

Can Self-Replicating Species Flourish in the Interior of a Star?

Luis A. Anchordoqui and Eugene M. Chudnovsky

Physics Department, Herbert H. Lehman College and Graduate School, The City University of New York
250 Bedford Park Boulevard West, Bronx, New York 10468-1589, USA

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The existing view of biological life is that it evolves under suitable conditions in the low-temperature world of atoms and molecules on the surface of a planet. It is believed that any plausible extraterrestrial form of life must resemble the life on Earth that is ruled by biochemistry of nucleic acids, proteins, and sugars. Going against this dogma, we argue that an advanced form of life based upon short-lived species can exist inside main-sequence stars like our Sun.

Conventional wisdom states that the search for exo-life calls for carbon-based organisms, operating in a water-based medium, with higher forms (perhaps) metabolizing oxygen. All forms of life on Earth share this same basic biochemistry. However, biological molecules are not stable in a thermodynamic sense [1]. *Life* can be thought-out as a dynamical hypercycle (DNA encode proteins, proteins help DNA to self-replicate, DNA encode proteins, ...) that can survive indefinitely as long as free energy is available for it, and as long as self-replication goes faster than destruction of information carriers. Mutations in the informational chain provide natural selection and evolution towards more complex species. Proteins are different chains of 20 (+2) amino acids. To encode amino acids, one needs a minimum of a triplet RNA/DNA code of 4 nucleotides: A,C,G,U, like AAA, AUG, etc. This gives $4^3 = 64$ different combinations.

Of course, all this can be totally different for a different form of life, but self-replication is a cornerstone of life and it is hard to imagine how any life can be formed without encoding information. If one accepts that *life* is merely self-replication with mutations that leads to the increasing complexity through natural selection, any system capable of such processes can be viewed as a form of life. As an example, self-replicating robots assembling themselves in the environment that can be vastly different from the ambient conditions we are used to have long been considered one such possibility. More concretely, *life* needs at the minimum of these three hypotheses:

1. The ability to encode information.
2. The ability of information carriers to self-replicate faster than they disintegrate.
3. The presence of free energy: At the minimum $\Delta F = T \Delta S$, needed to constantly create order out of the disorder by decreasing entropy S through self-replication, where T is the temperature of the system.

Armed with this extreme reasoning, we ask whether some form of life could flourish deep inside the core of main-sequence stars like our Sun. We speculate that it is possible to satisfy hypotheses 1 and 3. Given how complex and non-obvious is the functioning of the biological cell that we are familiar with, and the fact that the early path of the biological evolution that has led to

it is unknown, we will not speculate about the intricate series of bionuclear reactions that can satisfy hypothesis 2.

It has long been suspected that any early universe phase transition occurring after inflation (say with symmetry breaking temperature T_c) may leave behind topological defects [2]. This is because when the system cools down below T_c there is some order parameter field multiplet ϕ which picks up a non-zero vacuum expectation value $\langle 0|\phi|0\rangle = \phi_0$. If this were the case and the system has a symmetry group G , then any operation $g \in G$ would transform the vacuum state ϕ into a degenerate vacuum state that has expectation value $g\phi_0$. Now, if we identify the subgroup leaving ϕ_0 invariant with $H = \{h \in G | h\phi_0 = \phi_0\} \subset G$, the vacuum manifold would be given by the quotient $\mathcal{M} = G/H$, viz. the set of left cosets $\{gH\}$ of H in G . The topology of \mathcal{M} characterizes the types of defects. For example, cosmic strings would form if the first homotopy group $\pi_1(\mathcal{M}) \neq 1$, where 1 stands for the group comprising the identity alone. Note that this entails \mathcal{M} contains closed loops that cannot be continuously shrunk to a point and so \mathcal{M} would not be simply connected. Likewise, monopoles would be produced if $\pi_2(\mathcal{M}) \neq 1$. Note that for this particular configuration there would be non-shrinkable two-dimensional surfaces in \mathcal{M} .

Appealing to our discussion is the formation of composite defects. This may take place if a theory with symmetry group G undergoes a phase transition (at T_{c_1}) in which ϕ acquires a vacuum expectation value breaking the theory to a subgroup $H \subset G$, and after that there is a second phase transition (at T_{c_2}) in which the field ψ gets a non-zero (but generally smaller) vacuum expectation value to break the symmetry further into $K \subset H$. One simple example is provided by the $SU(2)$ symmetry group. In the first stage of symmetry breaking, in which ϕ becomes non-zero, the symmetry breaks down to $H = U(1)$ leading to the formation of 't Hooft-Polyakov monopoles [3, 4]. In a second stage, the symmetry breaks further into $K = \mathbb{Z}_2$ where strings would form. Remarkably, there is a stable configuration, the bead, in which the magnetic flux of the monopole $4\pi/e$ is confined to two stable \mathbb{Z}_2 strings, each carrying a flux of $2\pi/e$ [5, 6]. Such string structures with monopole beads are so-called "necklaces." Remarkably, multiple strings can originate

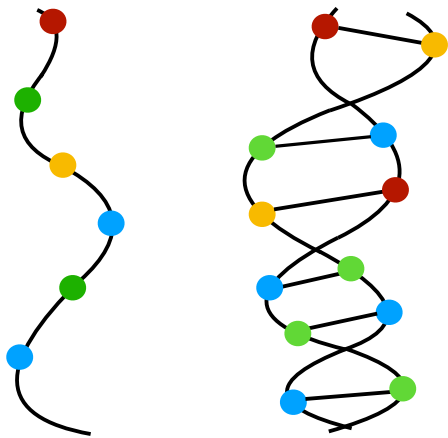


FIG. 1: Encoding information with cosmic necklaces consisting of beads on strings (left), and a string double helix resembling DNA (right) [12].

from monopoles and connect them into two- and three-dimensional structures, resembling atoms coupled by chemical bonds [7]. Since information needs to be written on a one-dimensional chain to ensure easy reading and transcription [8], monopoles and antimonopoles of one kind would not be sufficient for that purpose. Each string carrying half of the magnetic flux that originates on a monopole has to go into antimonopole, thus making monopoles and antimonopoles of one kind alternating in a one-dimensional chain. Such a chain would not carry any information. However, with various kinds of monopoles and non-Abelian cosmic strings discussed in literature, it is easy to envision more complex sequences capable of encoding information. For example, two adjacent semipoles [9], unlike monopoles, need not have total charge zero and can repel each other instead of moving towards each other and annihilating [10, 11]. Such single- and double-chain structures formed by beads on necklaces (with a complex flux) are shown schematically in Fig. 1. Semipoles correspond to an element of \mathbb{Z}_4 [9]. A semipole flux of $4\pi\{1, i, -1, -i\}/e$ can be inferred from the differences between the fluxes of adjacent strings shown in Fig. 1, with $1 \equiv \text{orange}$, $i \equiv \text{green}$, $-1 \equiv \text{red}$, and $-i \equiv \text{blue}$. The flux configuration exhibited in Fig. 1 reads: $-1 + i \rightleftharpoons 1 + i \rightleftharpoons 1 - i \rightleftharpoons -1 - i \rightleftharpoons -1 + i \rightleftharpoons -1 - i \rightleftharpoons -1 + i$.

The lifetime of such objects can be very short as far as their individual dynamics in vacuum is concerned. It can be longer in a plasma of a star (see below) and can also be controlled by the metabolic process they encode. Note in this connection that any biological organism, when considered individually, is unstable. Compared to the lifetime of a star, its lifetime is an instantaneous spark of light in the dark. What is important is that such a spark manages to produce more sparks before it fades away, thus providing a long lifespan of the species. The complexity evolving through mutations and natural selection increases with the number of generations passed. Consequently, if lifetimes of self-replicating nu-

clear species are as short as lifetimes of many unstable composite nuclear objects are, they can quickly evolve towards enormous complexity.

We now turn to speculate on the capture of necklaces by stars and discuss hypothesis 3. To develop some sense for the orders of magnitude involved, we assume that the strings are produced at the electroweak phase transition and so $T_{c_2} \sim 100$ GeV, yielding a mass per unit length of string $\mu \sim \hbar c^3 T_{c_2}^2 \simeq 10^{-6}$ g/cm. Before proceeding, we pause to note that for ultrarelativistic particles in thermal equilibrium, the blackbody formula gives the energy density-temperature relation $\varepsilon = CT^4$, where the constant C depends on the number of degrees of freedom. For the electroweak phase transition, the energy density that must be deposited in the collision region to achieve the conditions for a phase transition, $\varepsilon \sim 10^{10}$ GeV/fm³, is 10 orders of magnitude larger than what is currently achieved in collisions at the CERN Large Hadron Collider [13].

In the spirit of [14], we consider superconducting strings (carrying electric currents and generating magnetic fields) that become magneto-hydro-dynamically frozen into plasma. The evolution process could begin with a single string in the system. Turbulence of the plasma stretches and twists the string loop, cutting it at the intersections, until an equilibrium network of string loops develops in which the process of stretching is balanced by the collapse of string loops due to tension. Note that the likelihood of a string being captured by star is quite small. This is because the plasma wind from the star would prevent the string to approach it. A more probable scenario would be to assume that the string is captured during the star formation. The process of star formation begins in weakly ionized clouds of density in the range $10^{-22} \lesssim \rho/(\text{g/cm}^3) \lesssim 10^{-20}$ [15]. Stars are formed as a result of slow gravitational condensation of matter in the high-density regions of the cloud. In the early stage of this process, neutral matter contracts together with plasma, and with the magnetic field and strings frozen into it. As the density increases, the degree of ionization falls and the neutral matter decouples from the plasma. During this stage strings can be left out from the protostar. However, in the course of further contraction, the protostar becomes thermally ionized and recaptures its coupling to the magnetic field and to the strings. The radius of the ionized material is typically $R_{\text{ion}} = 10^8$ km. For typical clouds, the dispersion velocity of the turbulent motion is in the range $10^5 \lesssim v/(\text{cm/s}) \lesssim 10^6$ [15]. The force of friction per unit length of string produced by a superconducting string moving in a magnetized plasma is driven by the string velocity, the external magnetic field, and the plasma density. An order of magnitude estimate of the characteristic string length, R_* , can be obtained by balancing the frictional force per unit length with the force per unit length due to the tension in the string. If the motion of the turbulent plasma is well approximated by a Kolmogorov

spectrum, R_* is found to be

$$R_* \sim 10^9 \times \mu_{-6}^{1/3} \times v_6^{-2/3} \times \rho_{-20}^{-1/2} \text{ km}, \quad (1)$$

where μ_{-6} is μ in units of 10^{-6} g/cm, v_6 is v in units of 10^6 cm/s, and ρ_{-20} is ρ in units of 10^{-20} g/cm³ [14]. A simple estimate of the fraction of strings captured by the ionized plasma of the protostar is given by $\langle (R_{\text{ion}}/R_*)^2 \rangle$. A straightforward calculation shows that a significant fraction of stars could be contaminated with necklaces.

Consumption of free energy by biological life on Earth has been constantly growing with time, starting with the use of solar energy, then utilizing in the last 200 years even greater amounts of solar energy accumulated in fossil fuels, and then proliferating to the consumption of nuclear power thanks to complexity developed from that massive most recent consumption of energy. By analogy, nuclear life if it develops, must accelerate burning of nuclear fueled by stars. Indeed, life in the interior of a star would change its thermodynamics as a fraction of the fusion energy would be used for self-replication, and for developing and maintaining a sophisticated order. Consequently, one way to search for nuclear life in the universe would be to look for stars whose behavior defies explanation based upon conventional theories.

Consider, for example, the flow of energy from the hot surface of a star into the open space. When the temperature gradient in the surface layer reaches a critical value, the transfer of heat from the hot bottom of the layer to the colder top switches from heat conduction to convection via formation of Benard cells, which is a trivial textbook example of self-organization. Hot plasma rises up from the bottom of the layer through the center of each cell, cools down at the top of the layer, and then sinks inside the walls of the cell. This accelerates the transfer of heat. The general principle behind it is the formation of structures that allows the fastest release of the free energy possessed by the star. The surface cools faster due to such self-organization.

In a similar way, from thermodynamic point of view, the formation of the nuclear life in the interior of a star will have a “purpose” to provide faster escape of the energy released by nuclear fusion from the core of the star towards its surface. It makes the star to cool faster via a complex process of self-organization maintained by the elevated flux of energy through it. This would provide the same end effect as advocated in [16] to explain the observed deviations from predictions of models of stellar evolution, which seem to indicate an over-efficient stellar cooling.

We will conclude by mentioning one such example. The NASA’s *Kepler* and *K2* missions provided long-baseline and high precision photometry for hunting exoplanets by searching for regular decreases in the emission light of a star caused by a planet passing between the star and the telescope on its orbit. These passes are called transits. Very recently, the *K2* Team reported that EPIC 249706694 (HD 139139), which is about 360 light years away, experienced 28 transient-like events over the course of its 87-day observation period [17]. The depths in the flux during these events are roughly 200 ± 80 parts per million, with durations varying between 1 to 7 hours, and a mean separation time of about 3 days. These intriguing dips, which would normally indicate an orbiting system of planets, exhibit no obvious periodicity and what is more the *K2* Team concluded that their arrival times could have been produced by a random number generator. The target object is a relatively unevolved star of spectral type G, with solar effective temperature and radius. The star rotation period of about 14.5 days yields a gyro-chronological age of 1.5 ± 0.4 Gyr. However, in the same photometric aperture there is a fainter neighboring star, somewhat cooler (4400 K), and separated from the target star by $3.3''$. There is insufficient Gaia kinematic data for the neighboring star to determine whether it is bound or not to the target star. Because of this, there is not certainty on which star actually hosts the transit-like events. The *K2* Team estimated that if the dips are real transits across the target star then the inferred planet size would be approximately 2 Earth’s radii, whereas if they shadow the neighboring star, then the planetary radii would be more like 1-2 times Jupiter’s size. All of the simple explanations have been ruled out by the *K2* Team.

Of course, attributing the anomaly in the luminosity of a star to *nuclear life* would be a very long shot. We just wanted to emphasize that such unexplained anomalies do exist. Maybe the answer to Fermi’s question: *Where is everybody?* can be found in the least expected places.

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- [1] E. M. Chudnovsky, *Thermodynamics of natural selection*, J. Statist. Phys. **41**, 877 (1985) doi:10.1007/BF01010008
 [2] T. W. B. Kibble, *Some implications of a cosmological phase transition*, Phys. Rept. **67**, 183 (1980). doi:10.1016/0370-1573(80)90091-5

- [3] G. 't Hooft, *Magnetic monopoles in unified gauge theories*, Nucl. Phys. B **79**, 276 (1974). doi:10.1016/0550-3213(74)90486-6
 [4] A. M. Polyakov, *Particle spectrum in the quantum field theory*, JETP Lett. **20**, 194 (1974) [Pisma Zh. Eksp. Teor.

- Fiz. **20**, 430 (1974)].
- [5] M. Hindmarsh and T. W. B. Kibble, **Monopoles on strings**, Phys. Rev. Lett. **55**, 2398 (1985). doi:10.1103/PhysRevLett.55.2398
 - [6] T. Vachaspati and A. Vilenkin, **Evolution of cosmic strings**, Phys. Rev. D **35**, 1131 (1987). doi:10.1103/PhysRevD.35.1131
 - [7] T. W. B. Kibble and T. Vachaspati, **Monopoles on strings**, J. Phys. G **42**, no. 9, 094002 (2015) doi:10.1088/0954-3899/42/9/094002 [arXiv:1506.02022].
 - [8] E. P. Wigner, **The probability of the existence of a self-reproducing unit**, in The Logic of Personal Knowledge: Essays Presented to Michael Polanyi on his Seventieth Birthday, pp. 23138. Routledge & Kegan Paul, London, 1961.
 - [9] M. Hindmarsh, K. Rummukainen and D. J. Weir, **New solutions for non-Abelian cosmic strings**, Phys. Rev. Lett. **117**, no.25, 251601 (2016) doi:10.1103/PhysRevLett.117.251601 [arXiv:1607.00764 [hep-th]].
 - [10] M. Hindmarsh, K. Rummukainen and D. J. Weir, **Numerical simulations of necklaces in $SU(2)$ gauge-Higgs field theory**, Phys. Rev. D **95**, no.6, 063520 (2017) doi:10.1103/PhysRevD.95.063520 [arXiv:1611.08456 [astro-ph.CO]]. Copy to ClipboardDownload
 - [11] M. Hindmarsh, A. Kormu, A. Lopez-Eiguren and D. J. Weir, **Scaling in necklaces of monopoles and semipoles**, Phys. Rev. D **98**, no.10, 103533 (2018) doi:10.1103/PhysRevD.98.103533 [arXiv:1809.03384].
 - [12] It is believed that microbial life first developed with RNA and then evolved into cells having DNA as the volume of heredity material increased. Damage in the DNA is easily repaired due to pairing in the double chain, which is basically the error correction mechanism. It requires one chain to be the mirror image of the other. Various kinds of beads discussed in literature can, in principle, provide such mirror pairing in a necklace double helix but we leave it to others to speculate about specific realizations.
 - [13] D. Boyanovsky, H. J. de Vega and D. J. Schwarz, **Phase transitions in the early and the present universe**, Ann. Rev. Nucl. Part. Sci. **56**, 441 (2006) doi:10.1146/annurev.nucl.56.080805.140539 [hep-ph/0602002].
 - [14] E. Chudnovsky and A. Vilenkin, **Strings in the Sun?**, Phys. Rev. Lett. **61**, 1043 (1988). doi:10.1103/PhysRevLett.61.1043
 - [15] M. R. Krumholz, **The big problems in star formation: the star formation rate, stellar clustering, and the initial mass function**, Phys. Rept. **539**, 49 (2014) doi:10.1016/j.physrep.2014.02.001 [arXiv:1402.0867].
 - [16] M. Giannotti, I. Irastorza, J. Redondo and A. Ringwald, **Cool WISPs for stellar cooling excesses**, JCAP **05**, 057 (2016) doi:10.1088/1475-7516/2016/05/057 [arXiv:1512.08108 [astro-ph.HE]].
 - [17] S. Rappaport *et al.* **The random transiter – EPIC 249706694/HD 139139**, Mon. Not. Roy. Astron. Soc. **488**, 2455 (2019) doi:10.1093/mnras/stz1772 [arXiv:1906.11268].