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Letter

Do we owe our existence to gravitational waves?

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ABSTRACT

Two heavy elements essential to human biology are thought to have been produced by the astrophysical *r*-process, which occurs in neutron-rich environments: iodine is a constituent of thyroid hormones that affect many physiological processes including growth and development, body temperature and heart rate, and bromine is essential for tissue development and architecture. Collisions of neutron stars (kilonovae) have been identified as sources of *r*-process elements including tellurium, which is adjacent to iodine in the periodic table, and lanthanides. Neutron-star collisions arise from energy loss due to gravitational-wave emission from binary systems, leading us to suggest that gravitational waves have played a key role in enabling human life by producing iodine and bromine. We propose probing this proposal by searching in lunar material for live ^{129}I deposited by a recent nearby kilonova explosion.

1. Introduction

Ever since observations of 'guest stars' were first recorded [1,2], there has been widespread interest in their possible significance as harbingers of life and death. Many of the most important elements in the human body, such as carbon and oxygen, originated in large part from supernova explosions [3]. Supernovae are thus essential for life, yet explosions too nearby may have caused one or more mass extinctions of life on Earth [4,5]. This motivated the search for nuclear abundance anomalies in geological strata from the time when the dinosaurs met their demise, which found the first evidence that their extinction was in fact due to an asteroid impact [6]. Detailed modeling [7] indicates that a supernova explosion within ~ 20 pc of Earth, which is expected to occur every few hundred million years, would cause a mass extinction. The presence of live (not decayed) ^{60}Fe in terrestrial and lunar samples dramatically confirms that near-Earth supernova explosions have indeed occurred over the past ~ 10 Myr and within ~ 100 pc [8].

In recent years there has been increasing interest in neutron-star collisions (kilonovae) [9–11]. These events are estimated to have a similar 'kill radius' to supernovae [12] unless the Earth is unlucky enough to be within the narrow line of sight of a Gamma-Ray Burst emitted in the merger event, but are much rarer than supernovae and hence less dangerous. In contrast to these existential dangers, we focus in this article on the benefits to life of kilonova explosions, arguing that they produce elements essential to human life, and that they are made possible by gravitational waves like those discovered recently [13]. In order to make this argument, we first review relevant aspects of human biochemistry.

2. The roles of heavy elements in human biology

The human body is largely composed of the elements hydrogen, carbon and oxygen, with smaller amounts of other elements. As summarized in [14,15], the total number of elements adjudged essential for life exceeds 20. Most of these have atomic numbers $Z < 35$ and are produced by supernovae [3]. However, two heavier essential elements stand out that are produced dominantly by the astrophysical *r*-process that we discuss below: bromine with $Z = 35$ and iodine with $Z = 53$.

Iodine is the better known of this pair: the thyroid hormones triiodothyronine and thyroxine play key roles in many physiological processes in the human body, including growth and development, metabolism, and controlling body temperature and heart rate [16,14]. The role of bromine is less commonly known, but it is an essential trace element for the assembly of collagen IV scaffolds in tissue development and architecture [17].

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We mention in passing some other heavy elements. Gadolinium and uranium ($Z = 64, 92$) are produced mainly by the r-process, as we discuss below, and play roles in the biochemistry of some bacteria [18], but there is no evidence for any biological action of these elements in mammalian biology. Molybdenum ($Z = 42$) is of human biological interest [19,14], and possibly cadmium ($Z = 48$) [15]. Both of these can be produced by the r-process, but this mechanism is not as dominant as for bromine and iodine.

It is also possible that the r-process elements thorium and uranium have been indirectly important for human life. Plate tectonics has played an important role in the evolution of life on Earth, and possibly could be similarly important on Earth-like exoplanets [20–22]. Tectonic activity is possible because the Earth's interior remains hot enough to enable plate motion. The decays of radioisotopes ^{235,238}U and ^{232}Th in the Earth's interior generate $\gtrsim 50\%$ of geothermal heat today, a fact confirmed by measurements of geoneutrinos also produced in these decays [23].

In the following we focus on iodine and bromine and their astrophysical origins.

3. Heavy element production via the *r*-process

The rapid neutron-capture process, known as the r-process, plays an important role in the production of atomic nuclei heavier than iron. Seed nuclei capture a succession of neutrons in time to avoid radioactive decay before another neutron is captured. The reaction pathway therefore lies far from stability, possibly out the neutron drip line, beyond which the nuclear force can no longer retain neutrons. The r-process yields characteristic abundance peaks at $A \sim 80$, 130, and 195, associated with the closed nuclear shells at the magic neutron numbers $N = 50$, 82, and 126. Whether all three abundance peaks owe their origins to the same astrophysical site is an open question, e.g. [24]. However, species within the same abundance peak, such as the elements tellurium ($Z = 52$) and iodine ($Z = 53$), are likely co-produced, with a ratio set by the properties of the unstable nuclear species along the relevant r-process pathway [25].

The r-process is not the only source of heavy elements in the solar system. The main other source is from slow neutron capture via the so-called s-process. In that case the nuclei remain close to stability, so the nuclear physics is very well understood, so that there are relatively tight predictions for solar system s-process abundances [26]. The astrophysical sites are dominated by the late phases of stars with masses above that of the Sun but less than that of supernova progenitors. These stars generate neutrons and forge heavy elements in the asymptotic giant branch (AGB) phase that precedes the ejection of the newly-synthesized elements as a planetary nebula.

The heavy elements present in the Earth's crust have been produced by a combination of r- and s-process contributions. Our calculations of the production of the ^{127}I that is essential for human life, based on the data of [27,28], indicate that the r-process has provided 96% of its abundance in the Earth's crust, as seen in Fig. 1. The r-process is also calculated to have provided most of the abundance of bromine and gadolinium in the Earth's crust, as well as all its thorium and uranium and a fraction of the molybdenum and cadmium.

In the following we consider candidate r-process sites, with a focus on kilonovae.

4. The *r*-process in neutron star collisions (kilonovae)

The r-process may occur wherever there is a high number of free neutrons per seed nucleus, and the nature of the dominant type of site has long been a subject of debate [30]. One of the possibilities is in the material ejected during rebound from the core of a core-collapse supernova (CCSN) [31], as part of supernova nucleosynthesis, and another is in the decompressed neutron-star matter ejected during a neutron star merger (kilonova) [11].

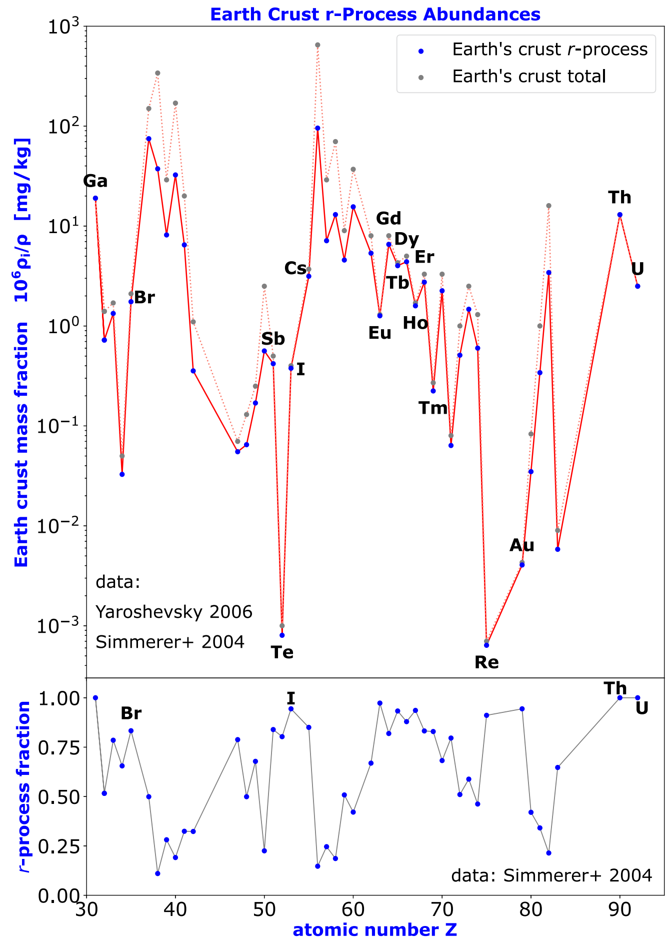

Fig. 1. *Top Panel:* A comparison of measured element abundances in the Earth's crust [29] (dotted line) with r-process portion (solid line) calculated using the r-process fractions from [28]. Elements for which the calculated r-process fractions exceed 75% are labeled. These include the elements bromine, iodine, thorium and uranium, whose relevance to life on Earth is discussed in the text. *Bottom Panel:* r-process fractions for each element, summed over isotopes; from [28]. Elements of particular interest are labeled.

Galactic chemical evolution models [32,33] have tended to favor an r-process site connected to massive stars, and a variety of possibilities have been proposed, ranging from standard CCSNe to rare events such as collapsars [34–36], MHD SNe [37,38], common-jet envelope SNe [39], and SNe triggered by a quark-hadron phase transition [40]. There is, nevertheless, considerable uncertainty in CCSN calculations of the r-process, e.g., in the physics of neutrinos and their impact on the neutron abundance [41] and in the effects of relativistic magnetohydrodynamic jets that can expel neutron-rich material from the protoneutron star [42]. In this connection, we note that JWST observations of the supernova associated with GRB 221009A have not found any evidence for r-process elements [43], in conflict with MHD and collapsar r-process predictions. Moreover, it is particularly difficult in CCSN models to produce the actinides such as thorium and uranium, which may have played in indirect role in the evolution of life on Earth, as discussed above. The presence in deep-ocean deposits of the live isotope ^{244}Pu (half-life 80 million years) suggests that there has been r-process production of actinides near Earth within the (cosmologically) recent past [44]. In view of the difficulties with CCSN calculations, we consider the possibility that this material is attributable to a neutron star merger (kilonova) [45].

Observations of the kilonova associated with the first binary neutron star merger observed by the LIGO and Virgo experiments to emit gravitational waves (GW170817, see below) indicate that it produced both tellurium and lanthanides as predicted in r-process calculations [46,47], with hints also of iodine production [46], and evidence for the production of tellurium and lanthanides by the kilonova associated with GRB 230307A has also been presented [48,49]. We recall that tellurium ($Z = 52$) is adjacent to iodine ($Z = 53$) in the periodic table and in the same abundance peak predicted by the r-process, indicating that GW170817 and GRB 230307A probably also produced iodine. State-of-the-art simulations of neutron star merger nucleosynthesis [50–53] are generally consistent with these observations. This supports the suggestion [45] that the kilonova postulated to have produced the terrestrial ^{244}Pu also produced iodine.

These remarks motivate the following question: Why do neutron stars collide?

5. Gravitational waves cause neutron-star collisions

The first, indirect evidence that gravitational waves control the evolution of neutron-star binary systems came from measurements of the binary pulsar PSR B1913+16 that was discovered by Hulse and Taylor in 1974 [54]. Following its observation, measurements of the rate of change of the periodicity of electromagnetic pulses from this system over four decades have verified with high accuracy the predictions based on gravitational-wave emission according to the general theory of relativity, which causes energy loss and inspiral of the binary components. The ratio of the observed rate of change compared to the predicted value is 0.9983 ± 0.0016 [55], a verification of the predicted gravitational wave emission at the level of 1.6×10^{-3}. However, this measurement has now been surpassed by observations of the binary pulsar system PSR J0737-3039 A, B, whose rate of change of periodicity is 0.999963 ± 0.000063 of the value predicted from gravitational wave emission in general relativity [56], a verification of the prediction at the level of 6×10^{-5}.

The first direct evidence for the role of gravitational wave emission in neutron star collisions came with the detection by the LIGO and Virgo experiments of a sequence of gravitational waves of increasing frequency (GW170817) as a pair of neutron stars approached merger [13]. The rate of increase of the gravitational-wave frequency over an observation period of ~ 100 s again agreed perfectly with predictions for gravitational-wave emission during the infall stage of a neutron-star binary system as predicted by general relativity.

We emphasize that these two sets of observations confirm the expected evolution of neutron-star binaries during very different stages of their evolution. The Hulse-Taylor pulsar is calculated to have a lifetime to merger of 3×10^8 y, whereas GW170817 was measured during its death throes. The combination of these measurements confirms gravitational-wave domination of the evolution of neutron-star binaries during very different stages of their existence.

Neutron-star collisions are caused by gravitational waves.

6. Lunar tests of iodine production by kilonovae

The chain of argument presented above suggests that the iodine essential for human life was probably produced by the r-process in the collisions of neutron stars that were induced by the emission of gravitational waves, along with other essential heavy elements. However, there are two weak points in this reasoning: one is that there are other possible sites for the r-process such as some CCSNe, and the other is that the evidence for iodine production in kilonovae is still only circumstantial.

Regarding the first point, calculations indicate that a kilonova origin for the ^{244}Pu detected in oceanic deposits would require the event to have taken place within a few hundred parsecs [57] within the last $\mathcal{O}(100)$ million years. It is expected that kilonovae leave behind black hole remnants weighing $\mathcal{O}(3)$ solar masses, so discovery of a nearby black hole in this mass range could provide supporting evidence for the kilonova origin of any lunar ^{129}I, particularly if its age could be established as $\lesssim 100$ million years. Measurements of the black hole proper motion on the sky would allow it to be tracked back to its location at the time of the ^{244}Pu production, in a similar way that a high proper motion neutron star has been proposed as the remnant of the supernova that delivered ^{60}Fe to the Earth and Moon 3 Myr ago [58].

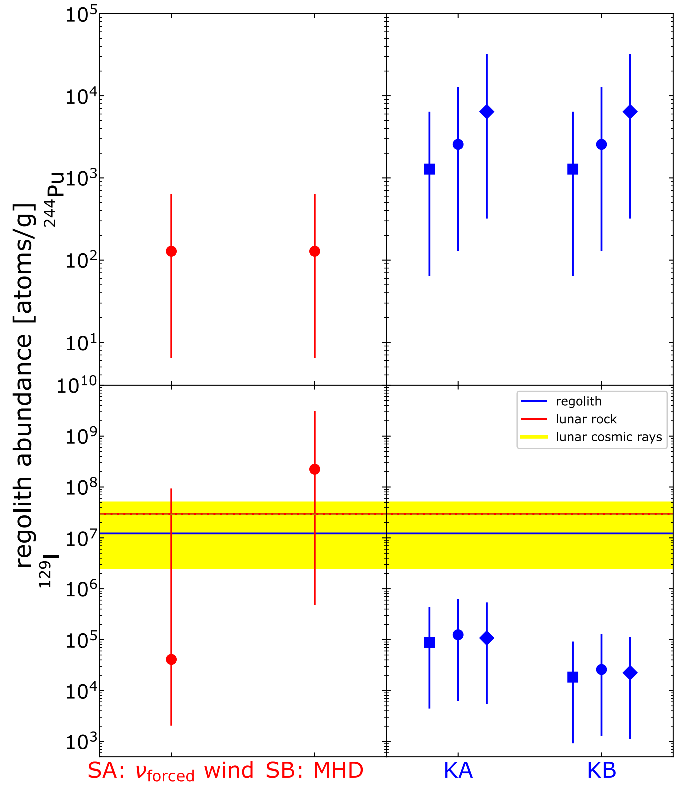

Fig. 2. Lunar abundances of ^{244}Pu and ^{129}I, for supernova (left) and kilonova (right) models. Supernova models are for an event at 3 Myr ago with flux spread over 1 Myr; left points are for a forced neutrino wind and right points are for a magnetohydrodynamic supernova. Kilonova models are for events 10, 20, and 50 Myr ago. The vertical bars include estimates of the nuclear uncertainties influencing the abundance predictions, as described in [57]. The cosmic-ray background (shown in yellow) is proportional to the abundance of barium in the regolith; the band shown is for a barium mass fraction $X_{\rm Ba} = 42 - 850$ ppm. The regolith and rock results shown are for sources with high $X_{\rm Ba}$. We see that the supernova signal is above background, while the kilonova signals are not, unless $X_{\rm Ba}$ is small. A regolith measurement of ^{129}I in conjunction with barium could distinguish between these cases.

Concerning the latter point, we reiterate that the iodine isotope essential for human life is the stable isotope ^{127}I, whose astrophysical origin is challenging to verify directly. However, astronomical observations of other elements in kilonova explosions, see, e.g., [48], provide a means of verifying that these outbursts are an important r-process sites, and recent observations of kilonovae indicate that they produce tellurium, which is adjacent to iodine in the periodic table and thought to be produced at a similar rate.

Moreover, novel astrophysical messengers can now offer complementary information. In particular, the unstable isotope ^{129}I (half-life 16 Myr) from astrophysical sources can in principle be detected using the ultraprecise accelerator mass spectrometry (AMS) technique. This has been used in terrestrial searches, which are unfortunately subject to anthropogenic contamination. Accordingly, we have suggested using AMS to looking for ^{129}I in conjunction with ^{244}Pu in samples of lunar regolith (soil) [57], which have no anthropogenic contamination *in situ*.

Fig. 2 shows predictions for ^{129}I abundances in lunar regolith for supernova and kilonova explosion models (left and right, respectively), normalized to the observed ^{244}Pu flux. Details of the models and background appear in ref. [57]. The supernova models are chosen because they are able to produce r-process actinides, forcing the n/p ratio to appropriate values as might happen in a neutrino wind, or expelling neutron-rich material via a magnetohydrodynamic jet. The kilonova models are for explosions 10, 20 and 50 Myr ago, with constant flux thereafter. We see that a kilonova should produce one or two orders of magnitude more ^{129}I than ^{244}Pu [57], reflecting fission cycling yields. However, the chosen supernova models produce higher ^{129}I/^{244}Pu ratios because they are less neutron-rich and struggle to reach the actinides. We note also that the extrasolar ^{129}I signal competes with the background from cosmic-ray ^{129}I production in the lunar regolith, mostly from spallation of barium. This cosmogenic component scales with the barium abundance, and appears in the yellow band which corresponds to barium content as measured in lunar regolith samples. We see that the supernova ^{129}I signal can be far above the cosmic-ray background, while the kilonova signal is generally below–though it could be discernible if there were a sample with a barium mass faction $X_{\rm Ba} \lesssim 1.5 \times 10^{-6} =$ 1.5 ppm. Thus a lunar measurement of ^{129}I in conjunction with barium could test the kilonova origin of the ^{244}Pu signal.

A caveat is that iodine is volatile, unlike ^{244}Pu and most other *r*-process radioisotopes of interest, which are refractory. This volatility affects the inclusion of iodine into cosmic dust and hence its propagation through the interstellar medium. Another factor affecting the relative abundances of ^{129}I and ^{244}Pu is the factor ~ 5 difference in half-lives: ^{244}Pu might have accumulated for period that is longer by a similar ratio. For these reasons, there is considerable uncertainty in the kilonova prediction for the abundance of ^{129}I in the lunar regolith relative to ^{244}Pu (which can be estimated from terrestrial measurements [44]). The latter uncertainty could be mitigated by the simultaneous detection of ^{129}I and ^{247}Cm, which has a similar half-life. As discussed in [59], the ^{129}I/^{247}Cm production ratio is sensitive to the *r*-process environment, and is expected to be preserved between production and incorporation into the Solar System. Current and upcoming radioactive beam facilities [60,61] will probe the unknown nuclear physics crucial for a detailed interpretation of this signal.

A successful search for lunar ^{129}I would have significant impact: it would provide circumstantial evidence that the *r*-process in kilonovae does indeed produce iodine, suggesting a positive answer to the question in the title of this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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