Single neutron star merger supplied half the Solar System’s plutonium

Enlarge / The aftermath of a simulated neutron star merger.

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We are all, as Carl Sagan said, star-dust. You might think that since most stars are pretty much the same, all star-dust is equal. But we have evidence that some star-dust is more equal than others. Yes, some elements seem to have a very special origin: neutron star mergers.

Most stars are pretty much all hydrogen. Near their center, fusion busily turns hydrogen into helium. Eventually, that hydrogen will run out and, like a pub that runs out of beer, the real destruction begins. The star starts turning helium into heavier elements at an increasingly feverish rate. The end, no matter how hot and heavy the star, comes when the star’s core is made of iron.

Up to iron, the process of fusion releases more energy than it consumes. But after iron, fusion consumes more energy than it releases, which essentially shuts the star down. Once this was understood, scientists were left wondering where the remaining 80 odd elements that are heavier than iron came from.

Bring on the neutron stars

Heavier stars end their life in a supernova—a violent explosion. These explosions can create many of the elements heavier than iron. However, a supernova will still only get us as far along the periodic table as molybdenum, leaving about 40 elements unexplained.

Then, a neutron star merger was observed, first via gravitational waves and later with various other hardware. It seemed that the merger produced the right conditions to create the remaining elements via a process called rapid neutron capture.

Imagine an iron atom sitting around minding its own business. Iron has 26 protons—the number of protons determines the element—and 30 neutrons, which act to glue the protons into the nucleus. Suddenly, thanks to a heavy neutron bombardment, the iron nucleus starts accumulating neutrons at a rapid rate. When the iron nucleus hits 32 neutrons, one of the neutrons emits an electron to turn into a proton. That turns the ion nucleus into a cobalt nucleus.

The capture and decay process can continue to encompass all the naturally occurring elements. But it only happens if there’s a large source of neutrons to bombard the atom, which a neutron star merger provides. We’ve only observed one neutron star merger at this point, though, which leaves things a bit uncertain.

How special are neutron star mergers?

In the new study, researchers have examined the ratio of elements found in asteroids. Asteroids are a bit like time capsules from the past. These rocks have floated around the Solar System doing basically nothing, at least until some of

them had the luck to land on Earth. Over that time, the radioactive elements will decay, leaving behind stable isotopes of different elements. For some elements with very long half-lives, some of the original radioactive material is still around in asteroids.

A team of researchers was able to estimate the abundance of actinides—elements with atomic numbers from 89 upwards—in asteroids and thus what it must have been in the primeval Solar System. That analysis showed that supernovae are almost certainly not the source of the actinides.

This conclusion is based on a reasonably long chain of logic. First, if supernovae are a major contributor to actinide formation, then there should be an average amount of actinide production per explosion. Stars follow a predictable life, so the researchers can estimate how many stars went kaboom in time to contribute material to the formation of our Solar System. But the numbers simply don't work out: if actinides were produced by supernovae, it would lead to a higher abundance of these elements than we actually observe.

On the other hand, the researchers are also able to estimate the number of neutron star mergers that could contribute material to the formation of the Solar System. Neutron stars are (from a computational point of view) nearly ideal stars, so we can model their behavior pretty well. Combine those models with our observations of a single neutron star merger, and researchers have a pretty good idea of actinide production.

Here the numbers seem to work out: the number of mergers that could have contributed to our early Solar System (a number based on how often these things seem to occur) produces an actinide abundance that brackets the one estimated from asteroids.

It gets even better. It seems that nearly half the plutonium

in the Solar System came from a single neutron star merger. That is fascinating: with such low numbers of neutron star mergers contributing to actinide abundance, the variation from solar system to solar system must be huge. Imagine, we could have ended up in a solar system with almost no uranium or plutonium.

Now, a note of caution: in this research, the scientists compared standard supernova with neutron star mergers. But there is a special class of supernova called collapsars that are a different story. Collapsars may also be able to supply actinides, but we still don’t know a lot about the physics there. And the researchers behind this paper suggest that they are too infrequent to have supplied the observed amount of actinides. This leaves neutron star mergers as the most likely option.

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