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Hypothesis

The Earth's Gold: Where Did It Really Come From?

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Abstract: Why is it that in the neighborhood of a calm ordinary star (the Sun) located at the quiet periphery of its galaxy (the Milky Way), non-native heavy elements are abundant in such concentrated form? Where did these elements really come from? Where did Earth's gold come from? Our analysis of the known data offers a fact-reconciling hypothesis: What if, in the early solar system, an explosive collision occurred – of a traveling from afar giant-nuclear-drop-like object with a local massive dense object (perhaps a then-existent companion of the Sun) – and the debris, through the multitude of reaction channels and nuclei transformations, was then responsible for (1) the enrichment of the solar system with the cocktail of all detected exogenous chemical elements, and (2) the eventual formation of the terrestrial planets that pre-collision did not exist, thus offering a possible explanation for their inner position and compositional differences within the predominantly hydrogen–helium rest of the solar system.

Keywords: Hypothesis, Collision, Heavy Elements, Solar System

1. Introduction

First, let us lay out certain facts which, while undoubtedly familiar to their primary-field specialists, may nonetheless be of some surprise to the boarder research community, and even to experts from non-related areas. Not mentioning these facts at the beginning might make the discussion of the essence of the hypothesis and of the scenario of the process (elaborated below) pointless because both the hypothesis and the scenario might then seem baseless. It is also possible that, unintentionally and due to subjective reasons, some of these facts might have previously escaped attention of modelers and theoreticians simply because these facts had not been aggregated in one place before. But when awareness of their *entirety* is lacking, even advanced models face the risk of potential discreditation.

The remainder of this presentation is structured as follows. Based on the material laid out in the introductory part (Sec. 2), we formulate the hypothesis (Sec. 3) which reconciles the entirety of the stated facts – so far we have counted fourteen of them. The key elements of the process are then discussed in Sec. 4. Section 5 concludes with a summary, discussion of implications, and additional considerations. We plan to present more detailed calculations pertaining to this multi-faceted subject in another, more comprehensive, publication.

2. Facts

(1) For an observer from afar, the solar system would appear to consist of the central star which we call the Sun (composed mainly of hydrogen in its ionized-plasma phase) and similar in chemical composition (hydrogen in its gas–liquid–solid phases) giant planets, which we call Jupiter, Saturn, Uranus, and Neptune. From afar, the set of "terrestrial" planets (Earth, Venus, Mars, and Mercury) would be virtually unnoticed – mass-wise it is negligible ($< 10^{-5} M_{\odot}$) and distance-wise it is effectively lumped near the Sun – just as unnoticed would be the relatively dismal in mass Asteroid Belt, Pluto, the moons, and the Oort cloud comets. Chemical composition of the "rocky" terrestrial planets is *fundamentally* different from that of the giants.

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In other words, the solar system possesses *two* chemically different groups of planets (jovian and terrestrial) whose formations, as it appears, must have followed different pathways, which means their timescales might have been independent.

The conventional conception is that the planets formed in the vicinity of the protosun from the surrounding cloud of gas and dust, as the result of condensation and self-gravity. It is presumed that the particles were composed of the elements heavier than lithium. This is the dust from which the terrestrial planets formed. And so immediately the question arises about the dust composed of much heavier elements, the ones with atomic numbers $A > 20$ – calcium, iron, gold, etc. – where did they come from?

In fact, Earth (and analyzed meteorites) contain a number of elements which cannot be produced in the solar system – all post-*Fe* elements, certain short-lived radionuclides, and *p*-process elements. And the Sun, due to its structure, cannot in principle generate many of the elements that Earth contains, even in its interior. (These points will be elaborated later).

(2) It is known that two lightest elements (which start the periodic table) – hydrogen *H* and helium *He* – appeared at the time of the Big Bang. A small portion of lithium *Li* (the 3rd element) was generated then as well. However, the main portion of *Li*, and also beryllium *Be* (the 4th element) and boron *B* (the 5th element), was generated later. Among the explanations of their origin, and the observed abundances, is the hypothesis that these elements were obtained via disintegration of heavy nuclei by cosmic rays in interstellar medium. [27] Naturally, the question arises: where then did *those initial* heavy nuclei come from?

The generally accepted hypothesis is that all heavy elements from carbon *C* to uranium *U* were generated during nuclear reactions *inside active superstars* of our own Galaxy (which, as known, contains approximately 10^{11} stars). According to Fowler [27], the general schema for the formation of elements is as follows: (a) the elements heavier than *H* are synthesized inside the active stars; (b) the energy produced inside the stars during this synthesis, is transported in the form of electromagnetic and neutrino radiation to the surface and released; (c) the stars (including the Sun) expel the "waste" from their "nuclear furnaces" into the interstellar space continuously or during explosions (as nova or supernova); (d) all the "exhaust" is mixed in the interstellar space; (e) the interstellar gas and (presumably) dust form; (f) condensation gives birth to young bright stars, which absorb the interstellar matter. And then step (f) loops back into step (a) to repeat the cycle, again and again.

This schema, which considers the evolution of active stars as the source of heavy elements in the interstellar space, does explain their presence in general, if the age of the Universe (estimated to be $\sim 13.6 \times 10^9$ years) is significantly greater than the characteristic period of the cycle. But the question nonetheless arises, which is impossible to brush off: why – in the vicinity of a very ordinary star (the Sun) located at the (not overpopulated) periphery of our galaxy – the heavy elements (post-*Fe* and post-post-*Fe*) are available in such tight region (a few AU's only) and in such condensed (chunky) form? How did they appear *here*?

(3) The very layout of the solar system adds to the puzzle. For a long time it was assumed that the solar system is a typical representative of planetary systems in general. With advancement of observational techniques over the last several decades, it has been discovered that the solar system is actually rather special. For example, most stellar systems are *binary*. Furthermore, observations of exoplanetary systems have revealed that, unlike the solar system, exoplanets are typically closer to the central body than the solar planets are to the Sun; exoplanets are often in mutual resonance; while most of the exoplanets discovered so far tend to be large (which could be the measurement bias), the smaller planets (the smallest found so far is $10 \div 10^2\ M_{Earth}$) tend to be positioned *extremely* close to the central star (with orbital periods measured in hours or days). However, the composition of the exoplanets is undetermined. In fact, chemical composition of remote stellar objects is deduced based on spectral observations, which are more likely to yield information about the objects' atmospheres than about what lies beneath.

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(4) The potential impact of (remote) stellar cataclysms on the chemical composition of the solar system has not been ignored. A number of studies have noted that supernovae, neutron star mergers, and other similar cataclysmic events, generate $r-$ and $s-$process elements, and thus can continually enrich the interstellar space and maintain a certain steady-state background level of the *long-living* elements. Luckily for the life on Earth, in the nearest vicinity of the Sun there are no potential sources of such production of heavy and hyper-heavy nuclei and scorching gamma-radiation that accompanies the cataclysms.

(5) But the puzzling presence of a number of *short-lived* $s-$process isotopes detected in meteorites implies that *they were products of a specific event* rather than continuous enrichment. Discoveries of certain *Be* and *Li* isotopes, and of $p-$process isotopes, produced by *completely different* mechanisms, need explanation of their origins. (Because Be^7 isotope half–life is only 53 days, its production mechanism had to be *local*.)

Overall, to explain all of the individual groups of elements in question, at least *several* separate element production mechanisms seem to be needed. However, if all the (so far) proposed mechanisms were working *together as assumed*, it would imply that *several cataclysmic stellar events* (such as several supernovae happening at such perfect distances that they managed *to enrich but not destroy* the solar system) had to occur in the quiet Sun's neighborhood within a time–window of about 20 *Kyrs* (more details later), but the resulting element abundance profile (obtained by superposition of all contributing enrichment mechanisms) would still contain unresolved peculiarities. For example, the *observed "excess"* in the solar system of $p-$process elements (more details later) would still need to be explained (see [57,60,70] and references therein).

In view of the presented facts, it is apparent that the current understanding of the solar system's chemical enrichment remains incomplete. The planetary structure also contains more puzzles, but before we list those, let us first explain our own hypothesis that we believe has the potential to resolve all of the above-mentioned puzzles, and several more.

We propose that – if – in the solar system (about 4.6 *Gyrs* ago) one collision occurred (with certain characteristics that are explained in later sections), it might have accounted for all of the noted peculiarities of the current solar system. Such event would have been *local*, by definition, thus addressing the presence of the puzzling short-lived isotopes in meteorites. Such event, as we envision it, would have had the potential for generating the *entirety* of the otherwise non-native elements in the solar system. Such event would have had the potential to alter the planetary layout and structure in the system. We are talking about a powerful collision of a very special kind.

But before diving into further details and the nature of such collision, in order to appreciate the advantage of the element-generating-collision scenario over the current ensemble of multiple independent scenarios, each tackling its own mini-puzzle, consider the challenges and statistical odds that the existing scenarios face, and note the additional puzzles of the solar system that the collision hypothesis helps resolve.

(6) *Tight Location and Timing Constraints for Multiple Supernova Scenarios.* To be able to provide the observed abundances of radioactive isotopes, the supernova must have been located *not too far* from the solar nebula. On the other hand, the distance had to be great enough so that the shockwave of matter from the supernova did not destroy the nebula. For the stars with $M \sim 25 M_{Sun}$ shown to provide the best ensemble of short-lived radioactive nuclei, this optimal range is quite narrow, $\simeq 0.1 - 0.3$ pc [2]. Furthermore, stars within the cluster typically form within 1-2 Myr [39] and the clusters disperse in about 10 Myr or less [3]. Since stars with mass $M \sim 25 M_{Sun}$ burn for ~ 7.5 Myr before core collapse [85], to fit the supernova enrichment scenario the Sun must have formed several Myr after the progenitor [2]. If located ~ 0.2 pc from the progenitor, the early solar nebula could have been evaporated by the progenitor radiation [34]. One way to reconcile this is to assume that the trajectories of the early solar nebula and the progenitor approached the 0.2 pc separation just before the supernova explosion [2]. Such timing requirement lowers the odds for the supernova enrichment theory [84].

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(7) *Multiple, Distinct, Quasi-Simultaneous "Sources" Required for Short-Lived Nuclides.* There is abundant evidence that short-lived nuclides once existed in meteorites. On a galactic scale, red giants and supernovae continually inject newly synthesized elements into the interstellar medium, and *unstable nuclides steadily decay away*. These two competing processes result in steady-state abundance of these nuclides in the interstellar medium near the active giant stars. The abundances of some of such discovered nuclides (^{107}Pd, ^{129}I, ^{182}Hf, for example) roughly match the expected steady-state galactic abundances and hence do not necessarily require a specific synthesis event. However, the appearance of ^{26}Al, ^{41}Ca, ^{53}Mn, ^{60}Fe, and a few other nuclides, in the early solar system require synthesis of them at the same time, or just before, the terrestrial component of solar system formed (see, among others, reviews by [83], [82] and references therein). The conventional view is that these nuclides were synthesized in a nearby supernova and/or a red giant and injected into the solar nebula just shortly before the solar system formation (see [13], [14],[11], [32], [58] and references therein).

However, various numerical models of stellar nucleosynthesis consistently show that one event by itself cannot provide the early solar system with the full inventory of short-lived nuclides. Depending on the model, certain isotopes are significantly over- or under-produced (see, among others, [28], [36], and references therein).

Meteoritic sample studies concur by revealing data signatures inconsistent with a single stellar origin. For example, the *Ivuna CI* chondrite analysis detected simultaneous presence of at least five mineralogically distinct carrier phases for Mg and Ca isotope anomalies, leading to the explanation that they must represent "the chemical memory of *multiple and distinct* stellar sources" [74].

(8) *Narrow Time-Window for Multiple Injection Events and Homogeneous Isotope Mixing.* If the short-lived radionuclides mentioned above were produced by *multiple* stellar sources (at least five, according to [74]), *all* of these injection events, as well as the subsequent highly homogeneous mixing of isotopes, had to occur within the time-span of only about 20,000 years, as constrained by the spread of calcium-aluminum inclusions (CAI's) condensation ages [36].

(9) *Inconsistent Abundances of ^{10}Be and ^{7}Li Isotopes.* Detection of ^{10}Be indicates that one more process, *local* to the solar system, must be added to the enrichment scenario. ^{10}Be is not synthesized in stars. Indeed, in most stellar events *Be* is destroyed rather than produced. Moreover, the discovered excess of ^{7}Li in CAI ([16]; [17]) points with certainty to its origin *within* the solar system, because ^{7}Li is produced by decay of ^{7}Be whose half-life is only 53 days. It was suggested that these elements were produced by spallation within the solar system as it was forming. Various groups tested this scenario by comparing the modeled nuclear spallation yields with the inferred solar system initial ratios (e.g., [55]; [33]; [31]; [56]). However, they failed to self-consistently explain the abundance discrepancies.

(10) *Unexplainable "Excess" of Proton-Rich Isotopes.* A number of *proton*–rich isotopes (*p*-nuclei) detected in the solar system, *cannot be made* by either $r-$process or $s-$process. Although their solar system abundances are tiny compared with isotopes produced in neutron–capture nucleosynthesis, the *site of their production* in the solar system is even more problematic. They can be produced either by *proton–capture* from elements with lower charge number, or by *photo–disintegrations*. Both production mechanisms require high temperatures and presence of seeds ($r-$ and/or $s-$process nuclides). *Proton capture process also requires a very proton–abundant environment.*

Currently, the solar system abundances of *p*-nuclei have been best fitted into the combination of contributions from *several* stellar processes. Photodisintegration in massive stars (*Type Ia*-supernova or a mass-accreting white dwarf explosion; see [71]) and neutrino processes (for ^{138}La and ^{180}Ta), can perhaps explain the bulk of the *p*-nuclei abundances. However, the abundances of light *p*-nuclei in the solar system significantly exceed the simulated production from the stellar processes, and this problem has not yet been resolved [71].

If the Element-Generating-Collision Hypothesis is accepted, its envisioned mechanism (explained in later sections) *enables, and certainly does not preclude*, production of *all and any* of the above-mentioned elements and isotopes, within the required timeframe and location, and the scenario eliminates the

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need for all unnecessary hypotheses related to the above-mentioned, and the following, puzzles of the solar system.

(11) *Unusually Spread-Out Jovian Orbits Without Typical Resonance.* Unlike the bulk of known exoplanetary systems, the orbits of the solar system's giant planets are remarkably widely spaced and nearly circular. (See, for example, overviews in [25] and [6]). *N*-body studies of planetary formation and orbit positions indicate that, due to the convergent planetary migration in times before the gas disk's dispersal, each giant planet should have become trapped in a resonance with its neighbor [48,61]. To explain its present, stretched and relaxed state, an evolution scenario is required where the outer solar system underwent a violent phase when planets scattered off of each other and acquired eccentric orbits [80,81], followed by the subsequent stabilization phase.

(12) *The Puzzle of One Missing Giant.* There are also indications that one more giant object initially might have been present in the solar system and then somehow disappeared at some point. For example, [64] attempted to determine which initial states were plausible and the findings showed that dynamical simulations starting with a resonant system of four giant planets had low success rate in matching the present orbits of giant planets combined with other constraints (e.g., survival of the terrestrial planets). A *fifth giant*, eventually ejected or destroyed, had to be assumed to produce reasonable results.

(13) *Inconsistencies Within Formation Models of Two Classes of Planets.* In the solar system, the gaseous planets are thought to have been formed either by nebula self-gravitation or by gas capture onto "rocky" cores, while the "rocky" objects are thought to have been formed by accretion (from dust grains into larger and larger bodies). Even disregarding the glaring question of where the dust grains came from, there seem to be inconsistencies within each of the planet formation models, which are not yet reconciled.

The "core accretion" model presumes that rocky, icy cores of giant planets accreted in a process very similar to the one that formed the terrestrial planets and then captured gas from the solar nebula to become gas giants. This model explains why the giants have larger concentration of heavier elements than the Sun has, but unfortunately numerical simulations yield formation times that are way too long unless the mass of the primordial nebula is increased.

The "disk instability" model posits that a density perturbation in the disk could cause a clump of gas to become massive enough to be self–gravitating and form the Sun and the planets [10]. Formation scale is then much more rapid, but the model does not readily explain the observed chemical enrichment of the planets.

(14) *Non-Uniform Distribution (Chunks) of Stable r- and s-Process Elements.* It is established that elements beyond *Fe* are produced in nature via *neutron capture* by seed nuclei only if *both abundant free neutrons and heavy nuclei are simultaneously available* for the reactions to proceed. Because the half–life of free neutrons is only $\sim$ 15 minutes, either the entire episode of heavy elements formation must be of short duration, or the flow of free neutrons with high concentration must continuously become available. Such environments are known to exist either during the collisions of neutron stars, or in the interiors of giant stars, in which case the only way for the elements to be released is by the star explosions. Thus, currently it is assumed that those solar system elements that are theoretically produced only by the *rapid* (*r*-) and/or *slow* (*s*-) processes, were actually produced in explosive stellar events and delivered to our system by propagating shockwaves and winds. However, if this were the case, then why do we find them as "chunks' on Earth, why are they not uniformly mixed?

3. Hypothesis

The hypothesis that we advance to reconcile all the above-mentioned puzzling facts, can be outlined as follows:

We suggest that early on, more than five billion years ago, our solar system had *no terrestrial* but *only jovian* planets. Perhaps, it had a companion closest to the Sun, such as a dwarf or super-Jupiter.

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We further propose that about 4.6 billion years ago (at the time currently defined as the birth of the solar system based on dating of meteorites' chemical composition), a traveling from afar object – born in an asymmetric stellar cataclysm and possessing rather specific inner-matter properties (discussed later) – intersected the path of the solar system and collided with the then-existent companion of the Sun. (Fig. 1.) More specifically, we suggest that it was a *giant-nuclear-drop-like* object (theoretical

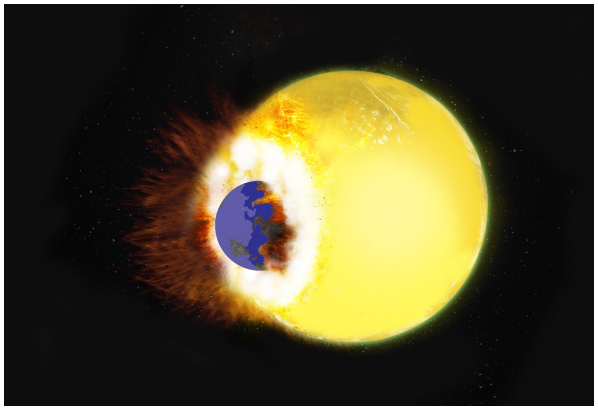

Figure 1. Artist depiction of the collision.

existence of which has been demonstrated and analyzed [78]) born as a result of destruction of some neutron-star-like stellar object by the super-massive black hole located at the center of our galaxy.

Certain details of this scenario are fundamentally essential: As the nuclear-drop-like object (traveling with hyperbolic velocity with respect to the solar system) collided with the Sun's companion, the decelerating object's inner matter stratified – first the spherical compression shockwave propagated from the front point towards the back, then (because the object's surface was strain-free due to extreme density contrast between the inner and outer media) the reflected shockwave reversed polarity and returned as the wave of decompression. [52,88] (See Appendix for details.) In a nuclear-like medium, the shockwave propagation speed is comparable with the speed of light – so the stratification process developed very quickly. During such short time, the shape of the droplet does not have time to change because propagation speed of surface perturbations is much slower than the speed of body waves. In the zones of decompression, the matter that was before the collision (thermodynamically) weakly-stable (perhaps due to aging and cooling of the object), now became unstable and "preferred' not the homogeneous but the two-phased state (the state of "nuclear fog' where "nuclear droplets' coexist with "nuclear gas'). In other words, inside the object, the (locally) decompressed matter became a conglomerate of "droplets' of charge-neutral nuclear matter as well as "gas' of alpha-particles, protons, electrons, and neutrons. Such charge-neutral "droplets' (obviously with hyper-large atomic numbers A) were structurally unstable and underwent spontaneous *fragmentation* and *fission* with release of neutrons. Due to the nuclear *mass-defect*, this process released a lot of energy – the system heated up – a "cloud' was formed composed of hyper-massive nuclei, alpha-particles, and protons and electrons to assure charge-neutrality of the system. All processes occurred at such fast nuclear-time-scales that the system exploded, and the matter became dispersed in the surrounding space. Overall, only insignificant mass remained within the orbit of the initial companion. The multitude of channels of reactions led to transformations of nuclei (from hyper-large A to moderate A).

This mechanism of element-generation critically differentiates the proposed hypothesis from the traditional conception of the element-formation in the solar system. In our hypothesis, the dominant mechanism is the process of *fission* (from large atomic numbers A to moderate A), while in conventional models the primary process is *nucleosynthesis* (from lower A to higher A).

Post-collision, the final products of the nuclear reaction channels created the environment containing post-*Fe* elements, as well as the previously mentioned short–lived radionuclides, various isotopes, and so on, – with the element abundance profile as we know it. Later on, the nuclei condensed

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into dust, and then into terrestrial planets and other "rocky' bodies, and also enriched the pre–existing jovian planets.

This hypothesis draws on the insight that over the course of its history the solar system could have undergone encounters with external objects of various mass (see, for example, a proposed explanation for the orbit of Sedna [47]), and also on the general acceptance that stellar collisions of giant-nucleus-like objects do indeed happen (for example, neutron stars are considered as giant-nucleus-like objects; black-hole/neutron star or two neutron star mergers have been extensively studied; see, among others, [26,53]). But the idea of a direct collision of a giant-nuclear-drop-like object with/within the solar system has never been advanced.

Naturally, such collision is an extremely rare event, perhaps it is a completely unique one. The odds for a similar occurrence are very small. (More about this later.) But if another one had happened or would happen elsewhere, the implications can be breathtaking. Humankind can certainly, and rightfully, feel beyond-grateful that "exotic" chemical elements, which are critical to the life as we know it, appeared at the perfectly habitable distance, next to the perfectly tranquil star (our Sun), in the perfectly quiet outskirt of our galaxy. Without these non-native to our system elements we wouldn't exist, any biochemist can prove it in many ways. Who knows what could happen at that "other" location.

This hypothesis is also notable not just because it offers an all-facts-reconciling explanation for how the exotic elements appeared in our planetary system, but also because the proposed collision mechanism can occur in such way that it does not demolish the entire system. A different object would either not create the necessary effects, or be too destructive. That is why the object has to be of a special, although not a particularly rare kind – the object has to resemble a giant nuclear-drop.

4. Key elements for the scenario

4.1. Colliding Object

Generally speaking, a number of exotic compact stars have been hypothesized, such as: "quark stars' – a hypothetical type of stars composed of quark matter, or strange matter; "electro-weak stars' – a hypothetical type of extremely heavy stars, in which the quarks are converted to leptons through the electro-weak interaction, but the gravitational collapse of the star is prevented by radiation pressure; "preon stars' – a hypothetical type of stars composed of preon matter. Indeed, various objects could have existed five billion years ago.

Just as a reminder, the standard neutron star forms as a remnant of a star whose inert core's mass after nuclear burning is greater than the Chandrasekhar limit but less than the Tolman-Oppenheimer-Volkoff limit. Due to certain aspects of their formation process, velocities of standard neutron stars are never high (relative to their original frame of reference). However, during the rotating core collapse, one or more self–gravitating lumps of neutronized matter can form in close orbit around the central nascent neutron star [42]. The unstable (in the phase–transition and nuclear-reaction sense) member of such transitory binary or multi-body system ultimately explodes, giving the surviving member a substantial kick velocity – as fast as $\sim 1600\,km/s$ [21].

Small fragments of such stars can also be formed and kicked, or catapulted, if a black hole tears a neutron star apart [72]. Fig. 2 illustrate such possibility (three scenarios depicted).

Objects smaller (even significantly smaller) than traditional neutron stars can indeed (theoretically) exist – and stay as dense as a nucleus, without the crust, and remain stable (in the liquid-gas-phase–transition and nuclear-reaction sense, and therefore, structurally) – if their equation of state fulfills certain requirements. [78]

In our hypothesis, the colliding object is essentially a giant "nuclear drop' (a hyper-nucleus) born in an asymmetric stellar cataclysm far away and traveling with sufficiently fast speed along the trajectory that crossed the solar system's path.

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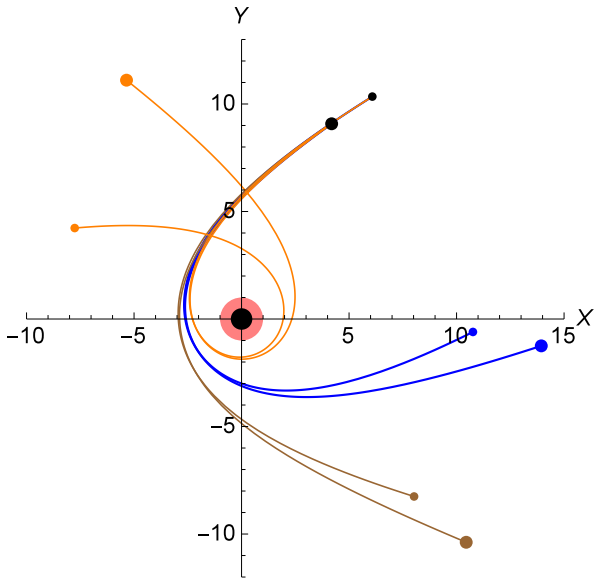

Figure 2. Illustration of the destruction process (three scenarios from [79]). A stellar body (depicted as the black dot near dimensionless coordinates (+6; +10)) that comes into vicinity of a rotating massive black hole (depicted as the black circle at the center) becomes torn apart by the fast-rotating black hole's gravity. Presumably, a part of plasma debris would remain trapped and funneled toward the black hole's event horizon. These viscously heated orbiting pieces of debris would start flaring up. Some fragments of the destroyed stellar body would escape the black hole's vicinity with high velocity.

4.2. Explosive Energy Burst Due to Collision

High-energy nuclear experiments have demonstrated that the matter of a nuclei is characterized by critical parameters of temperature T_c and density ρ_c (see for example [18,43–46,78] and references therein). In laboratory conditions, $T \ll T_c \sim 15\,Mev$ and $\rho_{nucl} \sim 2 \div 3\rho_c$. Below T_c, depending on its density, the nuclear matter can exist in 'nuclear liquid' phase (higher range of densities), or 'nuclear gas' phase (lower range of densities), or as 'nuclear fog' which is a mixture of both phases (within the 'spinodal zone' of the density range corresponding to its T).

In our scenario, for the colliding object, if the equilibrium state of the inner 'nuclear liquid' is initially close to the boundary of the liquid/gas phase transition, then the liquid phase can decompress into the fog phase because of deceleration. The matter would then exist as a mixture of two phases of nuclear matter – either liquid droplets surrounded by gas of neutrons, or generally homogeneous neutron liquid with neutron-gas bubbles. In such state, the matter can reach substantial further rarification, reducing density by a factor of 10^2 or more due to hydrodynamic instability. At this stage, nuclear *fragmentation* of the colliding object and subsequent *fission* of the debris may start.

Below density ρ_{drip} – even if in some small physical domain within the object – beta–decays become no longer Pauli–blocked and significant amounts of energy become released. Indeed, simulations of r-process nucleosynthesis in neutron star mergers demonstrated that from ρ_{drip}-level, density decreases extremely fast – the matter initially cools down by means of expansion, but then heats up again when the β-decays set in. [26]

This process triggers *fragmentation* of these supersaturated hyper–nuclei. (See for example [7], [38], [59].) These reactions, known to release even more energy ($\sim 1 MeV$ per fission nucleon, as seen in transuranium nuclei fission events), proceed effectively at the same moments as the beta-decay reactions. Everything happens very fast, practically with nuclear-time scales ($\sim 10^{-22} \div 10^{-15}\,sec$). When perturbations of the equilibrium of a 'neutron liquid droplet' permit production of charged protons (even in small numbers, and in small localized regions), spontaneous *fission* reactions commence.

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Generally speaking, at different stages (with respect to applied energy/excitation of hyper-nuclei), different types of reactions occur. [46] When a hyper-nucleus is excited (relatively) weakly, only γ–*emission* occurs. At a higher level of excitation, *neutron–emissions* start taking place. When even more energy is applied to the hyper-nucleus, it deforms and *fission* starts because, as known, for deformed charged nuclei with parameter $Z^2/A > 50$, electrostatic repulsion starts exceeding surface tension of a nuclear drop. And finally, when injected energy is sufficiently high, *fragmentation* – splitting into fragments ("droplets" if the initial nucleus is a hyper-nucleus) – occurs, followed by the cascade of further splitting into fragments and strong neutron emissions.

4.3. Deceleration and (Localized) Decompression as Trigger for Explosion

A number of mechanisms contribute to the object's deceleration as it collides – classical drag [52], dynamical friction [15], accretion (acquisition of target particles onto the gravitationally–powerful object) [77], Cherenkov–like radiation of various waves related to collective motions [69] generated within the target [67,68], distortion of the magnetic fields, and possibly others. Obviously, some deceleration causes would be dominant and some would be negligible.

Analytical and numerical treatment of the deceleration process can quickly become complex and cumbersome. Furthermore, as numerical studies of magnetized stars revealed, if the velocity, magnetic moment and angular velocity vectors point in different directions, the results become strongly dependent on model choices.

However, in the context of the question of whether explosion can be triggered by internal instability, the *"strength" of deceleration should be defined not in the kinetic sense, but in the thermodynamic sense.*

Indeed, as already noted, if the initial phase state of the nuclear liquid is rather close to the boundary of the two-phase (spinodal) zone, even deceleration with small magnitude in the kinetic sense, can still trigger sufficient density stratification (decompression in the rear part of the object). In the spinodal zone, any small density fluctuation or induced perturbation develops extremely fast. (Specifics of the process are described in more detail in Appendix.)

Since nuclear processes occur with faster time scales ($t \sim 10^{-22} \div 10^{-15}$ sec) than thermodynamic processes, even a small localized decompression can trigger the cascade of spontaneous fragmentation and fission.

The closer the object's initial state is to the liquid/gas phase-transition boundary, the smaller the deceleration magnitude is required for the sufficient decompression and subsequent nuclear reaction cascade. The lower the initial density and temperatures of the object are, the more likely it is to have its initial (T, ρ)-phase state closer to the phase-transition boundary. Lower density and temperature may occur if the object is smaller / less massive and if it had time to cool down (for example, if it is older). Theoretical plausibility of existence of small stable objects (spherical configurations) with such properties has been demonstrated. [78] Astronomically, however, such smaller and cooler objects are difficult, if not impossible, to detect with current observational methods.

4.4. Element Production

To attempt to simulate numerically the outcome of element production chains will be extremely challenging for several reasons.

First, the theory of *fission* (and even more so of *fragmentation*) of hyper-nuclei ($lnA \gg 1$) is not developed at all, mostly because observational data are impossible to collect, and experimental studies are impossible at present to conduct. Split of nuclei with high A numbers into several with lower A numbers leads, via different channels, to the unpredictable composition of the fission products, which vary in a broad probabilistic and somewhat chaotic manner. This distinguishes fission from purely quantum-tunnelling processes such as proton emission, alpha-decay and cluster-decay, which give the same products each time.

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Second, while *r-process* capture of free neutrons (leading to transformation of nuclei from the lower to higher A numbers) has been more studied and can be better modeled, the results strongly depend on the assumed equation of state (EOS) of absorbing matter ([26]), the neutron/seed ratio, and the composition of the seed, which in models are characterized by the proton/electron-to-nucleon ratio, Y_p or Y_e, of the ejected and expanding matter into the target. The value of Y_e has basically dual effect: (1) It determines the neutron-to-seed ratio, which finally determines the maximum nucleon number A of the resulting abundance distribution, and (2) it also determines the location (neutron separation energy) of the r-process path, and thus the β-decay half-lives to be encountered. This influences the process rapidity and the energy release. Thus, Y_e of the ejected matter strongly depends on how much seed matter is contained in the domain of interaction of components. Also, various processes such as neutrino transport, neutrino captures, or positron captures, alter Y_e evolution. Indeed, as well-acknowledged, in neutron star merger modeling, test calculations using different polytropic EOSs (a rather simple initial assumption) demonstrate strong dependence of the amount of ejecta on the adiabatic exponent of the EOS – stiffer equations result in more ejected material. [26]

Finally, the data on the abundance yields from the observed supernovae are not useful for modeling the collision element production. The two processes (supernova and collision) fundamentally differ in several aspects.

With respect to the nucleosynthesis reactions, the two processes have substantially different seed nuclei composition and neutron–seed ratios. In supernova explosions, when the core collapses once Coulomb repulsion can no longer resist gravity, the propagating outward shockwave causes the temperature increase (resulting from compression) and produces a breakdown of nuclei by photodisintegration, for example: $^{56}Fe_{26} + \gamma \rightarrow 13\,^{4}He_2 + 4\,^{1}n_0$, $^{4}He_2 + \gamma \rightarrow 2\,^{1}H_1 + 2\,^{1}n_0$. The abundant neutrons produced by photodisintegration are captured by those nuclei from the outer layers (the "seeds") that managed to survive. Thus, the resulting abundances depend strongly on the characteristics of the star. Indeed, astronomical observations confirm that supernova nucleosynthesis yields vary with stellar mass, metallicity and explosion energy (see, for example, [65]).

As for the production of gold, it occurs, for example, by free-neutron-capture of exited nuclei of mercury, which serve as seeds. Nucleus $^{198}Hg_{80}$ captures a rapid free neutron, produces exited nucleus $^{198}Hg_{80}{}^{*}$, which then turns to $^{197}Au_{79}$ via β-decay: $^{197}Hg_{80} + {}^{1}n_0 \rightarrow {}^{198}Hg_{80}{}^{*} \rightarrow {}^{197}Au_{79} + {}^{1}n_0 + {}^{0}\beta_{+1}$. The existing theories of element-enrichment in the solar system posit that these seeds (mercury nuclei) and resulting elements (gold) are formed during supernova (and other stellar cataclysms). In our scenario, they are (mostly) formed during the proposed collision as fragments of nuclear droplets underwent fission (and subsequent transformations).

Overall, the proposed collision and supernova events produce completely *different distribution of seed nuclei* available for subsequent reactions. The fact that in the collision scenario *reactions of fission* play dominant role in the element production process, while during supernova dominant are the reactions of *nucleosynthesis*, is also key fundamental distinction between the two types of events.

How exactly the chain reactions unfold in the collision scenario, is currently difficult to specify any further. The only thing that can be said at this point is that, in the framework of the outlined hypothesis, the observed abundances of the solar system represent the single outcome of such collision event known to us (of course, even with the collision, the observed abundances also include contributions from stellar and other *in situ* sources). We do not have a statistical sample to make any comparisons. If the fission and nucleosynthesis reactions were better understood, the only subsequent approach would have been to solve the *inverse problem*, i.e. to find out what the initial conditions had to be so the model resulted in the observed abundances.

4.5. Collision Target

We can envision several candidates for the "target'.

First, a number of independent analyses have pointed at the potential existence of an additional giant object in the early solar system (see argumentation for example in [64], [4], [66]). Thus, one

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candidate could be a large hydrogen-rich planet - a "super-Jupiter' - rotating around the Sun at the first orbit (located inside the Jupiter's orbit, which would have been second at that time).

Second, it is not impossible that the Sun initially had a close binary companion – a dwarf, or a main-sequence star, larger or smaller than the Sun. Indeed, the majority of solar–type stars are found in binary systems (see [1], [22], [49]). The well–known problems with angular momentum dispersal (e.g., [8] and references therein) indicate that protostars should end up in binary or multi-stellar formation. Furthermore, the 7^o misalignment between the Sun's rotation axis and the north ecliptic pole (see, e.g., [5]), may indeed be supportive of such scenario. In our case, both companions would have had to form a close binary and remain inside the orbit of Jupiter (wherever it was positioned at that time).

Finally, a scenario can perhaps be envisioned in which the (relatively tiny) compact object (the fragment of a neutron-star-like stellar body, as discussed) flies through the "edge" of the Sun (without significantly disrupting it), decelerates (sufficiently in the hydrodynamic sense defined above to trigger localized decompression, instability, and channels of transformations of nuclei, as outlined earlier), and explodes at the distance $\sim 1AU$. In such version of the scenario, the target is effectively the Sun. No additional solar system object is then required to have existed, but the general hypothesis of element formation could still be valid.

To compare the sizes of all objects that are potentially involved, recall that the mass of Jupiter is $10^{-3}M_{Sun}$, while a typical white dwarf has mass $\sim 0.5 - 0.6M_{Sun}$ (with density $\sim 10^6\, g/cm^3$ and size $\sim R_{Earth}$). The mass of all terrestrial planets is $\sim 10^{-5}M_{Sun}$, so the colliding object's net element production had to be not less than that in terms of mass. Overall, the object had to be such that it could explode (conditions for which are determined by several key factors discussed earlier), create the elements for the terrestrial planets (and other "rocks'), but *not destroy* the remaining solar system in the process.

5. Summary and Discussion

Overview of The Element-Generating-Collision Hypothesis

The entirety of puzzling peculiarities of the solar system – ranging from the availability of non-native chemical elements whose origins are difficult to explain, to the presence of atypical features in the planetary structure and dynamics – inspired us to inquire whether one event (an explosive collision) could have been responsible for all of the peculiarities at once.

In this paper, we described our hypothesis – we suggest that early on, more than five billion years ago, our solar system had *no terrestrial* but *only jovian* planets and possibly a companion closest to the Sun (perhaps a dwarf or super-Jupiter) and that about 4.6 billion years ago (at the time currently defined as the birth of the solar system based on dating of meteorites' chemical composition) a traveling from afar object collided with the solar system. More specifically, we suggest that it was a *giant-nuclear-drop-like* object (theoretical existence of which has been demonstrated and analyzed [78]) born as a result of destruction of some neutron-star-like stellar body by the super-massive black hole located at the center of our galaxy.

As the result of the collision, the decelerating object's inner matter stratified – first the spherical compression shockwave propagated from the front point towards the back, then (because the object's surface was strain-free due to extreme density contrast between the inner and outer media) the reflected shockwave reversed polarity and returned as the wave of decompression. [52,88] (See Appendix for details.) In a nuclear-like medium, the shock wave propagation speed is comparable with the speed of light – so the stratification process developed very quickly. During such short time, the shape of the droplet does not have time to change because propagation speed of surface perturbations is much slower than the speed of body waves. In the zones of decompression, the matter that was before the collision (thermodynamically) weakly-stable (perhaps due to aging and cooling of the object), now became unstable and "preferred' not the homogeneous but the two-phased state (the state of "nuclear fog' where "nuclear droplets' coexist with "nuclear gas'). In other words, inside

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the object, the (locally) decompressed matter became a conglomerate of "droplets' of charge-neutral nuclear matter as well as "gas' of alpha-particles, protons, electrons, and neutrons. Such charge-neutral "droplets' (obviously with hyper-large atomic numbers A) were structurally unstable and underwent spontaneous *fragmentation* and *fission* with release of neutrons. Due to the nuclear *mass-defect*, this process released a lot of energy – the system heated up – a "cloud' was formed composed of hyper-massive nuclei, alpha-particles, and protons and electrons to assure charge-neutrality of the system. All processes occurred at such fast nuclear-time-scales that the system exploded, and the matter became dispersed in the surrounding space. Overall, only insignificant mass remained within the orbit of the initial companion. The multitude of channels of reactions led to transformations of nuclei (from hyper-large A to moderate A).

After the collision (which occurred in the zone where current terrestrial planets are located), the final "products' of the nuclear reaction channels created the environment containing post-Fe elements, as well as the previously mentioned short–lived radionuclides, various isotopes, and so on, – with the element abundance profile as we know it. Later on, the nuclei condensed into dust, and eventually into terrestrial planets and other "rocky' bodies, and also enriched the pre–existing jovian planets.

The described mechanism of element-generation critically differentiates the proposed hypothesis from the traditional conception of the element-formation in the solar system. In our hypothesis, the dominant mechanism is the process of *fission* (from large atomic numbers A to moderate A), while in conventional models the primary process is *nucleosynthesis* (from lower A to higher A).

Likelihood: Plausibility vs Probability

The very thought of a collision often brings up a question of its likelihood. But in any context, it is very important to be clear what the term 'likelihood' is meant to describe.

The first kind of likelihood is 'plausibility', which inquires, in essence, whether the laws of physics permit the occurrence of the event in the first place. Understanding how a combination of various mechanisms can produce the event in question yields conclusion that the event is *plausible* – in other words, *not impossible*, not forbidden by the laws of physics.

The second kind of likelihood is 'statistical probability', which is about statistical odds of mental repetition of a *similar* event, not about whether the *first* (prior) event can happen. Questions about statistical probability always *imply* that the first event can or did happen. The concept of *statistical* probability of an event is connected with the concepts of the most *expected* outcome, the *frequency* of repeated events, and other similar characteristics.

The "frequency of collisions', $\nu \equiv \tau^{-1} = n\langle\sigma V\rangle$, gives indication about the *chance* of the occurrence of the event (collision) during some increment of time. Here, n is concentration of the target population, σ is target-object interaction cross-section, and $V \times 1$ is the distance covered by the moving object over the unit of time. Expression $P = \nu\Delta t = \langle n\sigma V\rangle\Delta t$ is defined over the *large* number of possible realizations (where $\langle ...\rangle$ denote statistical averaging, which is equivalent to ergodicity). Similar estimation is made, for example, for collisions between (microscopical) molecules of gas in a (macroscopical) container. Time increment τ is compared with the full time of experience Δt (traveling time of the object). If $\Delta t \ll \tau$, i.e. $P = \nu\Delta t = \langle n\,\sigma V\rangle\Delta t \ll 1$, it can be said then that a collision of the object with one of the targets during its journey most likely would not occur.

In our scenario, $V\Delta t \sim 3 \times 10^4$ light-years (distance from the center of our galaxy to the solar system). This is the distance that a traveling object with velocity $V \sim 3 \times 10^{-3}$ of light-speed, i.e. $10^3\, km/sec$, would cover in 10^7 years – not too long of a time in comparison with the age of the universe ($\sim 10^{10}$ years). Assuming $n \sim 1^{-3}$ light-years^{-3} (based on the average distance between stars in the central part of our galaxy ~ 1 light-year), $\sigma \sim (10^{-4})^2$ light-years^2 (estimated using average radius of capture for typical star-target $\sim 10^{-4}$ light-years, then taking into consideration collisional logarithm of Landau; this cross-section is roughly the area within Jupiter's orbit). Then $P \sim 10^{-4} \ll 1$, which implies that the object can reach current solar system location in about ten million years, without colliding with another star system along the way.

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But the statistical odds have nothing to do with the question of whether the proposed collision could indeed have happened 4.6 Gyrs ago. Such collision would have been (was) the *first* event. (And hence the only relevant inquiry is its plausibility.) And we humans should be very happy that the odds of the *second* such collision happening in our solar system again are low.

Hypothesis Implications and Further Research Wish-List

Understanding of how enrichment of the solar system with chemical elements occurred, is based on a set of models. These models propose and simulate a variety of local and distant element-generating mechanisms, each capable of generating its own set of elements, and then combining the resulting abundances, for each element, thus assembling the final abundance profile. This profile is then compared with data from direct measurements, and determinations are then made about the comprehensiveness of the envisioned enrichment scenario.

Based on detection on Earth and in sampled meteorites of "native' and "exotic' elements (such as long- and short-living $r-$ and $s-$process elements, radioactive isotopes, $p-$process elements), the *conventional scenario* currently presumes that all of the following element-generating mechanisms must have been involved:

(1) The Big Bang, which generated hydrogen (H), helium (He), and a portion of lithium (Li). These elements are the basis of the gaseous solar system objects – the Sun and the giants (Jupiter, Saturn, Uranus, and Neptune).

(2) (Continuous) ejections from interiors of *distant active stars, supernovae, and stellar collisions*, which over the lifetime of the Universe, created the interstellar background level containing (stable and long-living) elements from carbon (C) to uranium (U).

(3) (Continuous) disintegration of heavier nuclei into lighter ones by cosmic rays in interstellar medium, which presumably fills the element-gap between Li and C.

(4) (Presumed) *several supernovae* that occurred *not too far and not too close* to the solar system, whose trajectories must have followed specific requirements. The supernovae assumption is needed to explain abundances of certain *radioactive* isotopes.

(5) (Presumed) *at least five*, *distinct* and *distant*, contributing events, which all must have occurred *within the span of about 20 Kyrs* to explain presence and mixing of certain isotopes in meteorite samples.

(6) (Presumed) *local* event (within the solar system), which is required to explain presence of ^7Li in meteorite samples. ^7Li is produce by decay of ^7Be whose half-life is only 53 days.

(7) (Presumed) *"something'*, which must explain the *excess* (beyond all considered models offered to explain the puzzle) of proton-rich isotopes (which can form only in a very proton-rich environment).

Alternatively, in the framework of the *collision hypothesis*, contributions from mechanisms (1)-(3) would naturally remain, while mechanisms (4)-(7) may be replaced by the proposed element-generating mechanism – fragmentation/fission (and subsequent transformations) of the traveling from afar giant-nuclear-drop-like object (a hyper-nucleus in its composition) due to collision with then-existent companion of the Sun.

Conceptually, the proposed collision-evoked mechanism is capable of producing *all* elements in lieu of mechanisms (4)-(7). However, understanding at a more detailed level can be achieved only if more answers come from high-energy/hyper-nuclei experiments. Indeed, mapping out the spectra of plausible cascades of nuclei transformations, and eventually solving the inverse problem – finding out what initial conditions had to be so the model resulted in the (actually measured) abundances of elements on Earth and other sampled objects of the solar system – would be the way to advance this hypothesis further.

Next, the collision hypothesis can be refined by numerical simulations of planetary structure and dynamics. For example, modeling can possibly answer which companion of the Sun would fit best the proposed scenario – a dwarf or a super-Jupiter – and what bounds can be imposed on its characteristics.

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Furthermore, numerical simulations can consider the two-stage evolution of the solar system – first, formation of the gaseous objects from the protocloud in accordance with disk instability model but assuming longer lifetime for the system; and second, collision-evoked formation of the terrestrial planets (and other "rocky' objects) affecting the terrestrial belt structure (and enrichment of pre-existing gaseous giants) and occurring in accordance with accretion model. Recall that the currently-assumed age of the solar system – 4.6 Gyrs – is derived based on dating of meteorites' chemical composition. In the framework of our hypothesis, this would be the time when the collision occurred.

Also, numerical simulations can perhaps revisit the question of how the Sun obtained its 7^o tilt to the planetary plane, as well as the questions about "missing giants' or "planet Nine', in the framework of the proposed hypothesis.

Overall, the proposed collision hypothesis is capable of explaining all of the previously-mentioned chemical and structural peculiarities of the solar system. Furthermore, it can answer, at least conceptually, another intuitively troubling question: If the solar system enrichment with heavy elements – such as gold or uranium, for example – happened because far away, stellar cataclysms and collisions of neutron stars dispersed nuclei of these elements throughout the interstellar vastness, and these nuclei later mixed with the solar system's proto-cloud or reached proto-planets as dust particles, then *why do we find them as "chunks' on Earth, why aren't they uniformly mixed*? In contrast with the conventional scenario, the collision scenario actually can produce chunky clusters that formed deposits of uranium or gold mines on Earth.

Appendix

Static Regime: Density Stratification

All objects are in actuality *elastic* (compressible) to a greater or lesser degree. Behavior of an elastic body in the frame of reference moving with acceleration/deceleration is analogous to its behavior in a homogeneous gravity field. This means that density stratification will always take place. This effect will be significant if the characteristic scale of stratification is much less than the size of the object. The characteristic scale here is defined as s^2/a, where s^2 is square of the isothermal sound speed within the elastic body, and w is gravity acceleration, or deceleration/acceleration magnitude for non-uniform motion [52].

In a scenario when an object decelerates, *significant* stratification means $s^2/w < R_s$, where R_s is the characteristic size of the object. The magnitude of deceleration, w, may be estimated as $w \sim (\rho_t/\rho_s)V^2/R_s$. This gives

$$s^2/V^2 < (\rho_t/\rho_s)(R_s/R_t) \tag{1}$$

Since $R_s \ll R_t$ and $\rho_t \ll \rho_s$, it necessarily implies that for a significant density stratification to take place, the elasticity of the inner matter (characterized by $s^2 = (\partial p/\partial \rho)_T$, calculated at constant temperature) must become "small' in the course of events. This is possible when the mono–phase state (liquid) of the matter approaches its thermodynamical (gas/liquid) stability threshold.

High-Velocity Collision of Drop with Target

When a droplet collides with some object (target), inside the droplet – as known – various motions arise, the speed of which is comparable with the speed of the droplet. If the droplet's initial speed is comparable with the speed of sound within the droplet's matter, then compressibility becomes apparent.

The following effects arise inside the droplet upon collision: excitation and propagation of shockwaves of compression and decompression, interaction of the waves with each other and with free surfaces, formation and development of radial near-surface cumulative jet, formation and collapse of cavitation bubbles inside the droplet, and other complex hydrodynamic phenomena.

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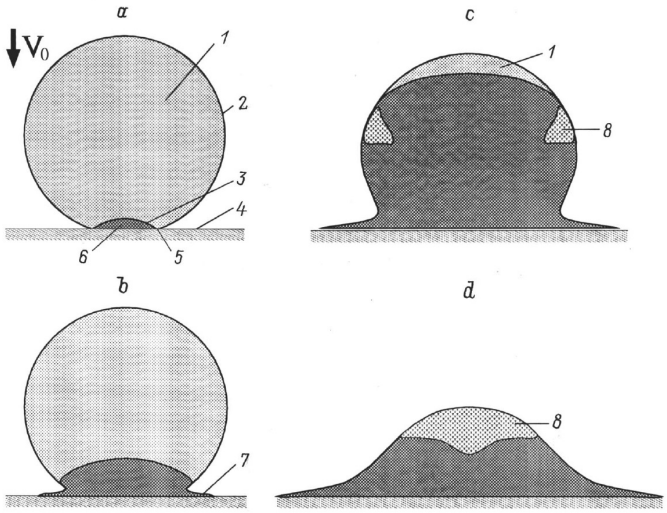

Figure 3. Schematic of drop impact (the drop is moving from above). Panels: (a) before spreading; (b) jet initiation; (c) shockwave approaches the top of the drop, toroidal expansion region is formed; and (d) initiation of vast expansion area with cavitation region. Zones: (1) unperturbed liquid, (2) free drop surface, (3) shockwave, (4) target's surface, (5) contact boundary, (6) compressed liquid area, (7) jet, and (8) cavitation region.

Quantitative numerical simulations of these effects show that results are strongly model-dependent, particularly, on the choice of the model EoS for the droplet's matter. Even the qualitative picture of a high-speed collision is not yet fully understood. Understanding of many aspects remains incomplete, such as roles of viscosity and surface tension even in the case of the simplest model EoS of the liquid, mechanisms of development and destruction of the cumulative jet, estimates of velocity of the radial jet, mechanism of formation of cavities, strains experienced on the target, and so on.

Qualitatively the process of high-speed collision can be described as follows (see Fig.3 taken from [19]):

During the process of interaction of the droplet with the surface of the target, the flow of fluid forms, which develops a strongly-non-linear wave structure and strongly deforms free surfaces.

One of the features of collision of a convexly-shaped droplet is that at the beginning stage, the free surface of the droplet that does not touch the surface of the target, does not deform. The region of compression is confined to the shockwave that forms at the edge of the contact spot (Fig.3a).

Furthermore, there develops a near-surface wave. (The front of which is tangential to the front of the shockwave, and starts from the edge of the contact spot. It is not shown in Fig.3a)

This is explained by the fact that the speed of expansion of the contact spot $V_0(t) = V_0 \cot \beta(t)$ (here V_0 is the initial velocity of the drop, $\beta(t)$ is the angle between the drop's free surface and the target's surface at moment t) is greater than the speed of propagation of the shockwave within the droplet's medium from time zero to the critical moment t_c when these speeds match – the speed of the contact spot boundary diminishes from its infinite value at the moment of contact, but remains greater than the speed of the shockwave until the moment t_c. Therefore, during this time perturbations expanding from the contact spot do not interact with the free surface of the droplet. At the edge of the contact spot, compression of the droplet's liquid is maximal.

At the critical moment of time t_c, the shockwave detaches from the edge of the contact spot and interacts with the free surface of the droplet, and a reflective decompression wave forms which propagates inward (toward the central zone of the drop). The free surface becomes deformed, and a near-surface high-speed radial jet of cumulative type forms (Fig. 3b). The time of formation of the jet

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depends on the viscous and surface effects within the liquid near the surface of the target, its velocity substantially exceeds the speed of collision.

Once the wave is reflected from the droplet's free surface, the change in polarity of impulse occurs. The reflective wave of decompression forms a toroidal cavity, the cross-section of which is qualitatively shown in Fig. 3c.

At the final stage of interaction, the wave of decompression collapses onto the axis of symmetry, and forms a vast cavity with most decompression occurring in the region near the axis (Fig. 3d).

During the propagation of the decompression wave toward the surface of the target, the cavity fills almost the entire volume of the droplet, except for the thin layer near the droplet surface and the zone occupied by the near-surface jet. As the result of development of instability within this thin envelop, the droplet becomes shaped as a "crown', and the matter of the droplet becomes splashed out in small fragments.

Thermodynamic Instability

If a system is thermodynamically unstable, the rapidity of development of small spontaneous perturbations of density is determined by the parameter called "adiabatical sound speed". This parameter (dimensionless here) for relativistic fluid is calculated using expression $V_s^2 = (\partial p/\partial \varepsilon)_s$ where p is pressure and ϵ is internal energy per particle. Quantity V_s^2 is calculated in condition that entropy per particle, s, is constant. However, pressure and internal energy are frequently given as functions of density $z = \rho/\rho_c$ and temperature $\theta = T/T_c$. In this case, it is natural to calculate V_s^2 using Jacobians and their properties (see [50], [73] for details):

$$V_s^2 \equiv \left(\frac{\partial p}{\partial \varepsilon}\right)_s \equiv \frac{\partial(p,s)}{\partial(\varepsilon,s)} = \frac{p_z - s_z(s_\theta)^{-1}p_\theta}{\varepsilon_z - s_z(s_\theta)^{-1}\varepsilon_\theta}. \tag{2}$$

Once the expression for free energy f – the equation of state (EoS) – of the model is known, then pressure p, entropy s, and internal energy ϵ, as well as all derivatives in Eq. (2), can be found. Then V_s^2 can be calculated using standard procedures.

Plots of functions $P(z)$ and V_s^2 for several illustrative cases are shown in (borrowed) Fig. 4 and Fig. 5. [78] The domain of inner matter where $P(z) < 0$ and $V_s^2 < 0$ is the *spinodal* region in plane (z, θ) (shown in Fig. 6). When $V_s^2 < 0$, the system becomes unstable with respect to small spontaneous perturbations (fluctuations).

In view of certain limitations on thermodynamical functions, a thoughtfully-designed interpolating expression for the dimensionless free energy may be constructed from which all thermodynamical quantities can be found.

Here are the considerations for such interpolation: [78] For small densities, $z \to 0$, the interaction between particles is weak, and the dominant term is the first term which describes a gas of non-interacting particles. As the density increases, the properties of the system differ more and more from the properties of the ideal gas, the interaction (logarithmic term in expression for pressure) becomes more and more significant. With further increase of density, $z \gg 1$, the gas enters its condensed state (liquid) – the term $\sim z$ in expression for f becomes most important. For high densities z, the equation of state has to be "hardened" to account for the dominance of the "repulsive core" in the potential of particle interaction. In such "hardened" state, repulsion between particles is very strong, and the properties of this interaction no longer depend on the specific type of the liquid, thus the corresponding term in the free energy has to have the universal form for the pressure $p \sim z^2$. [86]

Furthermore, conceptually, and in view of specific experimental data, the interpolating expression incorporates the following considerations: (a) the equation of state (EoS) following from f has to have a form admitting the existence of the critical point where $p = \partial_z p = 0$; (b) the pressure $p(z_1) = 0$ for some value $z_1 \neq 0$; (c) the critical density ρ_c is of order of $(0.1 \div 0.4)\,\rho_0$, i.e. $z_1 \simeq (3 \div 7)$; (d) compressibility factor $K \sim (240 \div 300)\,Mev$; (e) the principle of causality must be respected – the adiabatical sound speed must be always smaller than the light speed. [78]

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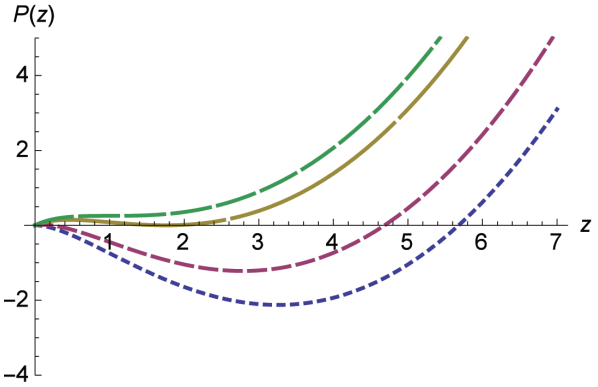

Figure 4. Pressure $p(z,\theta)$ as a function of normalized density $z = \rho/\rho_c$, for the model of nuclear-drop-like object with equation of state described by interpolating expression permitting mono- and two-phase states. [78] Several values of normalized temperature $\theta = T/T_c$, $T_c \sim 15\,Mev$ are shown: $\theta = 0$ (lowest line), $\theta = 0.3$ (second line from bottom), $\theta = 0.8255$ (second line from top) which contains the point where $p = \partial_z p = 0$, and the critical isotherm $\theta = 1.0$ (upper line) which contains the point where $\partial_z p = \partial_{zz} p = 0$. The lowest curve represents the hypothetical case where the thermal term in the expression for free energy is omitted. All curves below the critical isotherm, i.e. when $\theta < 1$, possess two turning points ($z_1 < z_2$) where $(\partial_z p)_{z=z_i} = 0$, i.e. $s^2(z_i) = 0$. In the domain $0 < z < z_1$, the matter is in its gas state. In the domain $z > z_2$, the matter is in its liquid state. Between z_1 and z_2, lies the zone where the gas and liquid phases co-exist.

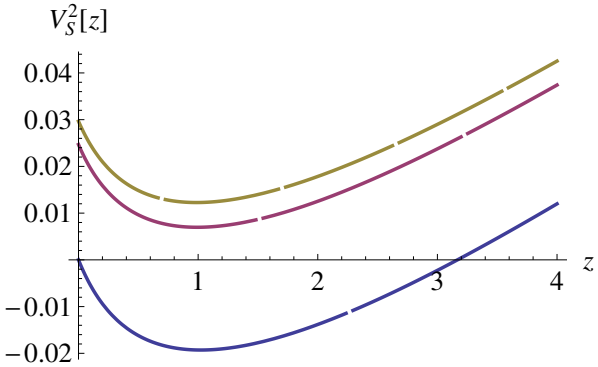

Figure 5. Square of adiabatical sound speed $V_s^2(z)$, normalized by the speed of light, as function of normalized density z, for the model of nuclear-drop-like object with equation of state described by interpolating expression permitting mono- and two-phase states. [78] Several values of normalized temperature $\theta = T/T_c$ are shown: critical isotherm $\theta = 1$ (upper line), $\theta \simeq 0.84$ (touching horizontal axis), and $\theta = 0$ (lower line). Domain with $V_s^2(z) < 0$ (where sound speed $V_s(z)$ is imaginary, i.e. the system is unstable) is the so-called "spinodal" zone, in which small spontaneous initial perturbations of density will grow exponentially fast once triggered. Development of instability in homogeneous medium leads to formation of two–phase pockets where liquid (drops) and gas (vapor) states co–exist. Only the states with temperatures below some temperature θ_* (unique for the medium), for which the curve $V_s^2(z)$ touches the horizontal axis in plane (z, V_s^2), may experience such instability. For the states with $\theta > \theta_*$, the speed of sound is always real ($V_s^2(z) > 0$) and the matter remains in its mono–phase state.

Analysis of the model with such interpolating expression, demonstrated theoretical possibility of existence of the spinodal zone – where the square of the sound speed is negative – for temperatures below critical, for a nuclear-drop-like object of any (even very small) size. [78] This signifies that, within the domain, small spontaneous initial perturbations of matter density do not propagate as acoustical waves in certain structures composed of nuclear matter, but grow exponentially fast (at

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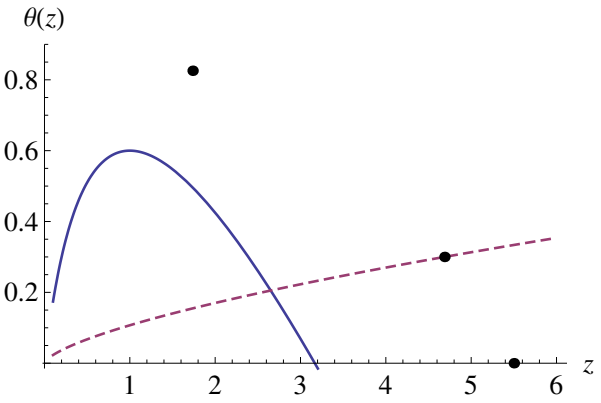

Figure 6. Spinodal region for the model of nuclear-drop-like object with equation of state described by interpolating expression permitting mono- and two-phase states. [78] Inside the domain, $V_s^2 < 0$; outside the domain, $V_s^2 > 0$. On the (θ, z)-graph, pressure points $p = 0$ are shown as black dots – their coordinates are $(5.5, 0)$, $(4.7, 0.3)$, and $(1.74, 0.83)$. Any process that decompresses and cools the system adiabatically (along line $\theta = \theta_0(z/z_0)^{2/3}$) from its initial mono-phase state (z_0, θ_0) would trigger development of collective instability and fragmentation of nuclear matter, once the system is in the spinodal region.

the beginning of the process). This instability process leads to formation of the two-phase (coexisting liquid–gas) state.

Any process that can "push' the system from its initial "liquid' state (z_0, θ_0) into the spinodal region – for example, adiabatically (following lines $\theta = \theta_0(z/z_0)^{2/3}$) – would trigger instability development. For a hyper-nucleus, such instability leads to fragmentation. Sharp (straight-line) deceleration and resulting (localized) decompression (for example, $\rho_0 \to \rho_0/2$) can serve as the trigger.

It is important to underscore, that in the proposed model for free energy, the speed of sound is always less than the speed of light, $V_s^2 < 1$ (the causality principle is respected).

Energy Effects

A stationary spherical configuration with the above-mentioned equation of state can indeed (theoretically) exist. [78]

In general, a stationary spherical configuration exists only if the boundary condition for pressure $p = 0$ is respected for some $z_1 \neq 0$. This means that (in terms of Fig. 4 graphs) for a given θ_1 there must exist an intersection of curve $p = p(z, \theta_1)$ with horizontal axis $p = 0$. The intersection value $z_1 \neq 0$ is the boundary value of density which corresponds to $p(z_1, \theta_1) = 0$.

If some mechanism – collision-evoked deceleration, for example – heated up the colliding object, the object's inner state would shift into another state characterized by the new (higher) temperature, $\theta_1 \to \theta_2 > \theta_1$. In terms of Fig. 4 graphs, the new $p(z, \theta_2)$-curve might rise above the horizontal axis $p = 0$ in such a way that no intersection points would theoretically exist. Physically, that would mean that no equilibrium spherical configuration would exist – the system would then disintegrate – the hyper-nucleus would split into fragments (likely unstable as well). Due to the nuclear *mass-defect*, such fragmentation/fission would release a lot of energy – since nuclear time-scales are extremely short, this would lead to a powerful explosion.

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