Formation of Heavy Elements Through R-Process

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Abstract:

Background: Scientists have long been trying to figure out how heavier elements are made. It is believed the natural abundances of heavier elements can be explained through neutron star mergers. Due to the intense heat and abundance of neutrons, it is predicted that this is the most likely source to account for the earth abundance of certain elements. **Purpose:** To determine how the heaviest nuclei are naturally formed along the neutron drip line. **Methods:** Much of the research on neutron star mergers is hypothetical, but observing stellar events, and data taken from particle accelerators comprise major contributions to the available body of information. **Results:** Available data suggests the heavier elements would be created in similar proportions to those modeled through the rest of the universe. **Conclusions:** Data supports the hypothesis that these elements are created by r-process in the neutron star merger. More powerful accelerators are being built to study these processes, and the body of existing data should increase drastically with each advance in accelerator technology.

I. Introduction:

R-process is the process by which half the heavier nuclei, such as gold and platinum, are believed to be made. This can only occur where intense heat and a large number of nuclei are present. With temperatures in the billions of degrees, it is impossible to study the actual conditions up close as r-process is occurring. Because these criteria are not going to be met naturally on earth, scientists look to the stars to account for the abundances of heavy elements in the universe. Scientists hypothesize the most likely sources of r-process nucleosynthesis is to be found in supernovae core collapse and neutron star mergers.

II. Star Formation:

Core-collapse supernovae, the most common supernovae found in nature, are responsible for creating both black holes and neutron stars (Woolsey). As Artemis Spyrou presented in her lecture, supernovae begin as big, cooler stars burning hydrogen through fusion. The star uses the hydrogen as fuel until it runs out, then it moves on to the next. “Each time one fuel runs out, the star contracts, heats up, and then burns the next one, usually the ashes of the previous stage” (Woosley). This process continues creating a progressively denser mass with each contraction and burning a little hotter to utilize the next available, somewhat heavier fuel source. Once the

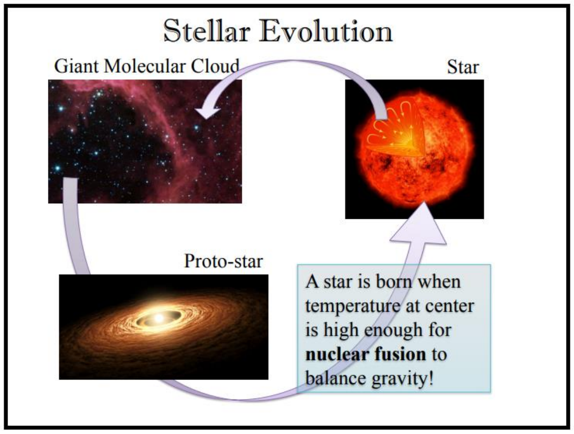

Figure 1: Star Evolution Artemis Spyrou's Lecture April 20,2018.

hydrogen is exhausted due to fusion, the core collapses, and the star begins to exhaust the supply of the helium created through the fusion of hydrogen. Once the helium has been exhausted, the star burns lithium, and so on.

III. SuperNovae:

The more massive stars will be able to continue this process of consuming the products of the last fusion fuel until they develop an extremely hot and dense core of iron. The nuclear binding energy of the elements increases up to iron 56 which is the most tightly bound nucleus. The coulombic force prevents anything heavier than this from being created by fusion at the temperature of an ordinary star (Cowan). After iron -56, heavier elements are created throught the process of fission and the fission products are endothermic.

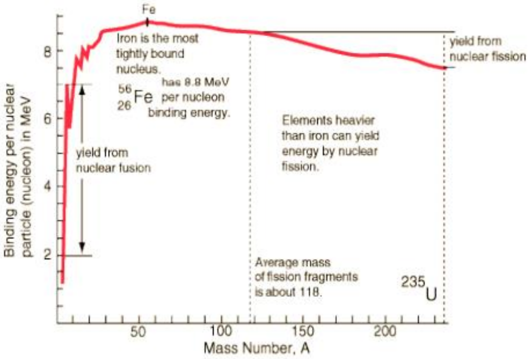

Figure 2: Binding energy per nucleon increases up to iron 56. Here, fusion stops and heavier nuclei are created through neutron capture (Riquelme).

The star becomes so dense it is unable to support its own gravity and the rapid collapse of the core causes shock waves resulting in an intense explosion known as a supernova (Physics, Spyrou, Woosley). The supernova is hotter and more intense than the initial conditions of the star and forms the heavier elements. The supernova is hotter and more intense than the initial conditions of the star and forms the heavier elements. The resulting explosion sends out a mix of isotopes of the elements created in the supernova. Stable only in the conditions of the supernova these isotopes decay rapidly into the stable elements we see distributed across the galaxy.

IV. Neutron Stars:

What's left of the star after this supernova explosion becomes a neutron star. The remaining matter is very neutron rich and the resulting body is extremely dense. According to Nasa.gov, "Neutron stars cram roughly 1.3 to 2.5 solar masses into a city-sized sphere perhaps 20 kilometers (12 miles) across" (Naeye). Being so dense, they have a strong gravitational pull.

When remnants of two such stellar bodies come close together, this strong gravitational pull causes them draw closer and closer together over time. As they draw closer, they orbit each other, forming a binary system which gradually draw in closer and closer until the stars merge (Mclaughlin).

When the stars come together, they "release energy in various forms including gravitational waves, matter, and light" (McLaughlin).

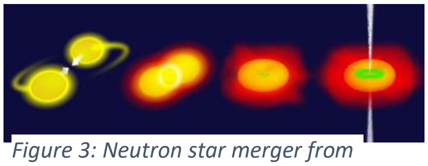

Figure 3: Neutron star merger from binary system (left) to a singular mass realising energy in gravitational waves, matter, and light. (McLaughlin)

In August of 2017, astrophysicists detected gravitational waves at multiple facilities across the world. This detection allowed scientists to observe a neutron star merger for the first time.

V. R-Process

R-process is a form of neutron capture. It describes rapid neutron capture. Because the r-process requires extremely high temperatures in a neutron rich environment, it has long been hypothesized that the source must be somewhere in the heavens. The extreme temperatures required for neutron capture is unobtainable on earth and this implies the matter must come from somewhere else. The recent neutron star merger finally allowed for observable data to be collected.

The matter ejected by the creation of a neutron star from a supernova and the matter ejected by the merger of two such stars include the heavier elements created by the r-process.

Nuclei created by r-process tend to follow a path that stays relatively near to the neutron drip line. The nuclei that are created are highly unstable outside the environment of the neutron star. The nucleus rapidly captures the excess neutrons in the extreme temperatures. When the matter leaves this environment, it cools rapidly and undergoes beta decay. The excess neutrons decay into protons or the nuclei are so unstable that the energy to remove a neutron is much less than or equal to zero, so it is lost. “After beta decay new nucleus will have new neutron drip line and in most cases able to capture more neutrons” (Burcher). This creates the next element up the table, capable of a different range of isotopes.

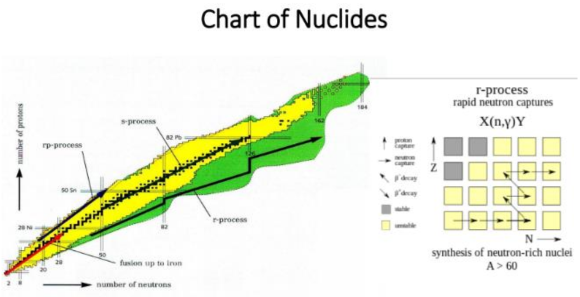

Figure 4:The nuclei created by the r-process follow a path along the neutron drip line (Burcher).

Observing the recent neutron star merger, physicists attempted to discern whether this merger was responsible for the creation of the heavier elements. They chose to look at the natural abundance of europium in the milky-way and compare it to the ejected yield of the event. The data they collected was representative of the assumption that neutron star mergers were responsible for the proportions of the elements found in the universe (Côté).

VI. Conclusions

Scientists have been seeking to explain the existence of the heaviest elements in the proportions in which they occur in our Milky Way. Based upon the expected abundances of the elements, it has long been thought that supernovae are not alone in the production of these elements. Which causes particular interest in neutron star mergers.

Because these events are so rare, it is hard to say whether the data collected can be considered to represent typical behavior of a neutron star merger. However, it does seem highly likely that this sort of stellar interaction is the predominant source of r-process nuclei.

Based on recent observations and comparisons to the expected values, the matter ejected from the explosion fit the expected values for it's abundance in the material.

But recent evidence and previous observation suggest that neutron star mergers are the dominant source of heavy nuclei ejecta. Coupled with supernova formation, these processes form the vast majority of the heavy elements across the universe.

As more advanced research facilities, such as the FRIB, are being developed, scientists soon will be better able to replicate the conditions they wish to study and more accurate data will be revealed.

Citations:

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