daughter elements have been detected.

However, recent measurements of the deposition of plutonium-244, including analysis of interstellar debris that fell to Earth and settled in the deep seas, suggest that only a very small amount of plutonium has reached Earth from outer space over the most recent 100 million years. This is in striking contradiction to its presence at the time when the Solar System was formed, and that is why the amount and origin of the Galactic radioactive plutonium has remained a puzzle.

The Hebrew University team have shown that these contradicting observations can be reconciled if the source of radioactive plutonium (as well as of other rare elements, such as gold and uranium) is in mergers of binary neutron stars. These mergers are extremely rare events, but they are expected to produce large amounts of heavy elements. The model implies that such a merger took place accidentally in the vicinity of our Solar System within 100 million years before it was born. This has led to the relatively large amount of plutonium-244 observed in the early Solar System. On the other hand, the relatively small amount of plutonium-244 reaching Earth from interstellar space today is simply accounted for by the rarity of these events. Such an event hasn't occurred in the last 100 million years in the vicinity of our Solar System.

Around the same time last year, scientists from RIKEN—Japan's largest comprehensive research institution—used their institution's RIBF, one of the world's most powerful devices for the creation of exotic atomic nuclei, to obtain precise measurements of the half-lives of 110 nuclei, 40 of which had never been measured before. These nuclei are located at the boundary of the known nuclear chart, and despite their short lifetimes—measured in milliseconds—these nuclei imprint their properties on the chemical composition of the Universe.

This research, published in *Physical Review Letters* within the last year, is a major step forward towards providing an experimental ground for models of the mysterious astrophysical r-process, which is believed to be responsible for the creation of many of the elements in the Universe heavier than iron. In fact, the astrophysical 's-process' is well-understood to produce approximately half of the heavy elements in the Universe. This is a nucleosynthesis process whereby heavier nuclei are created by slow neutron capture. A new element is formed when the captured neutron transforms into a proton, emitting an electron in the process, which is known as radioactive beta (minus) decay.

The r-process, on the other hand, can only take place in extreme conditions, such as when the core of a supernova collapses to become a neutron star, releasing tremendous energy in the process. Under those extreme neutron-rich conditions, atomic nuclei absorb neutrons to become increasingly heavy, and then undergo beta decay, leaving the nucleus one element higher on the periodic table. Gradually, the nuclei creep up the periodic table, leading to the creation of new elements.

There are hundreds of isotopes that participate in the process, which takes place extremely rapidly. Without accurate knowledge of the half-life of each of these isotopes—how quickly it casts off an electron—it is difficult to make a model that can accurately describe the violent processes that lead to the creation of the elements that we see today.

While significant progress has been made in understanding this complex process, the current models cannot fully explain the abundances of elements found in stars, and work is still ongoing to create better models.

> According to Giuseppe Lorusso, who led the research as a postdoctoral researcher at RIKEN, "*It was very exciting to explore unknown territory in the nuclear chart and discover the half-lives of isotopes that had never been measured before. This new data allows us to get closer to understanding the mystery of nucleosynthesis. The use of the new experimental data removes some longstanding discrepancies between calculated and observed r-process abundances patterns, showing that current models may actually be capturing the essential physics of the r-process*."

However, the findings also brought a surprise.

> "*We found*," he continues, that "*after reducing the uncertainties of nuclear physics with our measurements, the difference in the abundance of elements such as tin, antimony, iodine, and cesium, among very old stars created in the early Universe can be understood as originating from differences in the r-process conditions. This opens up the possibility that by looking at the distribution of elements in those stars, we can gain an understanding of the precise environment in which the r-process took place*."

I find it particularly fascinating that by combining astrophysical observations with laboratory experiments we can actually gain useful new insights into the violent processes that take place in the interiors of the most massive stars in the Universe.

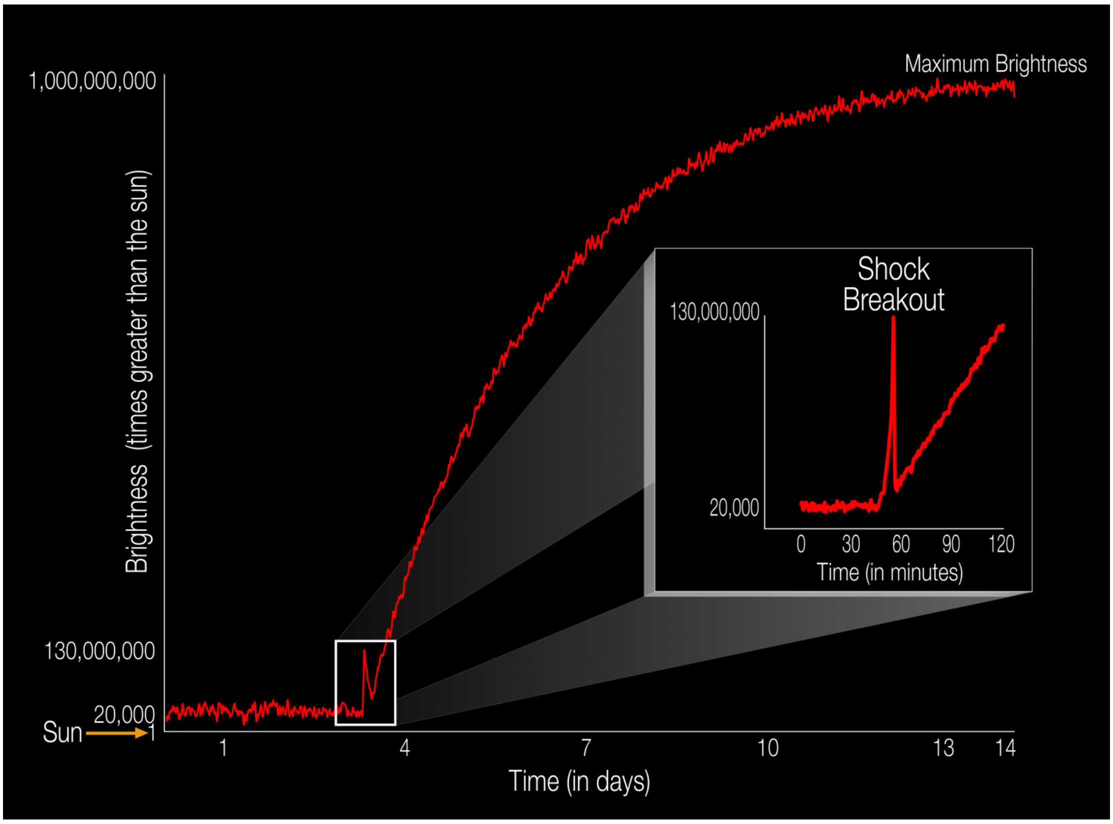
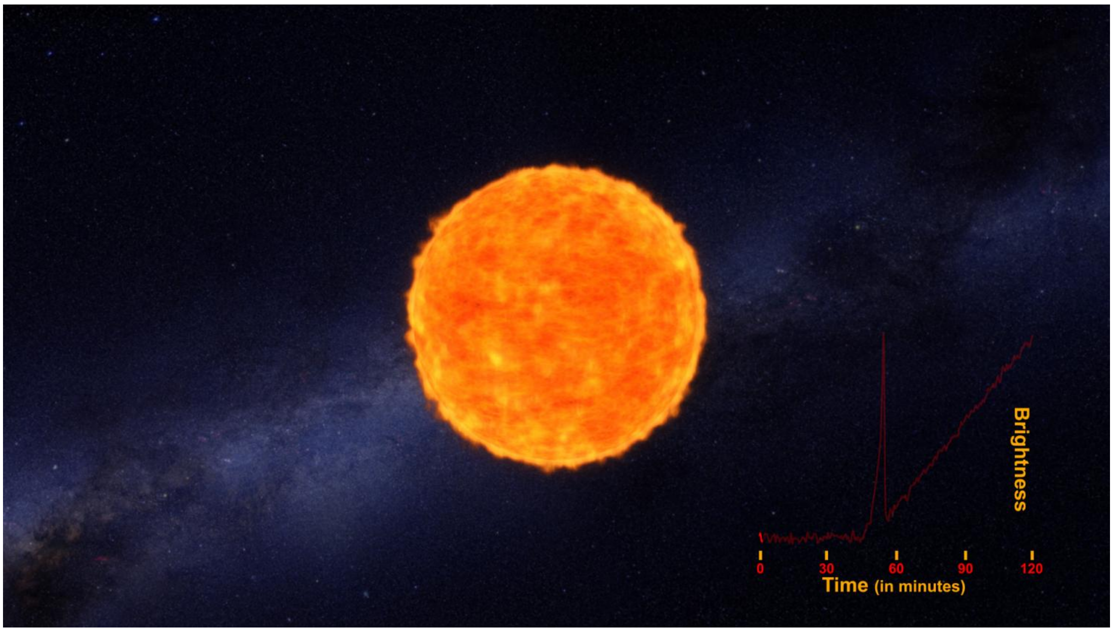
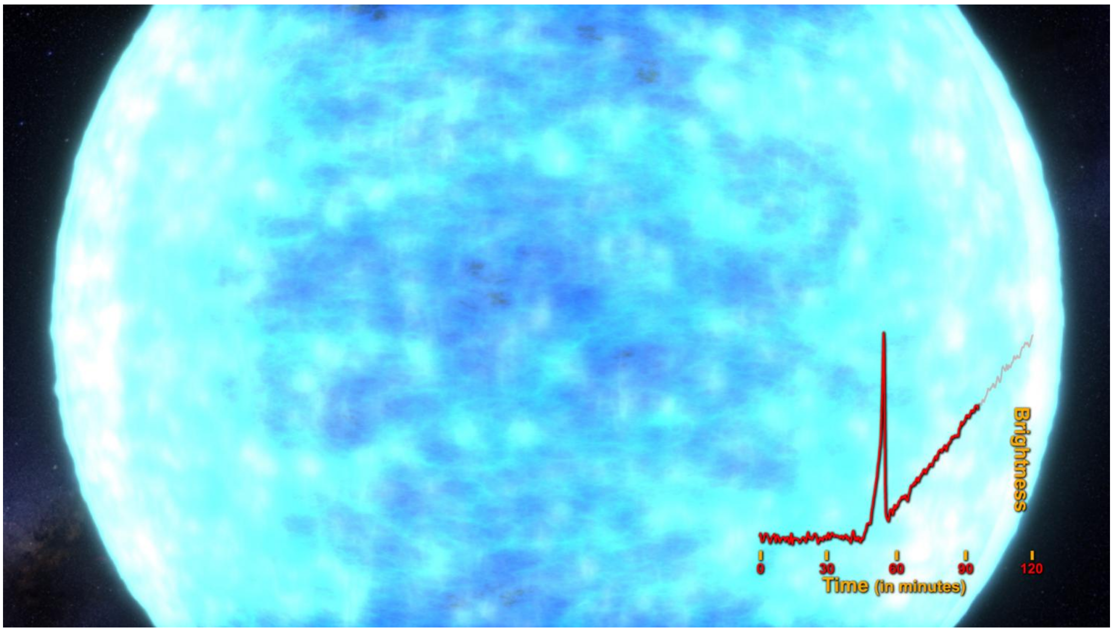


Figure 1: This diagram illustrates the brightness of a supernova event relative to the Sun as the supernova unfolds over time. For the first time, a supernova shock wave, or shock breakout, has been observed in visible light as it reached the surface of the star from deep within the star's core. The explosive death of this star, KSN 2011d, reached its maximum brightness in about 14 days. The shock breakout itself lasted only about 20 minutes (see inset). *(Credit: NASA Ames/W. Stenzel)*

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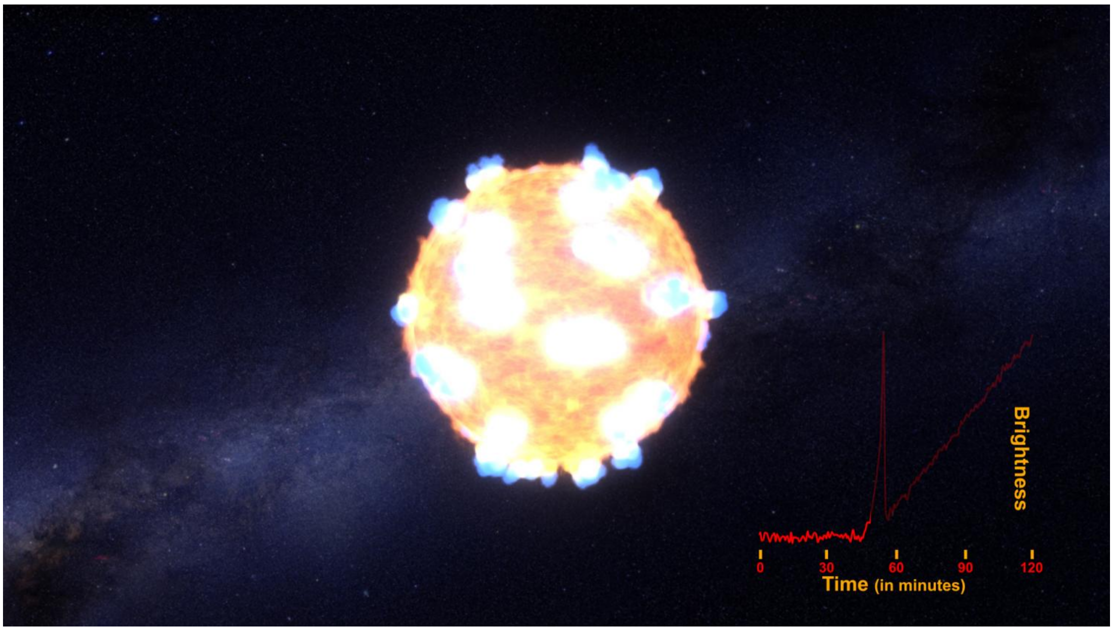
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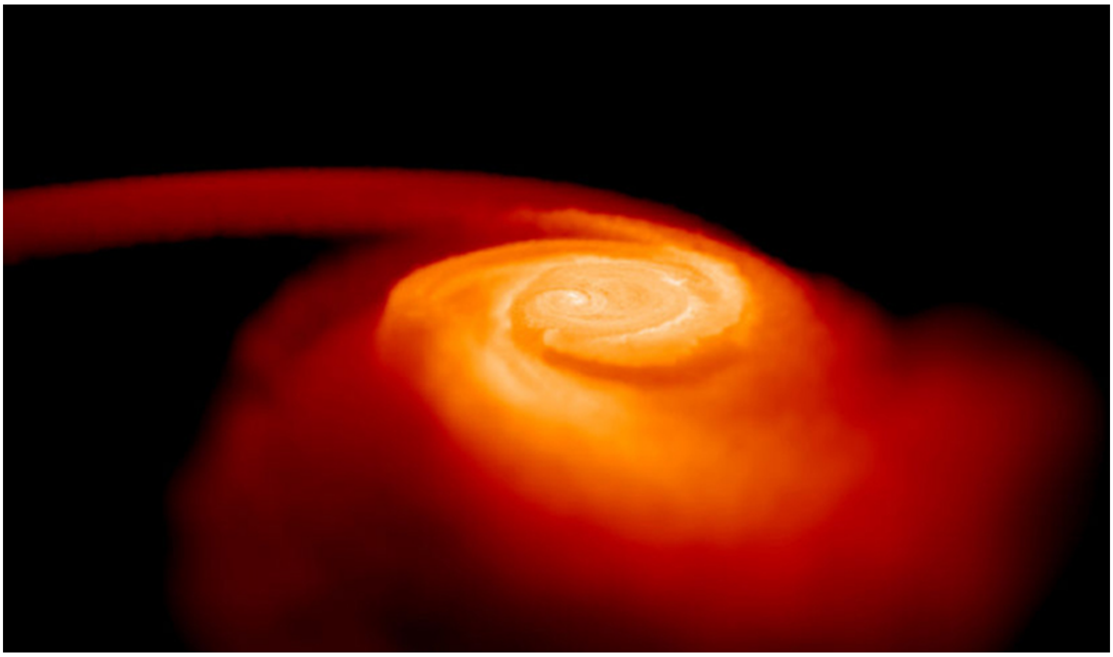

Figure 5: This illustration depicts two neutron stars colliding. As they merge, the stars eject material into space at 10% to 50% of the speed of light. Mergers of these kinds of stars are thought to be the source of gold and other heavy metals found throughout the universe. *(Credit: Stephan Rosswog, Jacobs University Bremen.)*

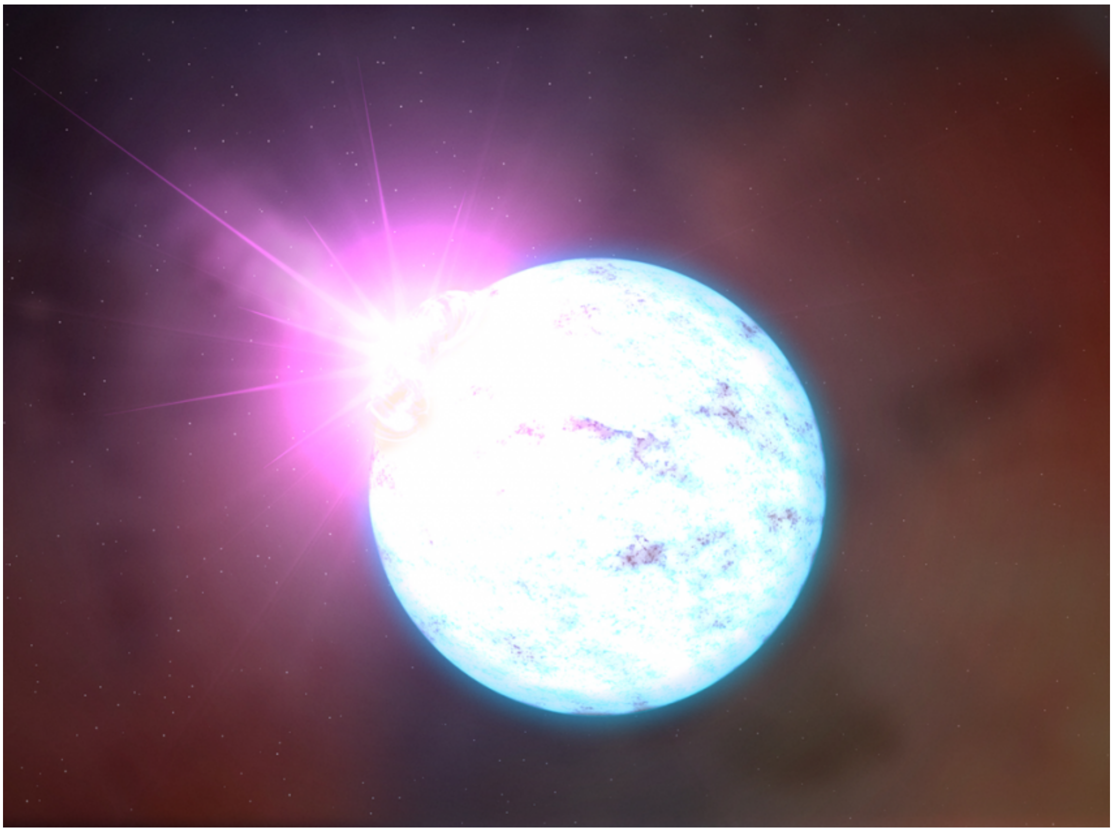

Figure 6: Neutron star. *(Credit: NASA)*

Figure 7: The table of nuclides maps the radioactive behaviour of isotopes. *(Credit: iStockphoto)*

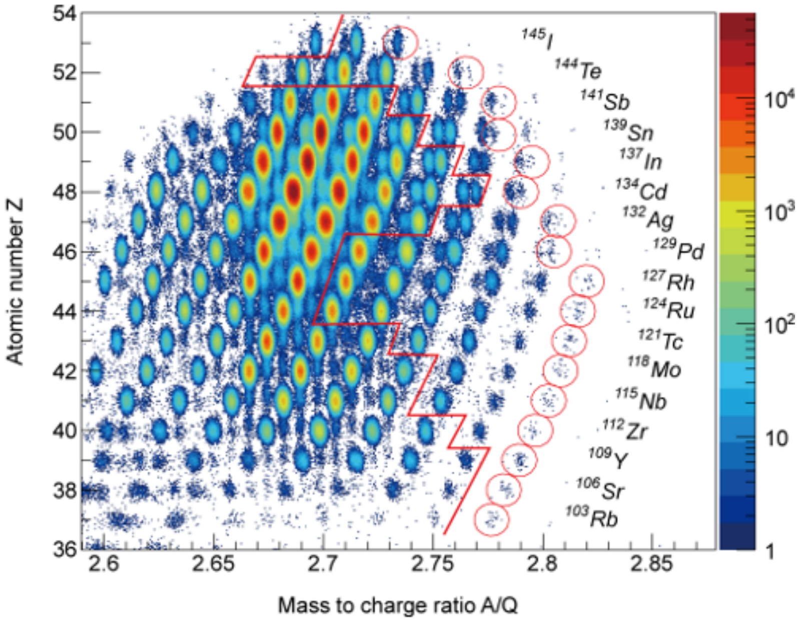

Figure 8: Nuclei with newly measured half-lives are on the right side of the red solid line. The heaviest masses for which half-lives can be measured are tagged for reference by red circles. The half-lives reported here are for the elements from rubidium (Rb) to tin (Sn).