Hypothesis

Hypothesis and Feasible Mechanism for Appearance of Post-Post-*Fe* Nuclei in Solar System

Elizabeth Pavlova-Tito [1], Vadim I. Pavlov [2]

1 Scientific Advisory Group, Pasadena, CA 91125, USA
2 Université de Lille, Faculté des Sciences et Technologies, DM, LMF de Lille - Kampé de Feriét, FRE 2017, F-59000 Lille, France
* Correspondence: vadim.pavlov@univ-lille.fr

Abstract: Conventional models do not fully explain composition of the solar system – for example, the presence of *p*-nuclei and post-post-*Fe*-nuclei remains not yet understood (and is one of the great unresolved puzzles of nuclear astrophysics in general); other puzzles exist. We offer a hypothesis which can explain the appearance of non-native elements in the solar system, and a feasible scenario for its implementation. The hypothesis suggests that a nuclear-fission "event" occurred in the inner part of the solar system at the time currently defined as the birth of the system. Conventional models have never considered fission as a contributing nuclei-production mechanism. Upon examination of the existing models and factual data (presented in volumes of publications but never combined into an aggregate), we identified one plausible scenario by which a fission event (not demolishing the entire solar system) could occur: an encounter with a compact super-dense stellar "fragment" (with specific properties) and its "explosion" in fission-cascades. Such scenario also helps resolve other long-standing puzzles of the solar system. For example, it provides that the fission-produced nuclei subsequently transformed into the material that (eventually) accreted into the "rocky" objects in the system (terrestrial planets, asteroids, etc.) and enriched the pre-existed hydrogen-helium objects (the Sun and the gaseous giants) – this offers an explanation for the planets' inner position and compositional differences within the predominantly hydrogen-helium rest of the solar system. Other implications also follow.

Keywords: Hypothesis, Fission, Heavy Post-Post-*Fe* Elements, Solar System

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1. Status of Current Understanding of Solar System Evolution: Fundamental Puzzles Remain

Despite the widely held belief that formation and composition of the solar system are well understood and only nuances remain unresolved, serious conceptual gaps in the understanding continue to exist. The goals of this paper are: to combine the (published) factual evidence into one multi-disciplinary *aggregate*; to advance a *hypothesis* that can offer resolution to the yet-unresolved puzzles and reconcile inconsistencies in the existing explanations; and based on examination of already-available (published) models and data, to identify a *scenario* of plausible (not forbidden by laws of nature) implementation of the hypothesis – for a conceptual hypothesis, its implementation "scenario" is an equivalent of a "model" in a phenomenological analysis.

1.1. Gaps in Understanding of Structural Formation

The following quote succinctly sums up the current status of comprehension [1]: "The breakthroughs achieved during the recent few decades in our understanding of solar system formation are impressive. However, they are yet insufficient to clarify many problems intrinsically related to planetary cosmogony. Moreover, very important new questions have been posed that should be pursued before a robust theory of solar system origin and early evolution appears." One of these questions is "What was the original structure of the solar system, how did it evolved to the contemporary configuration, and what determines the planetary system final architecture?"

1.1.1. Origin/Position of Distinct Classes within Planetary Structure

Review of planet formation models brings to focus some specific areas of concern: "There remain considerable uncertainties at each step of planet formation. ... even our most successful models are built on a shaky foundation" [2]. "The solar system is characterized by a trimodal structure" containing terrestrial planets (rocky and relatively small), the asteroid belt (with cumulatively negligible mass), and the giant planets (beyond 5AU). "How this trimodal structure was set is still an issue of open debate" [2]. Even (excluding asteroids) the "bimodal structure is puzzling. Assuming that planetesimals formed everywhere in the disk with comparable masses ... the subsequent process of planet growth

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by pebble accretion should favor the bodies closer to the Sun ... In other words, giant planet cores should have formed in the inner disk and Mars mass embryos in the outer disk!" [2] "The analysis of meteorites shows indeed that there were at least two generations of planetesimals in the inner disk. ... It is unclear whether there was a gap in time in planetesimal formation and even whether the first and last generations of planetesimals formed in the same place" [2]. "How they grew to pebble-boulder size or larger bodies (specifically around the "meter-size barrier") is not completely clear ..." [1].

1.1.2. Unresolved Issues in Accretion and Disk Instability Formation Models

Furthermore, while the rocky objects are thought to have formed by accretion (from dust grains into larger and larger bodies), two competing theories exist about formation of the giants – the core accretion model and the disk instability model. In either case, reconciliation of formation of two classes of planets has not been successful yet. 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 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 spontaneous density perturbations in the primordial disc could have caused clumps of gas to become massive enough to be self-gravitating and form the Sun and the planets [3], [4]. Formation scale is then much more rapid, but the model does not readily explain the observed chemical enrichment of the planets.

1.1.3. Atypical Characteristics in Comparison with Exoplanetary Systems

As the set of exoplanetary data continues to expand [5], the historical presumption that the solar system is "typical" (just an ordinary planetary system evolved in an ordinary way) becomes increasingly questioned [2]: " ... how typical was the solar system's evolutionary path? ... Or was the solar system's path unusual in some way? ... Based on statistically sound exoplanet observational surveys, the Sun-Jupiter system is special at roughly the level of one in a thousand. First, the Sun is an unusually massive star ... Second, only $\sim$ 10% of Sun-like stars have gas giant planets with orbits shorter than a few to 10 AU... Third, only about 10% of giant exoplanets have orbits wider than 1 AU and eccentricities smaller than 0.1. Taken together, these constraints suggest that the Sun-Jupiter system is a 0.1% case. ... The numbers quoted here are a simple order of magnitude, but they clearly illustrate that the solar system is not a typical case in at least one regard: the presence and orbit of Jupiter" [2].

Indeed, the orbits of the solar system's giant planets are widely spaced and nearly circular, which is unusual [6], [7], [8]. Remarkably, they also do not exhibit any resonance despite the fact that, as N-body studies of planetary formation and orbit positions indicate, 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 [9], [10]. Some studies have also exposed the possibility that one more giant object initially might have been present in the solar system and then somehow disappeared at some point – dynamical simulations starting with a resonant system of four giant planets showed low success rate in matching the present orbits of giant planets [11] (see also discussion in Sec. 4.4).

1.2. Gaps in Understanding of Nuclear Origination of Chemical Elements

But the most significant deficiency in the understanding of the solar system's evolution concerns not its *structural formation* but the *nuclear origination* of its chemical elements. A number of anomalous for the solar system nuclides – varied in lifetimes (from stable to very short-lived) and produced by r-, s-, p-, or γ-processes (not natural for the solar system) – have been detected in the terrestrial and meteoritic material [12]. Theoretically, these nuclei can be produced, directly or via chains of transformative reactions, in specific stellar events (each having its own "signature" – its own nuclei-generation profile). However, the ways in which these nuclides had mixed and solidified in meteoritic samples

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have imposed significant constraints on the timing (and location) of their origination. A number of challenges and inconsistencies exist in the models that have been proposed so far. Furthermore, some issues continue to remain unanswered. Here are the fundamentally important ones.

1.2.1. Challenges to Explanations of Short-Lived Nuclides Origins

The appearance of ^{26}Al, ^{41}Ca, ^{53}Mn, ^{60}Fe, and a few other nuclides, in the early solar system require their production at the same time, or just before, the "rocky" components of solar system formed (see, among others, reviews by [13], [14], and references therein). 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, [15], [16], and references therein).

The conventional belief 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 [17], [18], [19], [20], [21], and references therein). However, 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" [22].

To reconcile various findings, the theory was advanced that the solar system formed as part of a star cluster [23] and therefore was enriched by multiple stars. The challenge is however that stellar clusters are potentially dangerous environments for planetary systems [1]. The multi-source enrichment theory also faces a timing challenge.

To be able to provide the observed abundances of radioactive isotopes, multiple supernova must have been located *not too far* from the solar nebula, but 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 [24]. But stars within the cluster typically form within 1-2 Myr [25] and the clusters disperse in about 10 Myr or less [26]. Since stars with mass $M \sim 25 M_{Sun}$ burn for ~ 7.5 Myr before core collapse [27], to fit the supernova enrichment scenario the Sun must have formed several Myr after the progenitor [24]. If located ~ 0.2 pc from the progenitor, the early solar nebula could have been evaporated by the progenitor radiation [28]. 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 [24]. Such timing requirement lowers the odds for the supernova enrichment theory [29]. The scenario in which multiple supernovae satisfied such trajectory and timing requirements has even lower odds.

Furthermore, when constraints imposed by the spread of calcium-aluminum inclusions (CAI's) condensation ages are taken into consideration, if the detected short-lived radionuclides were produced by multiple stellar sources (*at least five* [22]), *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* [16].

1.2.2. Inconsistent Models for ^{10}Be and ^{7}Li Enrichment

Detection of ^{10}Be indicates that one more (high-energy) 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 [30], [31] 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 (high-energy nuclear reaction in which target nuclei are struck by bombarding particles) within the solar system as it was forming. Various research groups have tested this scenario by comparing the modeled nuclear spallation yields with the inferred solar system initial ratios (e.g., [32], [33], [34], [35]). However, they failed to self-consistently explain the abundance discrepancies.

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Indeed, understanding of mechanisms of ^{7}Li production / destruction is generally incomplete. For example, the "lithium problem" – the mismatch between the (higher) predictions of primordial abundances by the Big Bang nucleosynthesis theory and (lower) measurements of the chemical content of the atmospheres of old stars – is still unresolved, despite the efforts to tackle the issue using various approaches [36].

1.2.3. (Fundamentally) Unexplainable "Excess" of Proton-Rich Isotopes

Most significant, however, is the fact that anomalous for the solar system proton-rich nuclides (the so-called p-nuclei) have been detected in the terrestrial and meteoritic material [37], [38], [39], [40]. Their abundances are relatively tiny. (Before astronomical observations of isotopic abundances at the required discrimination level become feasible, if ever, it is impossible to determine p-abundances elsewhere [37].) The question of how these elements appeared in the solar system is not yet answered [37], [38]. Indeed, understanding the origin of proton-rich nuclei in general is the great challenge of stellar nucleosynthesis because p-nuclei cannot be made in the s- and r-processes.

Conceptually, in stellar events, p-nuclei can be produced either by proton-capture from nuclei with lower proton 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. The conventionally considered scenario for creating these isotopes involves the post-supernova photodisinteration p-process – the so-called γ-process – a complex network of reactions of photodisintegration (of the pre-existing intermediate and heavy nuclei) whose inputs are the outputs of the inverse reactions (proton-, α- and neutron-capture) that occur during the explosion of a supernova (mainly in explosive Ne/O burning during a core-collapse supernova) [41]. Even so, the origin of the proton-rich *post-post-Fe* nuclei still remains one of the greatest puzzles of stellar nucleosynthesis [37], [38].

Currently, the solar system abundances of p-nuclei have been best fitted into the combination of models of *several* stellar processes [37], [38]. Photodisintegration in massive stars Type Ia-supernova or a mass-accreting white dwarf explosion [37] 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 model-simulated production from the stellar processes, and *this problem has not been resolved yet* [37].

Even though abundances of the p-nuclei detected in meteoritic and terrestrial material of the solar system are tiny, their unexplainable "excess" is very significant, because the *quality* of the understanding of what had contributed to the solar system's chemical composition is gauged by comparing (1) the "observed" profile of element abundances (consensus of direct/indirect measurements) with (2) the "simulated" profile that sums up outputs from all modeled mechanisms (superposition of models). A meaningful "mismatch" with respect to any one element (isotope) indicates that the understanding is incomplete – either (a) assumptions and superposition weights of contributing models may need adjustments (which may be difficult due to other physical constraints), or (b) a new mechanism/model is required to explain the mismatch. Since the detected p-nuclei abundances *exceed* best simulation results, it means that there has not been found a combination of model parameters that could match observations. Thus, a new model or mechanism is needed to explain the factual evidence.

2. Hypothesis: Nuclear-Fission "Event" Occurred in Inner Solar System (Birth of "Rocks")

The presence of p-nuclei in the solar system is the greatest conundrum on the list of puzzles (Sec. 1); it also offers perhaps the greatest pointer. According to the conventional view (see, for example, review [38] and numerous references therein), p-nuclei can be produced via captures of various types and photodisintegration. *But p-nuclei can also be produced via fission of heavy nuclei.* Furthermore, *fission* of hyper-nuclei (nuclear droplets) via spontaneous nuclear transformation cascades can yield not only p-nuclei, but also *all other* types of nuclei, including *post-post-Fe* nuclei (their production mechanism

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currently remains yet another unresolved puzzle of nuclear astrophysics), as well as all other "exotic" nuclei detected in the solar system.

In view of this insight, our hypothesis[1] proposes that: *A nuclear-fission "event" occurred in the inner part of the solar system at the time currently-seen as the birth of the solar system* (4.6 billion years ago, based on the dating of meteorite samples), and that: (a) the solar system was formed *before* the event and initially had only giant hydrogen-helium objects; (b) the debris from the event formed the "rocky" objects in the system (terrestrial planets, asteroids, and so on) and also enriched the pre-existed hydrogen-helium objects (the Sun and the gaseous giants); and (c) the fission-driven production of nuclei during the event was in fact the *primary* source of all "exotic" nuclei in the solar system (see Sec. 1), while enrichment via other mechanisms (supernovae, giant stars, distant or local photodisintegration, and so on) can be viewed as contributing.

The remainder of the article is focused on the analysis of factors that would be *required* for successful implementation of the proposed event. Our examination of the existing models and experimental results from related disciplines identified one scenario that is physically *plausible*, i.e. not impossible or forbidden by the laws of nature. However, before any qualitative estimates, systems of equations, or model simulations can be built, further (technologically complex and financially expensive) experimental determinations (from various fields, and particularly from high-density nuclear experiments) and establishment of initial-condition anchors (constraints) for the model are necessary. (The challenges are described in detail in Sections 4.3 and 4.4.) Nonetheless, while certain aspects of the *scenario* may be revised in time as additional data and insights become discovered, any calls to dismiss the *hypothesis* simply because "it just does not quite fit the mainstream belief-system and hence can't be true" must be refuted in view of the abundant factual evidence (indicating the critical need for a fundamentally new mechanism for nuclei production and planetary formation) provided in more than a hundred publications cited in this paper and all the literature supporting those publications.

The *plausible scenario* of the event captures the following: Because there exist no natural "sources" of stellar-sized fission in the solar system, for the fission enrichment to occur as evidence suggests, the "source" had to arrive from afar. As Sec. 3.1 elaborates, a compact super-dense stellar "fragment" could have delivered the nuclear matter necessary for the fission event. The object had to be super-dense (with density like that of a giant-nucleus) to produce fission. The object had to be compact (small in terms of stellar size) because the fission event had to be "powerful" enough to create all the nuclei in question (forming and enriching terrestrial planets, asteroids, cores of gaseous planets, etc.), but not too "powerful" so the release of energy and matter did not destroy the solar system altogether. A stellar "fragment" born and catapulted in a galactic cataclysm (see Sec. 3.1) could have had the necessary properties.

In Sections 3.2, 3.3, and 3.4, we reference available models and outline the sequence of steps and requirements that can make such event feasible. In brief, upon the encounter with the solar system, the traveling object (possessing specific properties) had to experience internal phase-instability and "explode". In Sec. 3.3 we propose one plausible *mechanism* for such internal instability.

Finally, within the solar system some specific "obstacle" had to play the role of instability trigger. In Sec. 3.5 we identify three candidates: the Sun itself (the edge of it), a potential binary companion of the Sun that could have existed pre-event, and another gaseous giant (a "super-Jupiter") that could have existed at the first orbit. Obviously, in the latter two cases the "obstacle" didn't survive the event.

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[1] The first attempts to express this idea were undertaken in [42] and [43].

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3. Analysis of Requirements for Plausible Scenario

3.1. Object Capable of Producing Nuclear Fission: Compact Super-Dense Stellar "Fragment"

Generally speaking, a number of exotic compact stars have been hypothesized [44], [45], 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. Even "dark energy stars" and "Planck stars" have been proposed. Indeed, various objects could have existed five billion years ago.

Just as a reminder, the conventional 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 conventional 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 [46]. 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 $\sim 1600\, km/s$ [47].

Small fragments of such stars can also be formed and kicked, or catapulted, if a black hole tears a neutron star apart [48]. Fig. 1 illustrate such possibility (three scenarios depicted).

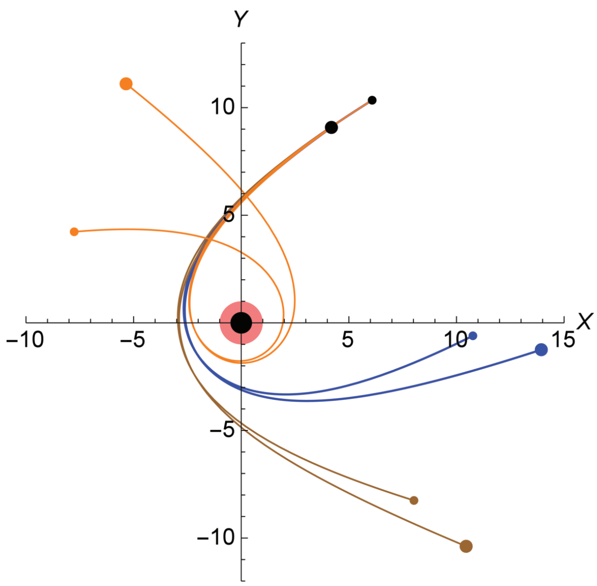

Figure 1. Illustration of the destruction process (three scenarios from [49]). A stellar body (depicted as the black dot near dimensionless coordinates (+6; +10)) that comes into vicinity of a rotating massive black hole (depicted as the black circle at the center) becomes torn apart by the fast-rotating 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.

Objects smaller (even significantly smaller) than conventional 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 [50]. In our hypothesis, the traveling object – the stellar "fragment" – resembles (in essence) a giant "nuclear drop" (a hyper-nucleus) born in an asymmetric stellar cataclysm far away and catapulted with sufficiently high velocity, whose trajectory happened to eventually (accidentally) cross the solar system's path.

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3.2. "Encounter" with Solar System: Explosive Release of Energy and Matter

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, [50], [51], [52], [53], [54], [55], and references therein). In laboratory conditions, for nuclear samples, $T \ll T_c \sim 15\,Mev$ and $\rho_{nucl} \sim 2 \div 3\rho_c$. Below the critical temperature T_c, depending on its density, 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). See Appendix A.

In our scenario, for the stellar "fragment", 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 as the result of perturbation (deceleration) – see, for example, [50], [51], [52], [53], [54], [55], and references therein. 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, cascading nuclear *fragmentation* of the nuclear-droplets and subsequent *fission* of the fragments may start.

Below density ρ_{drip} – even if in some small physical domain within the object – β-decay becomes no longer Pauli-blocked and significant amount of energy becomes 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-decay sets in [56].

This process triggers cascading *fragmentation* of these supersaturated hyper–nuclei (see, for example, [57], [58], [59]). These reactions, known to release even more energy ($\sim 1MeV$ per fission nucleon, as seen in transuranium nuclei fission events), proceed effectively at the same moments as the β-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 cascading *fission* reactions commence.

Generally speaking, at different stages (with respect to applied energy/excitation of hyper-nuclei), different types of reactions occur [55]. 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 subsequent splitting into fragments and strong neutron emissions. (See Sec 4.5 regarding the status of contemporary experimental investigations of super-heavy nuclei fission.)

3.3. Mechanism for Internal Instability: (Localized) Decompression Due to Deceleration

A number of mechanisms contribute to the object's deceleration as it penetrates a medium: classical drag [60], dynamical friction [61], accretion [62], Cherenkov-like radiation of various waves related to collective motions [63] generated within the medium [64], [65], 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

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the boundary of the two-phase (spinodal) zone, deceleration with even "negligible" magnitude in the kinetic sense can in fact be a "significant" perturbation capable of triggering "sufficient" density stratification. In the (highly unstable) spinodal zone, even small perturbations develop *extremely* fast. (See Appendix B..) Since nuclear processes occur with even faster time scales ($t \sim 10^{-22} \div 10^{-15}$ sec) than thermodynamic processes, even "minor" localized decompression can trigger a cascade of spontaneous fragmentation and fission.

The lower are the nuclear-drop-like object's initial inner density and temperature "at birth", the less time will it take for its (T, ρ)-phase-state to shift (via cooling) towards the nuclear-liquid/nuclear-gas phase-transition boundary. The closer is the (T, ρ)-phase-state to the boundary, the smaller is the minimal perturbation (deceleration) magnitude necessary to produce decompression "sufficient" for triggering the cascade of nuclear transformations.

Theoretical plausibility of existence of small stable objects (spherical configurations) with the above-mentioned nuclear-drop-like properties has been demonstrated [50]. Astronomically, however, such small and cool objects are difficult, if not impossible, to detect with current observational methods. The smaller (less massive) are the objects from the start, and the older they become, the lower are their temperatures (and densities).

3.4. Nuclei Transformation Cascades: Production of Full Spectrum of Elements/Isotopes

At this stage of the scenario, strictly speaking, the following model-system should be considered: strongly-deformed heavy nuclei in the environment of "vapor" of free protons, neutrons, α-particles, β-particles, neutrinos, and γ-radiation. For this system, the expression for free energy (or Gibbs potential) must be written and solved for its extremum for fixed temperature and pressure. This extremum imposes certain constraints for the first and second derivatives of entropy calculated from the potential. The Second Law of Thermodynamics establishes some inequality expressions for the entropy's second-derivatives, which assure that the system does not leave the vicinity of the equilibrium state, i.e. does not evolve. If any of the inequalities is broken, the system becomes no longer able to exist in the state of thermodynamic equilibrium, and explosive process takes over.

To attempt to simulate numerically the outcome of the explosive nuclei-production chains is 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 practically impossible to collect, and experimental studies are quasi-impossible at present to conduct. Splitting of nuclei with high A numbers into several with lower A numbers leads, via different channels, to the unpredictable composition of fission products, which vary in a broad probabilistic and somewhat chaotic manner. This distinguishes fission from purely quantum-tunnelling processes such as proton emission, α-decay and cluster-decay, which yield the same products each time. Unfortunately, even with respect to attempting to model fission of (not hyper- but) super-heavy nuclei, the critical input data – such as experimental measurements of interaction cross-sections for the entire spectrum of nuclei (whose half-lives range as widely as $10^{-19} - 10^{+24}$ s) that would normally go into numerical simulations – are not yet collected. Such experiments require enormous government funding for state-of-the-art facilities which only in recent decades started seeing early advances in exploration of super-heavy nuclei, but much more experimental work is still needed. (See Sec 4.5 regarding the status of contemporary experimental investigations of super-heavy nuclei fission.)

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 [56], 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. 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

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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 [56].

Finally, the data on the abundance yields from the observed supernovae are not useful for modeling the proposed event nuclei production. The two processes (supernova and event) 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: ${}^{56}Fe_{26} + \gamma \rightarrow 13^4He_2 + 4^1n_0$, ${}^4He_2 + \gamma \rightarrow 2^1H_1 + 2^1n_0$. 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, [66]).

As for the production of gold, it occurs, for example, by free-neutron-capture of excited nuclei of mercury, which serve as seeds. Nucleus ${}^{198}Hg_{80}$ captures a rapid free neutron, produces excited nucleus ${}^{198}{Hg_{80}}^*$, which then turns to ${}^{197}Au_{79}$ via β-decay: ${}^{197}Hg_{80} + {}^1n_0 \rightarrow {}^{198}{Hg_{80}}^* \rightarrow {}^{197}Au_{79} + {}^1n_0 + {}^0\beta_{+1}$. The conventional 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 event once the fragments of nuclear droplets had undergone fission (and subsequent transformations).

Overall, the proposed event and supernova explosion produce completely *different distribution of seed nuclei* available for subsequent reactions. The fact that in the proposed event 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 proposed event 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 event known to us (of course, even with this event, 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 be 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.

3.5. Candidates for Explosion-Triggering "Obstacle" in Original Solar System

Our scenario proposes that an inner-galaxy-born fast-traveling compact super-dense (nuclear-drop-like) stellar "fragment" (capable of phase-transitioning into unstable "nuclear fog" state if perturbation of its inner matter is triggered) crossed the path of some accidentally-encountered stellar system (where subsequently the mankind evolved and which we now call "the solar system") and, as the result of this encounter, the traveling object "exploded" in a cascade of fragmentation/fission-type nuclear transformations.

At this point, we can envision three conceptual possibilities for how the object's internal instability was triggered.

(1) *"The (Edge of) Sun"*. The object could have penetrated the "edge" of the star (the Sun), in which case the Sun is effectively the "fission-triggering obstacle". In this scenario the encounter must have

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occurred in such a way that the Sun continued to exist as we know it. The encounter could have altered the Sun's dynamics and its interior structure and composition. Indeed, the "solar abundance problem" – the conflict between the standard solar models and the internal structure of the Sun, as measured by the helioseismology – has not been solved yet [67], [68], [69], [70], [71]. Perhaps the absorbed debris from the encounter is the source of the conflict.

(2) *"Binary Companion".* Perhaps the Sun had a companion – a dwarf, or a main-sequence star, larger or smaller than the Sun – which was destroyed as the result of the encounter. Indeed, a significant portion of solar-type stars are found in binary systems (see [72], [73], [74], [75]). The well-known problems with angular momentum dispersal (e.g., [76] 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., [77]) may indeed be supportive of such scenario. In such case, both companions most likely formed a close binary and remained inside the orbit of Jupiter (wherever it was positioned at that time).

(3) *"Super-Jupiter".* Perhaps the Sun had another gaseous giant – a "super-Jupiter" (with the orbit located inside the Jupiter's orbit) – which was destroyed as the result of the encounter. Indeed, a number of independent analyses have pointed at the potential existence of one more giant in the early solar system (see, for example, [11], [78], [42]). In this context, at a quick glance, an argument may be raised that (within the conventional framework) near the Sun, inside the so-called *snowline*, no additional gaseous giant could have formed. But the location of the snowline is derived based on the assumed model of thermal regime. Because conventional models assume that gaseous and rocky bodies of the solar system formed contemporaneously, the models utilize meteoritic data as critical constraints shaping the view about the protodisc's thermal regime. Detection of high temperature condensates in meteorites has led to the acceptance of the *hot* model of thermal regime during formation of *all* solar system bodies [1]. However, within the framework of the proposed hypothesis, the meteorites formed (as the result of the explosive event) *after* the gaseous objects had already formed. Obviously, constraints derived from the post-event data should not influence the pre-event evolution scenario. If meteoritic constraints are set aside, the least complicated scenario would seem to presume that all gaseous objects formed (before the explosive event) from the ("dust-less") protodisc – composed predominately of H/He, with infusion of whatever additional nuclei that were natural for the protonebula's "neighborhood", and presumably rather *cold* before viscous heating took place and later the Sun ignited – via local clumping and rapid gravitational collapse of the (marginally unstable) protodisc [3]. Such scenario does not seem to preclude formation of another gaseous giant in the inner part of the solar system. Modeling of the process, however, is complex (see discussion in Sec. 4.4).

To form an opinion about which solar system object was most likely "responsible" for triggering perturbation of the traveling-from-afar nuclear-drop-like object's inner mater (leading to explosive nuclear-fission-type transformations and eventual formation of rocky "debris"), the proposed alternatives should be analyzed and compared with several considerations in mind: (1) the thermodynamically "meaningful" perturbation / deceleration must have occurred (as described in Sec. 3.3), (2) the location of the debris must have ended up forming the terrestrial belt, (3) the explosion must not have destroyed the Sun (and the rest of the solar system that apparently survived), and (4) to the extent the cascade of nuclear transformations may have required some hydrogen-rich environment, it should have been available. Numerical models specializing in planetary dynamics may perhaps be best equipped to bring further insights into which of the alternatives is most plausible, but the models need to re-examine and re-validate their inputs and assumptions before conducting any simulations (see discussion in Sec. 4.4).

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4. Implications, Validation Directions and Challenges

4.1. Hypothesis and Scenario Summary

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) and various gaps or inconsistencies in the available conventional models, prompted us to inquire whether one event (a fundamentally new mechanism) could have been responsible for all of the peculiar features at once (and thus resolve the model inconsistencies).

Critically important evidence is the "excessive" presence of p-nuclei which currently cannot be explained by the conventional models. Since p-nuclei, as well as *post-post-Fe* nuclei (their production mechanism currently remains yet another unresolved puzzle of nuclear astrophysics), and all other "exotic" nuclei detected in the solar system, can be produced by nuclear fission, we advanced the hypothesis that *a nuclear-fission "event" occurred in the inner part of the solar system at the time currently-seen as the birth of the solar system* (4.6 billion years ago, based on the dating of meteorite samples [1]). This also presumes that at first, more than 4.6 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 (which then did not survive the event) – and that the debris from the event formed the "rocky" objects in the system and enriched the gaseous giants.

We examined the already-existing models and experimental results from related disciplines and analyzed factors that would be *required* for successful implementation of the proposed event. As the result, we identified one scenario that is physically *plausible*, i.e. not impossible or forbidden by the laws of nature.

In this scenario, we propose that the nuclear-fission "event" could have occurred because a traveling-from-afar compact super-dense stellar "fragment" (with specific properties) – perhaps born in an asymmetric catapulting cataclysm and already sufficiently cooled so its inner state was capable of phase-transitioning into unstable "nuclear-fog" state if perturbed – crossed the path of the solar system and, once perturbed, "exploded" within the inner part of the solar system. We proposed that, for the nuclear-fission-type cascades to unfold, the "fragment" had to possess the characteristics of a "giant-nuclear-drop" (theoretical existence of such objects has been analyzed [50]). Such object could have been born as a result of destruction [49] of some neutron-rich stellar object by the super-massive black hole located at the center of our galaxy. As the nuclear-drop-like object entered the inner part of the solar system and experienced "sufficient" perturbation (deceleration), the object's inner matter stratified – first the 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 [60], [79]. In a nuclear-like medium, the shockwave propagation speed is comparable with the speed of light, so the stratification process developed very quickly. In the zones of decompression, the matter that was previously (thermodynamically) weakly-stable (perhaps due to aging and cooling of the object), became unstable and "preferred" not the homogeneous but the *two-phased state* (the state of "nuclear fog" where "nuclear droplets" coexist with "nuclear gas"). Charge-neutral "droplets" (obviously with hyper-large nucleon numbers A) were structurally unstable and underwent spontaneous cascading *fragmentation* and *fission* (notably, with very abundant 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, α-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 at the orbit where the explosion occurred. Post-event, the final products of the nuclear transformations (that occurred via the enormous multitude and variety of random channels of reactions that were possible in such conglomerate of components exposed to such high-energy emissions) created the environment

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containing post-*Fe* elements, as well as the detected *p*-elements and short–lived radionuclides – with the element abundance profile as currently known. After the processes and the system settled, these nuclear components became the building blocks of dust, grain particulates, pebbles, and later planetesimals, and eventually, the terrestrial planets and other "rocky" bodies. These nuclei also enriched the pre-existing jovian planets.

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

4.2. Likelihood: Plausibility vs Probability, Expectation vs Realization, and Meanings of Numbers

The very thought of an event occurrence 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 related concepts. Generally speaking, the "statistical odds" have nothing to do with the question of whether the event proposed in our hypothesis could indeed have happened 4.6 Gyrs ago. Such event 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* event happening in our solar system are low.

Also, when talking about probabilities, it is important to remember the difference between "expectation" and "realization". For a collision, the often-used word "target" can mean two different things: the "intended-goal / specific aim for the path" (like the rope for hanging that Clint Eastwood's hero was shooting from afar to release his co-conspirator in the movie "The Good, the Bad, and the Ugly") and the "accidental-result / random obstacle on the path" (like the hole that is left in a wall by a blind-man's accidental gunshot). Using these metaphors, we can say that our scenario is not about "whether a bullet can hit the distant rope", but instead we note that "the hole in the wall looks like it came from a bullet", so what kind of bullet must that have been and what might have happened. For accidental-results (obstacles), post-event, statistical odds are irrelevant. Upon realization, P=1.

Nonetheless, let's look at the probability numbers for additional insight. 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 obstacle population, σ is interaction cross-section, and $V \times 1$ is the distance covered by the moving object over the unit of time. Properly speaking, expression $P = \nu\Delta t = \langle n\sigma V\rangle\Delta t$ is defined over the *large* number of possible realizations (where symbol $\langle ...\rangle$ denotes 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 should be compared with the full time of the experience Δt (the 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 (potential) obstacles 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) and $\sigma \sim (10^{-4})^2$ light-years^2 (which corresponds roughly to

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the area within Jupiter's orbit, implying that a collision may in fact "perturb" the object and the system, and thus end the journey), the frequency of collisions is then $P \sim 10^{-4} \ll 1$. Even this (higher-end) estimate shows that the object *could have reached* the current solar system location in about ten million years, *without an encounter* with another system along the way – indeed our galaxy is very "scarcely populated". Such long journey would have allowed the object to sufficiently cool down, so its nuclear inner state could have approached its thermodynamical instability threshold (see Appendix B. and [50]) – this condition allows for the "successful" explosion. In order words, *lower "collision" odds actually imply higher "success" odds in our scenario.*

4.3. Chemical Composition of Solar System: Implication and Directions for Validation

To explain the chemical composition of the solar system, the conventional theory contemplates the following element-generation mechanisms in the scenario of the solar system evolution [80], [81]:

(1) The Big Bang, which generated light elements up to Li. These elements are the basis of the gaseous solar system objects – the Sun and the giants.

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

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

(4) (Hypothesized) *several supernovae* that must have occurred *not too far and not too close* to the solar system (see Sec. 1).

(5) (Hypothesized) *at least five*, distinct and distant, contributing events which all must have occurred *within the span of about 20 Kyrs*. These events need to be presumed in order to explain the detected presence and mixing of certain isotopes in meteorite samples (see Sec. 1).

(6) (Hypothesized) *local high-energy* process (within the solar system) suggested to explain the detected presence of ^7Li in meteorite samples. ^7Li is produced by decay of ^7Be whose half-life is only 53 days (see Sec. 1).

(7) (Unknown) "something" that must explain the excess (beyond the so far considered models) of certain proton-rich isotopes (see Sec. 1).

In the fission-event scenario, the number of hypothesized events and mechanisms can be reduced and the unresolved item (7) gains an explanation. Naturally, the Big Bang and the interstellar-background enrichment events (those that are typical for the neighborhood where evolution of the solar system took place) are the mechanisms that generated nuclei of the original protonebula – they are the *natural* formational basis of the solar system, identical in both scenarios. But events (4)-(7), conventionally hypothesized to explain the presence of nuclei that are *anomalous* for the solar system, are no longer required. While other cataclysms may still have contributed to the full inventory of nuclei in the solar system, just *one event* (the fission event) is proposed to be the *primary* source of all exotic nuclei found in the solar system (and the material concentrated in the terrestrial belt).

The reason why the fission-event is capable of generating the entire inventory of nuclei detected in the solar system is because the created environment (the unstable "nuclear fog") is the mixture of all necessary "building blocks" for the entire spectrum of potential outcomes. The mixture contains nuclear "droplets" spontaneously splitting (via fragmentation and/or fission until about $A \sim 200$) into fragments of, generally speaking, random (not necessarily equivalent) mass, surrounded by abundant free protons and neutrons, powerful γ-radiation, and so on. The "temperature" is enormous (this term is only conditionally used here because, as known, in rapid non-stationary processes this thermodynamical parameter is not properly introducible). Thus not only reactions of "fission" (transformations from large to small A) but also reactions of "fusion" (transformations from small to large A) take place. Importantly, these reactions can occur along *any and all conceptually possible* channels, thus leading to production of any and all of the detected isotopes (i.e. the entirety of the material observed in the terrestrial belt).

However, currently, to quantitatively analyze the process, a set of model equations is difficult to construct. The process is thermodynamically non-stationary, and therefore, in our opinion, even in the simplest semi-empirical form, such analysis would require development of a system of kinetic equations, the complexity of which would be overwhelming. Obviously, the rates of concentrations' evolution (time-derivatives in the left sides of these equations) are defined by the mechanisms of inter-component interactions which are described (in their simplest forms) by pairwise- and cross-products of components' concentrations (with possible emission and decay retardation effects) and by kernels/coefficients/cross-sections of interactions. But for the temperatures and densities characteristic for the hypothesized nuclear-fission event, no experimental data exist that could substantiate the structure of these kernels, even approximately (see Sec. 4.5).

4.4. Planetary Structure of Solar System: Implications and Directions for Validation

Section 1 has listed a number of puzzles of the solar system' structure and configuration. They are unresolved in the conventional framework, but immediately make sense once the nuclear-fission event is hypothesized.

For example, in the conventional framework, the existence of the bimodal planetary structure is perplexing and the process of formation of two classes of planets is not fully understood [2]. The consensus is unanimous that rocky planets formed by accretion, but two competing theories continue to exist about formation of gaseous planets because inconsistencies remain within each theory. With respect to the giants, the core accretion model explains why they have larger concentration of heavier elements than the Sun has, but numerical simulations yield formation times that are way too long unless the mass of the primordial nebula is increased. The disk instability model produces much more rapid formation rate, but does not explain the observed chemical enrichment of the gaseous planets.

Within the framework of the proposed nuclear-fission-event hypothesis, the evolution scenario is straightforward and self-consistent, accepting both accretion and disk-instability models but utilizing them sequentially: first the gaseous giants formed as the result of protodisc instability, and only after that, and after the proposed explosive event, the post-fission-cascade "debris" accreted into rocky bodies of the solar system *and also* enriched the original gaseous giants.

In favor of such scenario speak numerous features of the solar system. Indeed, if observed from afar, the set of terrestrial planets would be virtually unnoticed – mass-wise it is negligible ($< 10^{-5} M_{\odot}$) and distance-wise it is effectively lumped near the Sun. Unlike the bulk of known exoplanetary systems, the orbits of the solar system's giant planets are remarkably widely spaced, nearly circular, and show no resonance (see, for example, [7], [8], [9], [10]). To explain its present, stretched and relaxed state, in the conventional framework, 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 [82], [83], followed by the subsequent stabilization phase. Within the framework of the nuclear-fission-event hypothesis, the proposed explosion may be the one responsible for the "violence" implied by the observations.

The finding that conventional model simulations struggle to find plausible evolution scenarios (that end up settling the existing giants at their current orbits) unless a *fifth giant*, eventually ejected or destroyed, is included [11], organically fits with the proposed nuclear-fission-event hypothesis. Indeed, such (destroyed) massive H/He giant could have served two purposes – it could have triggered the perturbation (deceleration) of the stellar "fragment" and supplied abundant proton-/α-particle-rich environment for nuclear transformations.

It is tempting to turn to numerical models of planetary dynamics to help examine the proposed scenario. For example, conceptually, simulations may perhaps clarify how the explosive "encounter" happened – which solar system's object was the most likely "trigger" for the explosion. As discussed in Sec. 3.5, three candidates can be envisioned – the edge of the Sun, the then-existing binary companion, or super-Jupiter at the then-first orbit. (Indeed, simulations can perhaps also revisit – in the framework of the proposed hypothesis – the question of how the Sun obtained its 7^{o} tilt to the planetary plane.)

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However, to accomplish such simulations, the *existing* models must first carefully examine and revise their inputs, assumptions, and initial conditions.

The obvious revision is due to the proposed sequential formation of planets. In the proposed framework, during the first stage of the solar system evolution, only gaseous objects formed from the protodisc – via local clumping and rapid gravitational collapse – in line with the disk instability model but assuming longer lifetime for the solar system. (Recall that the currently-assumed age of the solar system – about 4.6 Gyrs – is derived based on dating of meteoritic isotopes. In the framework of our hypothesis, this would be the time when the proposed nuclear-fission event occurred. Therefore, the gaseous objects had to form earlier.) In the second stage of the solar system evolution, after the explosive event, the "debris" accreted into the terrestrial planets (and other rocky objects). The nuclei generated by the event also enriched the pre-existing jovian planets.

The less obvious revisions, but critically important ones, must concern all basal-level assumptions. This is not a trivial exercise because most models are built using outputs of other models and many of the primary assumptions are buried under the layers of complexities. If such assumptions were conditioned or skewed by presumptions of the conventional framework, and if they happen to contradict the newly proposed framework, the erroneous biases will propagate and distort results. For example, as already noted in Sec. 3.5, the conventional use of meteoritic data to constrain models has led to the selection of the "hot" rather than "cold" model of thermal regime during planet formation, but in the framework of our hypothesis, inclusion of the constraints derived from meteorites (which formed post-event) would be incorrect when modeling the pre-event stage of the solar system formation.

The need to re-examine all assumptions of the existing models starting from the very beginning – from the protodisc stage – greatly complicates any efforts to quantitatively analyze the proposed hypothesis. As noted in [1], "[w]hen the main dynamical forces controlling the rotating disc flattening (gravitational and centrifugal) are in balance, weaker factors, such as the thermal/viscous processes, turbulence, and electromagnetic phenomena dominate the disk's evolution. They affect the condensation of volatiles, [...] and bear significant effect on the relative content and abundance of gaseous species and solid particles, as well as disk energetic and angular momentum transport." Furthermore, "[t]he content and size distribution of solid particles (granules) affects the disc medium opacity and turbulence flow patterns. They strongly influence the disk thermal regime, viscous properties, chemical transformations in a gaseous medium and, in the end, its evolution including the processes' dependence on the radial distance from the protosun and the early subdisk formation." [1] With this reminder, it seems apparent that because the proposed hypothesis posits that solid particles primarily formed *after* formation of gaseous objects completed, the protodisc evolution scenarios may meaningfully differ between the conventional and proposed frameworks. Differences in the (modelled) protodisc composition may lead to meaningful differences in how and where (and how many of) the gaseous bodies formed. The subsequent planetary dynamics would be affected. Other consequences may also follow.

4.5. Fission of Super-Heavy Nuclei: Experimental Data Are Critically Needed

According to our hypothesis, in the "explosive" encounter of the compact super-dense stellar "fragment" with the solar system, the nuclei-transformation process is *top-down*: from the stellar-size "fragment" of nuclear-like matter (a "giant-nuclear-drop"), to unstable "nuclear fog", then to "droplets" of nuclear matter, then to hyper-heavy nuclei, super-heavy nuclei, heavy nuclei[2] – to smaller and

[2] Keep in mind the difference in nomenclature: "heavy" nuclei are defined differently among fields. Stellar studies operate with mass fractions ($X + Y + Z = 1$) which focus on H, He, and "everything else"; and "metallicity" Z aggregates elements from Li and beyond. In planetary sciences, "heavy" elements fall within the "refractory" ones (Fe is among them). In nuclear physics, however, Fe is "medium"; the "heavy" elements are gold, uranium, and so on; and "super-heavy" are the nuclei within the region of "stability island" near proton number $Z = 114$ and neutron number $N = 184$ predicted within the macroscopic–microscopic nuclear theory. Indeed, subsequent "stability islands" are hypothesized to exist, implying that the periodic table may be significantly expanded [84].

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smaller sizes – down to stable nuclei, via α-decay, as well as β-, ν-, γ-emission, and (unavoidable) *spontaneous fission*.

In contrast, in the laboratory conditions, the process of production of heavy/super-heavy nuclei is *bottom-up* – it is realized in the opposite direction, via the process of beam-induced fusion. (For current status, challenges, and prospects, in super-heavy nuclei research see such reviews as [84], [85], [86].) For example, the heaviest nuclei are produced by bombardment of high-energy heavy-ion beams (such as ^{48}Ca) onto actinide targets (such as ^{237}Np, $^{239,240,242,244}Pu$, ^{243}Am, $^{245,248}Cm$, ^{249}Bk, and $^{249-251}Cf$ [86]).

Experiments consistently show that (once a super-heavy nucleus is formed and is unstable) the chain of transformations starts with a series of consecutive α (and β) decays, down to the longer-living nuclei, which then (always) undergoes *spontaneous fission* (split into two not-necessarily-identical nuclei). See, for example, [87]. The decay-series (the cascade branches) vary probabilistically.

Such experiments provide invaluable information about the processes involved in production/ transformation of the nuclei. However, at present attempting to construct a robust model for our scenario (based on the mentioned experimental results) would be too speculative, for a number of reasons. (Not the least of which is the noticed sensitivity of the available astrophysical reaction rates to nuclear uncertainties: laboratory cross-sections exhibit different sensitivities in forward and reverse reactions [37], [88].)

For example, to quantitatively analyze a nuclear transformation process, a set of model equations needs to be constructed. Cross-sections of interactions between reactions' components are the key parameters. Unfortunately, present experimental techniques are sensitive only in a limited range of fission half-lives, often $10^{-5} - 10^{+3}$ s, while the actual range of fission half-lives is much wider: $10^{-19} - 10^{+24}$ s [85]. Further investigations of the heaviest nuclei and synthesis of the new elements call for considerable increase in the sensitivity of equipment used in experiments – quality spectroscopic data on excited states of super-heavy nuclei are essential to constrain theory. Such improvements, however, depend on advancements in practical implementation of experiments, on construction of state-of-the-art experimental facilities, and on development of expertise (career investments) by not a few but numerous scientists needed for design and execution of such projects – all of which require substantial long-term funding at the scales feasible only to governmental agencies and multi-national state-sponsored institutions; the funding is critically needed to achieve further fundamental breakthroughs.

Also, new theoretical investigations of the fission process raise questions about the adequacy of calculations based on fission barriers. Uncertainties in fission barriers have very large effects on the cross-section calculations (as well as on the determination of half-lives and decay modes).

Unfortunately, at present, these challenges are extremely difficult to overcome.

4.6. Galactic and Phenomenological Perspective: "Normal" vs "Exotic" Aspects of Scenario

Although at a first glance our hypothesis may appear exotic, actually it is not – it is simply multi-disciplinary. The mentioned facts, mechanisms, and models from each field are well-known. They are straightforward in conceptual understanding (although nuanced in terms of details).

1. It is a fact that at the center of our galaxy exists a super-massive rotating black hole capable of devouring and metamorphosing *any* object trapped by its gravitational field.

2. It is also known that fragments of such objects [48] can be catapulted with meaningful velocities across the galaxy [89]. Observations have detected fast-moving objects with velocities $\sim 1600\ km/s$ [47]. Such high velocity is consistent with Penrose effect. The phenomenon was featured in the popular movie *Interstellar* for which visualization was simulated under supervision of Nobel Laureate Kip Thorne [90].

3. When such catapulted fragments are essentially "chunks" of nuclear matter, they form compact "drops" of various stellar sizes [44], [91], [92], [93], [94]. A mercury droplet may perhaps be a good visual metaphor for such giant nuclear-matter drop. In our prequel publication [50], we demonstrated

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that such objects (dense as a nucleus) can be "small" in (stellar) size and remain stable when their equation of state (EoS) fulfills certain requirements. In general, as mentioned in 3.1, various compact objects/stars have been hypothesized and numerous models of EoS for these exotic stellar objects in our galaxy have been proposed [95].

4. When the object's inner-matter phase-state crosses its nuclear-liquid/nuclear-gas phase-transition boundary – because of cooling or externally-triggered perturbation – the matter becomes unstable (enters the "nuclear fog" state). This phenomenon is well-covered in literature (see Appendix A..) Nuclear instability leads to nuclear-transformation cascades (fragmentation, fission, capture-processes, and so on).

These facts imply that when the "giant nuclear drops" are created, they travel away from their origin until something happens to them: either (a) the "drops" cool down to the instability-threshold limit and "explode" in the interstellar "emptiness" – perhaps some of the observed interstellar nuclei, particularly heavy-nuclei, are produced via such mechanism (in addition, of course, to the commonly-presumed supernova or neutron-star mergers); or (b) the "drops" stumble onto some obstacles, and also "explode".

With this in mind, it is apparent that (in essence) what our hypothesis and scenario propose is that such giant-nuclear-drop had traveled far from its origin and reached a tranquil stellar system at the periphery of the galaxy (the system that we humans later named the solar system), that the drop either "missed" or didn't quite "reach" the star before becoming internally-unstable (thus not leaving all of its debris inside the star), and that the explosion didn't demolish the entire system (which could have happened if the nuclear-drop were "bigger"). Indeed, when looking at the proposed event from this perspective, there seems to be nothing particularly "exotic" about such circumstances.

Ironically, and luckily for us humans, the "remarkable" aspect of the proposed hypothesis is that the primordial characteristics and the galactic location of our Sun (system) are "unremarkable": the nuclei-generating *explosive fission-cascades* – which may perhaps happen often in the galaxy in general – occurred in a *normally non-explosive* stellar environment without destroying the hydrogen-helium planetary system, thus letting its tranquil existence continue for billions of years, but now with added "enhancements" which allowed complex and intelligent life-forms to evolve.

If similar encounters are happening to other stellar systems, unfortunately at this point we simply would not know about them. Astronomical observations and Gaia-type surveys may perhaps be helpful in detecting explosions or trajectories that may offer some insight, but low-power explosions or small/cool stellar objects may be too difficult to detect. Further breakthroughs and advancements of observational techniques, and investments in facilities and technologies, are needed.

If such encounters happened elsewhere in the past, interpreting present-day observations and issuing definitive validations of nuclei origins (even if data existed in greater detail) would be no less challenging than with our own solar system. Nonetheless, conceptually speaking, the idea of such encounters may not be as "extraordinary" as it may appear at a first glance.

5. Final Remarks

Despite the widely held belief that formation of the solar system is well understood and only nuances remain unresolved, serious conceptual gaps in the understanding continue to exist. These gaps concern both the chemical composition and the planetary structure of the solar system. The conventional models fail to resolve (at all, or self-consistently) such puzzles as the unexplained existence of the trimodal structure of the solar system and the presence of p-nuclei, post-post-Fe-nuclei, and short-lived nuclei (Sec. 1). Currently, to explain the presence of the nuclei that are non-native for the solar system, quasi-simultaneous occurrence of numerous explosive stellar events (unusual for the solar system neighborhood), in combination with other high-energy mechanisms, is hypothesized. Notably, inconsistencies within and between the existing conventional models remain, and "the mystery of the origin of the p-nuclides is still with us" ([37], p. 32).

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But as Occam's Razor principle suggests, simpler solutions are more likely to be correct than complex ones. In contrast with the *multi-event* framework, we propose a hypothesis that involves *just one event*. All pieces of the "grand puzzle" fall in place if one presumes that a *nuclear-fission event* occurred within the inner part of the solar system at the time that we currently define as the birth of the solar system based on dating of meteoritic isotopes. Conceptually, the nuclear-fission event is capable of creating all the nuclei of the "rocky" objects of the solar system – the terrestrial planets, meteorites, asteroids, and likely the cores of the gaseous giants. However, this event had to be such that it did not destroy the solar system but impacted its composition and orbital structure to such degree that the system eventually settled into its present (different from its original) state.

The proposed 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 [96]), and also on the general acceptance that stellar "collisions" of dense objects do indeed happen (for example, neutron stars collisions, black-hole/neutron star mergers have been studied; see, among others, [56], [97]). But the idea that the solar system's path was crossed by an object capable of "exploding" with nuclear-fission transformations thus creating nuclei that enriched the system, has never been advanced. Furthermore, while the conventional models have considered mechanisms of *nucleosynthesis* and/or induced *disintegration*; until now the mechanism of *fragmentation / fission* had not been proposed, not in the solar system enrichment context, nor in any other enrichment context.

We examined the already-existing models and experimental results from related disciplines and analyzed factors that would be *required* for successful implementation of the proposed event. As the result, we identified one scenario that is physically *plausible*, i.e. not impossible or forbidden by the laws of nature. We defined and discussed the key aspects of such scenario (Sec. 3), but how exactly the details unfolded is not possible to say at this time. The challenges are rooted in the needs to (1) develop a valid model-set of kinetic equations for the (non-stationary) nuclear transformation cascades, for which no substantiating experimental data exist due to enormous temperatures and densities of the nuclear matter involved in the scenario (Sec. 4.3), and (2) examine and revise basal-level assumptions in all models of planetary formation and dynamics (starting with the protodisc evolution stage), which then face enormous uncertainties because, at minimum, the conventional constraints offered by meteoritic data must be set aside for the pre-event timeframe (Sec. 4.4). Until these challenges are dealt with, any attempt at "quantitative analysis" or "numerical simulation" of the proposed scenario would be not just speculation, but profanation. Instead, once the spectra of plausible cascades of nuclei transformations are (experimentally or at least theoretically) mapped out, one way to advance this hypothesis would be to solve the *inverse problem*: to find out (with proper correction for the fluctuations/uncertainties-driven "noise") what initial conditions had to be so the model resulted in the (actually measured) abundances of elements on Earth and in samples from other objects of the solar system.

This paper lays out the *hypothesis* and *one plausible scenario* for its implementation. As more scientific data become available, certain aspects of the scenario may require adjustments, if not outright revisions. Nonetheless, the general idea can remain insightful. Notably, besides explaining a great number of chemical and structural peculiarities of the solar system (formation of two classes of planets, configuration of the solar system, and presence of "exotic" nuclei), the proposed hypothesis/scenario can answer, at least conceptually, another intuitively troubling question: how is it that exogenous elements (such as iron, gold, uranium) managed to become clustered – like the deposits at mining sites, or the *internally-uniform tonne-plus-sized* chunks of the Sikhote-Alin meteorite (composed of 88% Fe, 5% Ni, and 2% Co [98], [99], [100]) – rather than become mixed quasi-uniformly with other granules as they presumably would have done (per Second Law of Thermodynamics) if they had originated in *distant* stellar cataclysms? The proposed *local* cataclysm indeed rapidly produces local "chunks".

To conclude, it is worth noting that, once/if proven to be true with certainty, scientifically speaking, the proposed hypothesis would serve as an important cornerstone in the overall understanding of the

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solar system evolution. But even now, it's a breathtaking thought that a stellar encounter could have created such marvel – our peaceful planet safely tucked away at the perfect distance near a tranquil star on a quiet galactic periphery, the planet enriched with such variety of chemical elements that complex intelligent life-forms have been able to develop and prosper. Indeed, the "life" as we know it (human biochemistry) critically depends on the non-native for the solar system iron, iodine, selenium, copper, molybdenum, or cobalt.[3] How many other corners of the universe may be this fortunate? Possibly none.

New hypotheses always lead to new ways of examining facts. The goal that many astro- and planetary researchers find most intriguing, is to understand the place of the solar system in the universe, the possible uniqueness of our home system and planet and, finally, the process that brought us to this world. And as we seek scientific insights to solve nature's puzzles and develop technological advances to fulfill humans' wishes, it is important to remember to also seek comprehension of gnoseological and moral implications of the discovered knowledge (and its constructive and especially destructive powers). We hope that this hypothesis contributes to these pursuits in multiple ways.

Appendices

Appendix A. Brief Overview of Equations of State for Nuclear Matter: "Nuclear Fog"

The fact that nuclear matter may in fact exist in the two-phase state has been known for a while. The equations of state of a multi–body system of nucleons interacting via Skyrme potential is presented in Fig. A1. The very steep part of the isotherms (on the left side) corresponds to the liquid phase. The gas phase is presented by the right parts of the isotherms where pressure is changing smoothly with increasing volume. Of special interest is the part of the diagram where the isotherms correspond to the negative compressibility, i.e. $(\partial P/\partial V)_T > 0$. This is the so-called *spinodal* zone where the matter phase is unstable and can exist in both liquid and/or gas states. Within the spinodal zone lies a particularly unstable two–phased region (marked by the hatched line in Fig. A2), in which random density fluctuations lead to almost instantaneous collapse of the initially uniform system into a mixture of two phases. For nuclear matter, it is either liquid droplets surrounded by gas of neutrons, or homogeneous neutron liquid with neutron–gas bubbles (i.e. the spinodal zone where the square of adiabatical speed is negative, is inside the coexistence zone where the square of isothermical speed is negative).

Critical temperature T_c for the liquid-gas phase transition is a crucial characteristic of the nuclear equation of state.

A typical set of isotherms for an equation of state - pressure versus density with a constant temperature - corresponding to nuclear interaction (Skyrme effective interaction and finite temperature of Hartree–Fock theory, see Jaqaman et al [51]) is shown in Fig. A3. It exhibits the maximum-minimum structure typical of the Van der Waals–like equation of state (EoS). Depending on the effective interaction chosen and on the model (see Jaqaman et al [51], [52], [103], [104]), the nuclear equation of state exhibits a critical point at $\rho_c \simeq (0.3 \div 0.4)\rho_0$ and $T_c \sim 5 \div 18\, MeV$ (Karnaukhov [53], [55]). Calculations of T_c were performed in [51], [105], [106], [107], [109], [110]. Experimental data are presented in Fig. A4.

[3] Iron ($z = 26$) is a key element in the metabolism of almost all living organisms; iron is contained in hemoglobin, the oxygen carrier in red blood cells. Copper ($z = 29$) is important as an electron donor in various biological reactions. Iodine ($z = 53$) is required for making of thyroid hormones, which regulate metabolic rate and other cellular functions. Iodine deficiency leads to goiter and mental retardation. Selenium ($z = 34$) is essential for certain enzymes, including several antioxidants. Molybdenum ($z = 42$) is essential to virtually all life forms. In humans, it is important for transforming sulfur into a usable form. Cobalt ($z = 27$) is contained in vitamin B12, which is important in protein formation and DNA regulation. Notably, among the listed elements, isotopes of selenium ^{74}Se and molybdenum ^{92}Mo and ^{94}Mo (detected in the solar system) are p-nuclei and cannot be produced by s- and r-processes, and thus, could not have been produced by supernovae.

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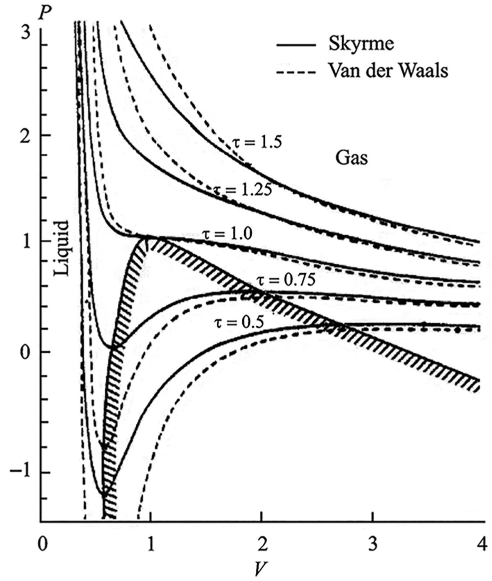

Figure A1. The equations of state $P(V)$ for a nuclear system interacting through a Skyrme potential and a Van der Waals compressible liquid–gas system (shown in relative units). From Jaqaman et al [51].

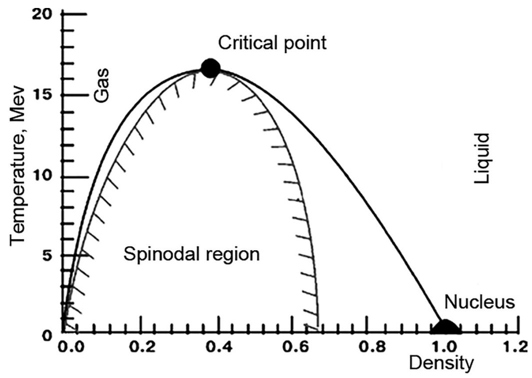

Figure A2. Theoretical $T(\rho)$ phase diagram for nuclear matter (adapted from Karnaukhov [53]). The solid line is determined by condition $\partial p/\partial \rho = 0$ and marks the phase transition zone. Density is expressed in units of $\rho_{nucleus} \simeq 2.85 \times 10^{14}\, g/cm^3$. Temperature is expressed in Mev units ($1\, Mev \simeq 10^{10} K$).

Appendix B. Internal Instability

Appendix B.1 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 [60].

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

$$s^2/V^2 < (\rho_t/\rho_s)(R_s/R_t) \tag{A1}$$

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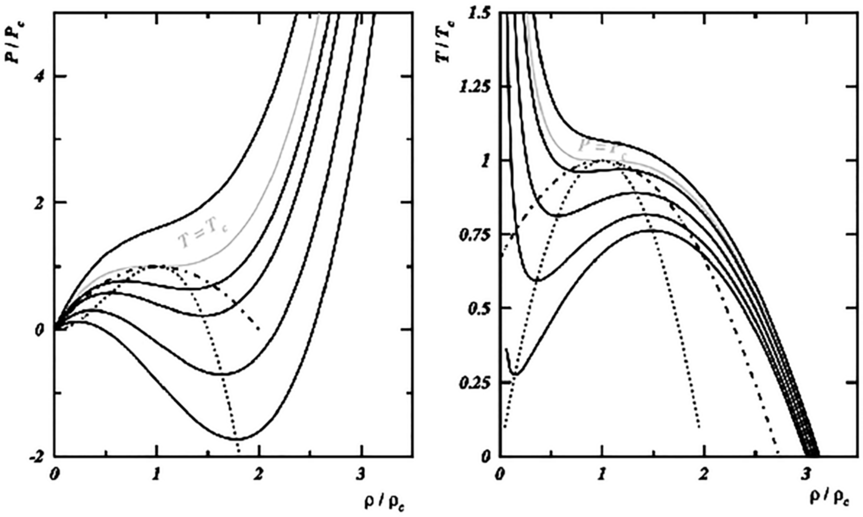

Figure A3. Equation of state for nuclear matter: pressure (isotherms, left panel) or temperature (isobars, right panel) as functions of density. (Parameters are normalized by their critical values). The dash-dotted lines are the coexistence lines, the dotted lines are the spinodal lines. From Borderie [102]. See also, Borderie and Rivet [101].

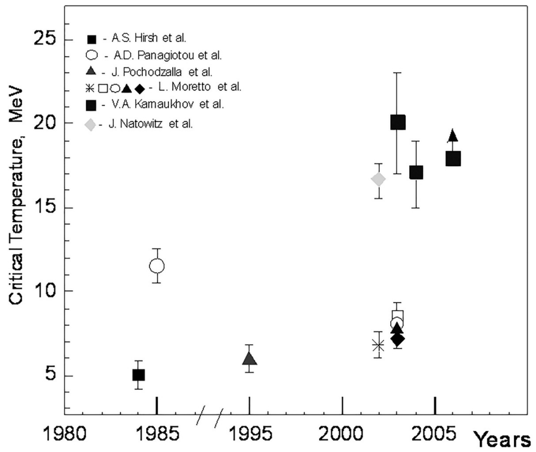

Figure A4. Values of critical temperatures of nuclei T_c measured by different techniques. From Karnaukhov et al [55].

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.

Appendix B.2 High-Velocity Collision of Drop with Obstacle

When a droplet collides with some object (obstacle), inside the droplet – as known – various motions arise, the velocity of which is comparable with the velocity of the droplet. If the droplet's initial velocity 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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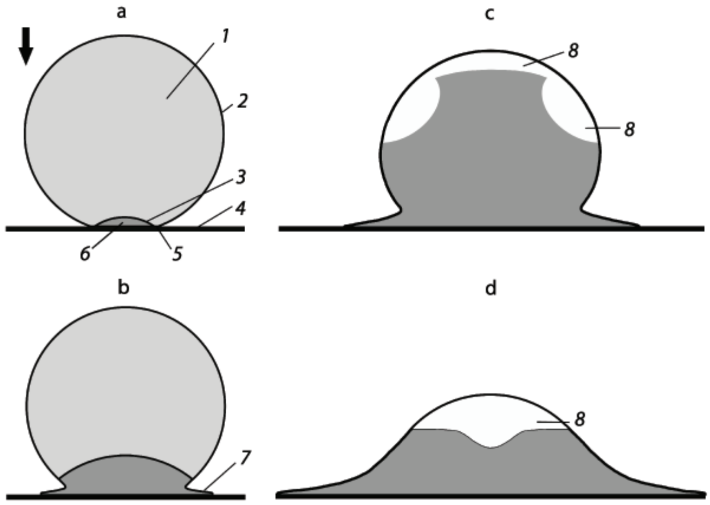

Figure A5. Schematic of drop impact (the drop is moving from above). Panels: (a) before spreading; (b) jet initiation; (c) shockwave approaches the top of the drop, toroidal expansion region is formed; and (d) initiation of vast expansion area with cavitation region. Zones: (1) unperturbed liquid, (2) free drop surface, (3) shockwave, (4) obstacle'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-velocity 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 obstacle, and so on.

Qualitatively the process of high-velocity collision can be described as follows (see Fig. A5 taken from [111]):

During the process of interaction of the droplet with the surface of the obstacle, 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 obstacle, does not deform. The region of compression is confined to the shockwave that forms at the edge of the contact spot (Fig.A5a).

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.A5a)

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 obstacle'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-velocity radial jet of cumulative type forms (Fig. A5b). The time of formation of

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the jet depends on the viscous and surface effects within the liquid near the surface of the obstacle, its velocity substantially exceeds the velocity 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. A5c.

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. A5d).

During the propagation of the decompression wave toward the surface of the obstacle, 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.

Appendix B.3 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 [112], [113] for details):

$$V_s^2 \equiv \left(\frac{\partial p}{\partial \varepsilon}\right)_s \equiv \frac{\partial(p,s)}{\partial(\varepsilon,s)} = \frac{p_z - s_z(s_\theta)^{-1}p_\theta}{\varepsilon_z - s_z(s_\theta)^{-1}\varepsilon_\theta}. \tag{A2}$$

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. (A2), 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 Fig. A6 and Fig. A7 (borrowed from [50]). 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. A8). 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 [50]: 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 $p \sim z^2$ [114].

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 [50].

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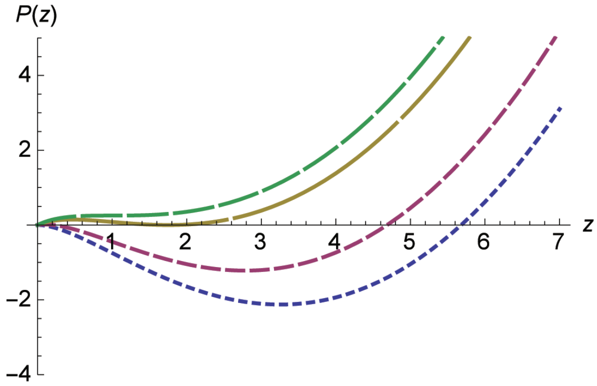

Figure A6. Pressure $p(z, \theta)$ as a function of normalized density $z = \rho/\rho_c$, for the model of nuclear-drop-like object with equation of state described by interpolating expression permitting mono- and two-phase states [50]. Several values of normalized temperature $\theta = T/T_c$, $T_c \sim 15\,Mev$ 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.

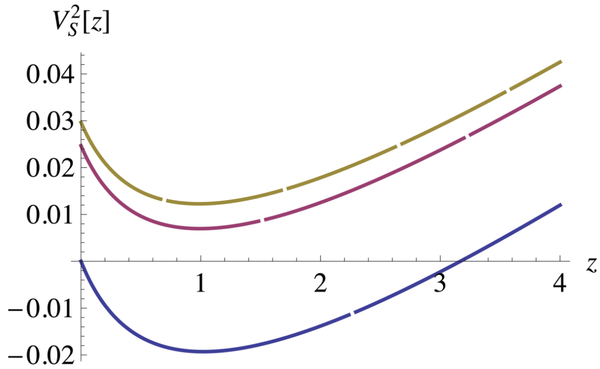

Figure A7. Square of adiabatical sound speed $V_s^2(z)$, normalized by the speed of light, as function of normalized density z, for the model of nuclear-drop-like object with equation of state described by interpolating expression permitting mono- and two-phase states [50]. Several values of normalized 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 [50]. 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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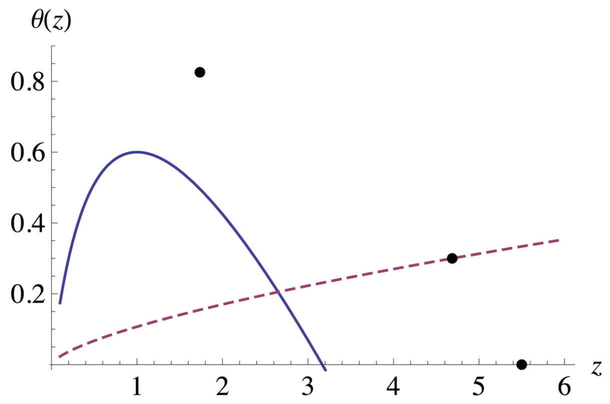

Figure A8. Spinodal region for the model of nuclear-drop-like object with equation of state described by interpolating expression permitting mono- and two-phase states [50]. Inside the domain, $V_s^2 < 0$; outside the domain, $V_s^2 > 0$. On the (θ, z)-graph, pressure points $p = 0$ are shown as black 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).

Appendix B.4 Energy Effects

A stationary spherical configuration with the above-mentioned equation of state can indeed (theoretically) exist [50].

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. A6 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. A6 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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