Cosmic crashes forging gold: Nuclear reactions in space do produce the heaviest elements

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Where did gold form? For a long time, the cosmic production site of this rare metal - here are shown natural gold nuggets from California and Australia - and of other very heavy chemical elements has been unknown. New theoretical models now confirm that it could be forged in the merger events of two neutron stars. Credit: Natural History Museum, London

(PhysOrg.com) -- Collisions of neutron stars produce the heaviest elements such as gold or lead. The cosmic site where the heaviest chemical elements such as lead or gold are formed has most likely been identified: Ejected matter from neutron stars merging in a violent collision provides ideal conditions. In detailed numerical simulations, scientists of the Max Planck Institute for Astrophysics and affiliated to the Excellence Cluster Universe and of the Free University of Brussels have verified that the relevant reactions of atomic nuclei do take place in this environment, producing the heaviest elements in the correct abundances.

Most heavy chemical elements are formed in nuclear fusion reactions in stars. Also in the centre of our Sun, hydrogen is “burned” to create helium, thereby releasing energy. Heavier elements are then produced from helium if the star is more massive than our Sun. This process, however, only works up to iron; further fusion reactions do not yield any net energy gain. Therefore heavier elements cannot be produced in this fashion. Instead, they can be assembled when neutrons are captured onto “seed”-nuclei, which then radioactively decay.

This involves two main processes: the slow neutron capture (s-process), which takes place at low neutron densities inside stars during their late evolution stages, and the rapid neutron capture (r-process), which needs very high neutron densities. Physicists know that the r-process is responsible for producing a large fraction of the elements much heavier than iron (those with nuclear mass numbers A > 80), including platinum, gold, thorium, and plutonium. However, the question of which astrophysical objects can accommodate for this r-process remains to be answered.

“The source of about half of the heaviest elements in the Universe has been a mystery for a long time,“ says Hans-Thomas Janka, senior scientist at the Max Planck Institute for Astrophysics and within the Excellence Cluster Universe. ”The most popular idea has been, and may still be, that they originate from supernova explosions that end the lives of massive stars. But newer models do not support this idea. “

Violent mergers of neutron stars in binary systems (see background information on neutron stars) offer an alternative scenario, when the two stars collide after millions of years of spiralling towards each other. For the first time, scientists at the Max Planck Institute for Astrophysics and the Free University of Brussels have now simulated all stages of the processes occurring in such mergers by detailed computer models. This includes both the evolution of the neutron star matter during the relativistic cosmic crashes and the formation of chemical elements in the tiny fraction of the whole matter that gets ejected during such events, involving the nuclear reactions of more than 5000 atomic nuclei (chemical elements and their isotopes (see background information on isotopes)).

”In just a few split seconds after the merger of the two neutron stars, tidal and pressure forces eject extremely hot matter equivalent to several Jupiter masses,“ explains Andreas Bauswein, who carried out the simulations at the MPA. Once this so-called plasma has cooled to less than 10 billion degrees, a multitude of nuclear reactions take place, including radioactive decays, and enable the production of heavy elements. ”The heavy elements are `recycled' several times in various reaction chains involving the fission of super-heavy nuclei, which makes the final abundance distribution become largely insensitive to the initial conditions provided by the merger model,“ adds Stephane Goriely, ULB researcher and nuclear astrophysics expert of the team. This agrees well with previous speculations that the reaction properties of the atomic nuclei involved should be the decisive determining factor because this is the most natural explanation for the essentially identical abundance distributions of the heaviest r-process elements observed in many old stars and in our solar system.

The simulations showed that the abundance distribution of the heaviest elements (with mass numbers A > 140) agrees very well with the one observed in our solar system. If one combines the results of the simulations and the estimated number of neutron star collisions in the Milky Way in the past, the figures indicate that such events could in fact be the main sources of the heaviest chemical elements in the Universe.

The team now plans to conduct new studies to further improve the theoretical predictions by refined computer simulations that can follow the physical processes in even more detail. On the other hand, observational astronomers look out for detecting the transient celestial sources that should be associated with the ejection of radioactive matter in neutron star mergers. Because of the heating by radioactive decays, the ejecta will shine up with almost the brightness of a supernova explosion — albeit only for a few days. A discovery would mean the first observational hint of freshly produced r-process elements in the source of their origin. The hunt is on!

More information: Stephane Goriely, et al., r-process nucleosynthesis in dynamically ejected matter of neutron star mergers, *The Astrophysical Journal*, 10. September 2011; doi:10.1088/2041-8205/738/2/L32

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