



Sites that Can Produce Left-handed Amino Acids in the Supernova Neutrino Amino Acid Processing Model

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Received 2018 January 1; accepted 2018 February 4; published 2018 March 21

Abstract

The Supernova Neutrino Amino Acid Processing model, which uses electron anti-neutrinos and the magnetic field from a source object such as a supernova to selectively destroy one amino acid chirality, is studied for possible sites that would produce meteoroids with partially left-handed amino acids. Several sites appear to provide the requisite magnetic field intensities and electron anti-neutrino fluxes. These results have obvious implications for the origin of life on Earth.

Key words: astrobiology – astrochemistry – meteorites, meteors, meteoroids – molecular processes – neutrinos

1. Introduction

A remarkable fact of nature is the left-handed chirality, or handedness, of nearly all the amino acids used by known living creatures in the production of proteins, to the near exclusion of the right-handed forms. Molecular chirality was discovered in the nineteenth century by Pasteur (Pasteur 1848; Flack 2009), and the homochirality of the amino acids was subsequently deduced. However, an explanation of the origin of the amino acid chirality has remained elusive.

We define enantiomeric excess as $ee = (NL - NR) / (NL + NR)$, where $NL(NR)$ is the number of left- (right-) handed molecules in an ensemble. Thus, Earth's amino acids have an $ee = 1.0$ (except for glycine, which is achiral), that is, they are left-handed and homochiral. If $ee = 0.0$, the ensemble is said to be racemic.

Although laboratory experiments in the 1950s (Miller 1953; Miller & Urey 1959) suggested that amino acids might have been produced in an early Earthly lightning storm, that scenario fails to explain how the amino acids might have become totally left-handed. Furthermore, the several suggested means of converting the racemic amino acids to homochirality via Earthly processes were discussed by Bonner (1991), and shown to be unlikely to produce the observed result. General discussions were also provided by Mason (1984) and Barron (2008).

However, analysis of meteorites has found that they do contain amino acids, meaning that they are made in outer space (Kvenvolden et al. 1970; Bada et al. 1983; Cronin & Pizzarello 1997; Cronin et al. 1998; Glavin & Dworkin 2009; Herd et al. 2011) and that some of them do exhibit nonzero enantiomeric excesses, typically at a level of a few percent, with a preference for left-handedness. Thus, cosmic production of the amino acids becomes a strong contender for explaining how Earth was seeded with amino acids, and how they came to have a left-handed chirality. The observed ees , however, necessitate the existence of amplification via autocatalysis (Frank 1953; Kondepudi & Nelson 1985; Goldanskii 1989), which is thought, and demonstrated in laboratory experiments (Soai et al. 1995, 2014; Soai & Sato 2002; Breslow & Levine 2006; Klusmann et al. 2006), to be able to convert small ees to Earthly homochirality.

One model that purports to explain how amino acids achieved their left-handed chirality in outer space has reached a sufficient stage of development that it now seems appropriate to consider its probability for producing chiral amino acids. The Supernova Neutrino Amino Acid Processing (SNAAP) Model (Boyd et al. 2010, 2011; Boyd 2012; Famiano et al. 2014; Famiano & Boyd 2016; Famiano et al. 2018a), has been developed over the past few years. Recent efforts using quantum molecular calculations have shown that this model appears to produce amino acids within its framework that do have a significant ee , and that it is positive for most of the amino acids studied. In this work we will address the issue of whether or not the SNAAP model can explain how the chiral amino acids observed in meteorites were made and to what extent they might have populated the galaxy.

Other models have also been developed to explain how the amino acids developed ees in outer space. Perhaps the best developed one is the Circularly Polarized Light (CPL) model, which relies on ultraviolet CPL, produced by first scattering the light from an extremely hot star to polarize it, then letting it process the amino acids. It was first suggested by Flores et al. (1977) and Norden (1977), and subsequently elaborated in detail by many groups (Rubenstein et al. 1983; Bailey et al. 1998; Meierhenrich et al. 2005, 2010; Takano et al. 2007; Meierhenrich 2008; Takahashi et al. 2009; Meinert et al. 2010, 2012, 2014; de Marcellus et al. 2011). Although there are certainly other suggested explanations for the origin of a preferred amino acid chirality in outer space, we believe that they are less well developed than either the CPL model or the SNAAP model. In any event, they have been discussed in other publications (Bonner 1991; Meierhenrich 2008; Gujjarro & Yus 2009; Boyd 2012).

The essential features of any model include (i) how it generates some enantiomerism in the amino acids, (ii) how that gets amplified, if necessary, to the few percent level found in carbonaceous chondrite meteorites, (iii) how the model explains the processing of some of the enantiomeric amino acids throughout the volume of the carbonaceous chondrite meteorites, and (iv) how its amino acids can be delivered to present-day Earth via meteorites.

In Section 2 we discuss the basics of the SNAAP model. Section 3 details how the above issues are solved within that model. Section 4 presents our conclusions.

2. The SNAAP Model

In this model (Boyd et al. 2010, 2011; Boyd 2012; Famiano et al. 2014, 2018a; Famiano & Boyd 2016) large meteoroids might be processed in the intense magnetic field and electron anti-neutrino (hereafter denoted “anti-neutrino”) flux from one of several stellar objects. The anti-neutrinos are selective in their destruction of the amino acids with right-handed helicity, a result of the weak-interaction nuclear physics that describes their interaction with the ^{14}N nuclei. The relevant nuclear reaction is

$$\bar{\nu}_e + ^{14}\text{N} \rightarrow e^+ + ^{14}\text{C}, \quad (1)$$

where $\bar{\nu}_e$ is an electron anti-neutrino and e^+ is an antielectron, a positron. If the $\bar{\nu}_e$ spin (1/2, in units of $\hbar$, Planck’s constant divided by 2π) is antiparallel to the ^{14}N (spin 1), then the total spin of 1/2 on the left side of the equation will equal the sum of the spin of ^{14}C (spin 0) and the positron (spin 1/2) on the right side. However, if the $\bar{\nu}_e$ spin and the ^{14}N spins are aligned, then conservation of angular momentum will require one unit of angular momentum to come from either the $\bar{\nu}_e$ wave function or the positron wave function in order for the total angular momentum on the right side to equal the 3/2 on the left side. From basic nuclear physics (Boyd 2008), a total angular momentum of 3/2 in this reaction is known to introduce roughly an order of magnitude smaller cross section than an angular momentum of 1/2 in the same reaction and is the origin of the effect predicted for the SNAAP model.

Detailed quantum molecular calculations have shown that the complex interactions of molecules with the intense magnetic field of the nascent neutron star in a developing supernova, or of the cooling neutron star following a supernova event, and the electric field caused by the motion of the meteoroids through the magnetic field do produce an environment that is truly chiral (Barron 1986, 2008). In this situation, the interactions of the ^{14}N with the $\bar{\nu}_e$ s are chirally selective, and will, at least in nearly every case, destroy more of the right-handed amino acids than the left-handed ones (Famiano et al. 2018b).

The meteoroids that are processed by the anti-neutrinos can be as large as needed to survive the possibly intense fields of the stellar object they pass by or orbit. That is not a particularly stringent assumption, since all that is needed is the magnetic field and the anti-neutrino flux, and there are several candidates that appear capable of satisfying those requirements: supernovae, cooling neutron stars, magnetars, Wolf-Rayet stars, and even “silent supernovae,” stars that are sufficiently massive that they collapse to black holes, develop strong magnetic fields, and emit the usual copious streams of neutrinos and anti-neutrinos while producing very few photons.

Calculations were performed (Famiano et al. 2018a, 2018b) with the quantum molecular code *Gaussian* to examine several possible ways in which the ^{14}N , coupled to the molecular chirality, could undergo chirality-dependent destruction. This was done for 21 amino acids. The motion of the meteoroids in the magnetic field of the central object is critical, as it induces an electric field from the cross product of the

velocity with that magnetic field. The angle that the nuclear magnetization makes with the anti-neutrino spin is then chirally dependent. The cross section for destruction of the ^{14}N by the anti-neutrinos, and hence of the molecule, depends on that angle, producing the chirality-dependent molecular destruction.

The most promising studied scenario (Famiano et al. 2018a, 2018b) appears to result from the coupling of the molecular electric dipole moment to the electric field induced in the meteoroid by its motion. This produces transverse magnetization components that differ between the two molecular chiral states. These components exist even without the coupling to the electric dipole moment (Buckingham 2004; Buckingham & Fischer 2006), but that coupling enhances the difference between the angles that the two chiral states make with the anti-neutrino spin, so that the difference in the destruction rates of left-handed and right-handed amino acids is enhanced (Famiano et al. 2018a). From the magnitude of these effects, one can determine the *ees* that might be expected for amino acids from the SNAAP model.

In principle, electron neutrinos could drive the ^{14}N to ^{14}O , but the threshold energy is higher for this reaction. Since the cross section for neutrino capture processes is proportional to the square of the energy above the threshold (Boyd 2008) this reaction has a smaller effect on the enantiomerism that results from the combined flux from anti-neutrinos and neutrinos.

3. Results

Can the SNAAP model produce ees in the amino acids? At present the quantum molecular calculations have assumed that the meteoroids pass by the central object, if it is a supernova or cooling neutron star, at mid-plane and normal to the axis that connects the poles. But the resulting *ees*, as high as 1%, with the amino acid isovaline in an aqueous environment, as has been suggested in recent meteoritic analyses (Herd et al. 2011), are particularly noteworthy in that they are in the ballpark of what is observed in the meteorites. However, if more sophisticated calculations fail to increase the predicted *ees* over the 1% level, some autocatalysis will be necessary for the SNAAP model to explain the meteoritic *ees*.

Can the SNAAP model produce sufficiently large ees that some autocatalysis can boost them to the levels observed in the meteoroids? The required level of any *ee*-producing mechanism might be relaxed if autocatalysis (Frank 1953; Kondepudi & Nelson 1985; Goldanskii 1989) can prevail in outer space. The experiments that have demonstrated autocatalysis (Soai et al. 1995, 2014; Soai & Sato 2002; Breslow & Levine 2006; Klusmann et al. 2006) have been performed in laboratory settings. Although the minimum *ee* required for that to take effect is not known, it can be safely assumed to be less than the roughly 1% level in the experiments in which it has been demonstrated. Since the SNAAP model appears capable of producing *ees* at roughly that level, the required *ee* should not be a problem at all, unless autocatalysis is more restrictive in the cold confines of outer space than it is on Earth. Of course, that is a possibility. Thus, experiments to determine the temperature dependence of autocatalysis would be very useful.

Can the SNAAP model predict that some of the carbonaceous chondrite meteorites that get to Earth will have nonzero ees? In order for any model to explain how some of the carbonaceous chondrite meteorites end up having *ees*, the model must either have a well-defined local source that can

produce *ees*, or it must explain how it can process the space debris in some larger region of space.

(a) One possibility might be the processing of the planets around a single massive star as it becomes a supernova. *KEPLER* (Borucki 2016) has now detected planets around many stars. Thus, it might be safe to argue that most, or at least many, stars do have planets associated with them. The inner ones will be completely processed by the anti-neutrinos, since nearly all of them will pass through any object, even a planet, as the star becomes a supernova. When the shock wave from the explosion hits the inner planets a few hours later, material will undoubtedly be spalled off, creating meteoroids. However, this model has a fundamental problem for the SNAAP model (and others) in that the magnetic field from the nascent neutron star extends to about 1 au, whereas the star, when it moves into its red giant phase, will extend to about that same distance. Thus, any meteoroids or planets that had any amino acids prior to the red giant phase would most likely have them destroyed when the star expanded. Although supernovae may be a major source of the galaxy's space debris, the amino acids in the resulting meteoroids would most likely have tiny enantiomeric excesses.

(b) Another possible scenario might result from a neutron star that is recoiling, after it has been produced in a supernova, typically at 1000 km s^{-1} or less, through the space debris of the galaxy for the 10^5 years it would be expected to continue to emit anti-neutrinos, processing each nearby floating planet (Sumi et al. 2011) or piece of space rock as it goes. We investigated this scenario, but found that even with generous estimates of the supernova frequency and the energies of the anti-neutrinos emitted by the cooling neutron star. (The anti-neutrino energies may be thermal, as described by Bahcall & Wolf 1965, but may also have considerably higher energies from the nuclear processes taking place in the cooling star, as noted by Fuller & Meyer 1991; Schatz et al. 2014; Misch & Fuller 2016 and Patton et al. 2017.) The volume of the space that could be processed by all the neutron stars produced since the Big Bang was more than 10 orders of magnitude less than the volume of the galaxy. Furthermore, the space rocks processed this way would be widely distributed, and this would not be likely to populate a restricted region of space.

(c) A third possibility might be a Wolf-Rayet star. When the star became a supernova any amino acids that resided within a passing meteoroid or in the material surrounding the star within an au of the star would be processed by the magnetic field and anti-neutrinos emitted. This does seem to be a plausible scenario for creating enantiomerism in the amino acids, although the trajectory of the passing meteoroid could not be too close to the hot star, or too far from it to experience its magnetic field, when it exploded. And dust grains within the surrounding cloud would have to have been in a sufficiently cool region for amino acids to form.

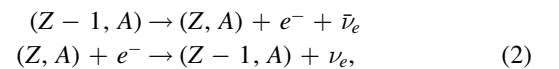
(d) Perhaps a more likely scenario is one in which a massive star exists as part of a close binary system in which the partner is a neutron star. In such a system, the neutron star gradually siphons off the outer layer of the massive star, producing a star that will ultimately become a SN Ib/c, and creating an accretion disk around the neutron star (Wolszczan 2008). The disk apparently ranges from close to, but slightly beyond, the surface of the neutron star (see, e.g., Ludlam et al. 2017) to beyond 10^5 km (see, e.g., Pringle 1982). The material would all be contained within the volume that includes the magnetic

field from the neutron star. The supernova, when it occurred, would be sufficient to provide a robust anti-neutrino flux near the neutron star. This scenario introduces a complex set of possibilities. Any planets that were in orbits around the massive star would lose some of their gravitational attraction to that star as its mass was transferred to the neutron star, so those in outer orbits might assume new, possibly highly elongated, orbits around the binary star system (see, e.g., Jain et al. 2017), or might undergo a hyperbolic trajectory bypass of the neutron star. In either scenario, the planet might be shredded by the strong gravitational field gradient, or as it passed through the accretion disk, so the result might produce the mass of the planet in meteoroids.

The accretion disk itself is thought to be a nursery for dust grains, meteoroids, and even planets (Lithwick 2009), and the temperature falloff with radius in the disk, thought to be $r^{-3/4}$ for a large enough distance from the neutron star (see, e.g., Mineshige et al. 1994), would eventually provide a sufficiently low-temperature environment in the outer regions of the disk that racemic amino acids could form, awaiting the anti-neutrinos from the exploding supernova to create some enantiomerism. The anti-neutrinos emitted by the cooling neutron star might become thermal soon after the neutron star is created so, except for those far out on the high-energy tail of the distribution, their energy would be insufficient to cause the conversion of ^{14}N to ^{14}C . However, as noted above, nuclear processes might modify that conclusion. But when the massive star companion became a supernova, the matter in the accretion disk would all be well within the range of the neutrinos emitted from the supernova, which would process any amino acids that had developed in the accretion disk. Furthermore, the intense emissions from the X-ray binary and the shock wave from the supernova would surely cause sufficient disruption of at least some of the material in the disk to propel it beyond the gravitational well of the two stars.

What would happen to the binary system that had now become two neutron stars? Recent gravitational wave and space borne gamma-ray detectors (Abbott et al. 2017; Goldstein et al. 2017; Savchenko et al. 2017) have shown that neutron star mergers can produce a huge abundance of neutron-rich material, and presumably enough of an accompanying shock wave to create a new stellar system from the material ejected from what was originally two massive stars. This system may be capable of creating its own new stellar system, complete with r-process nuclides and enantiomeric amino acids.

(e) A recent study (Schatz et al. 2014) of the crust in a neutron star deserves special note. It suggested that the nuclei that are contained in the matter that is accreted from the companion star into the neutron star accretion disk, and subsequently onto the surface of the neutron star, would be absorbed into the surface region of the star. They would encounter the essentially neutron-pure matter ultimately to a depth of about 150 m, and would be driven to the neutron drip line by successive beta-decays and electron captures. The processes that would occur in one of the shells of the star would be



where (Z, A) is a nucleus with proton number Z and nucleon number A . The star is cooled by the emission of the neutrinos, ν_e , and anti-neutrinos, $\bar{\nu}_e$. As the nuclides are pushed more

deeply into the neutron-rich region below the crust, they become increasingly neutron-rich until they reach the neutron drip line. The result could be a so-called URCA process (Gamow & Schoenberg 1941) that would emit electron neutrinos and anti-neutrinos.

The anti-neutrino endpoint energies would be expected to achieve several MeV for some of the neutron-rich nuclides created. While the intensity of the resulting anti-neutrinos would not be as high as those emitted when the supernova explodes, they would be high enough in energy to process any amino acids that had been produced. Furthermore, they could continue to be processed for years, creating an additional opportunity to process any amino acids created in the accretion disk around a neutron star from the electron anti-neutrinos emitted.

Thus this scenario might enhance the enantiomerism produced in the accretion disk in a binary system discussed in Section 3.

Could this model populate the entire Galaxy with enantiomeric amino acids? That is very doubtful. Wolf-Rayet (WR) stars and binary systems of the type discussed are not extremely rare, but neither do they occur frequently. However, the meteoroids thrown out from the accretion disk of the binary system or the WR star would attain enough momentum from the SN Ib/c to carry them to appreciable distances from the central system, and thus to populate a region that would ultimately be considerably larger than the stellar system.

This would suggest that, although the potential for life would not be uniform throughout the Galaxy, there should be numerous pockets in which life might have been initiated as the enantiomeric amino acids were distributed around the binary star systems. Even though planets might lie in the Goldilocks Zone, that is, within a temperature range that is neither too hot nor too cold for life to exist, they might not have amino acids that had received the necessary processing to make them enantiomeric. However, there might also be systems, specifically remnants of binary massive star systems, that would be strong candidates for life. Indeed, if the SNAAP model is the correct description of amino acid enantiomeric excess production, remnants of such systems should provide good places for astronomers to search for chiral amino acids.

Can the SNAAP model produce meteorites that can make it to Earth's surface? Since the anti-neutrinos will have processed the entire meteoroid, no matter how large it was, the *ees* established would prevail throughout its body. Thus, assuming that any meteoroids would suffer some ablation in passing through the Earth's atmosphere, whatever portion remained would carry the *ees* it achieved prior to entering Earth's atmosphere. Dust grains would not be so fortunate; they would be likely to burn up before reaching the surface of the Earth.

4. Some Conclusions

Several effects that are beyond the scope of the current paper will be dealt with in future studies. These include more calculations of quantum molecular chemistry and inclusion of time changing magnetic fields. Although we cannot be sure how these will affect the *ees*, those calculated in the simplified model assumed in Famiano et al. (2018a) were approaching the levels found in the meteorites. Thus the SNAAP model may require little, if any, outer space autocatalysis to produce the few percent *ees* seen in meteorites.

Perhaps the most troublesome aspect of the SNAAP model is that its *ee* predictions are, at this stage, completely theoretical. Although the calculated *ees* are the result of state-of-the-art quantum molecular codes, it would be helpful if some experiments could be performed to demonstrate the viability of at least some of its predictions. Experiments do appear to be feasible, and are under consideration. Nonetheless, there do seem to be several plausible sites that apparently could produce the necessary magnetic fields and anti-neutrino fluxes to convert the amino acids produced in the outer reaches of the accretion disk from racemic to the slightly enantiomeric values found in some of the meteorites that made it to the surface of the earth.

The predictions from this model are compelling. The enantiomeric levels achieved are approaching the levels seen in the meteorites, even without autocatalysis. And the possibility of a massive star–neutron star binary system being able to produce pockets of enantiomeric amino acids suggests that this might well be the origin of the molecules found in the meteorites, and perhaps even of those required to initiate life on early Earth. It might behoove astronomers, when they are able to detect amino acids in space, to direct their efforts to determining enantiomerism toward the regions around close massive star–neutron star binaries.

We note that another scenario for producing enantiomeric amino acids in outer space, from Barron & Vrbancich (1984) and Rikken & Raupach (1997), would be facilitated by the sites we discuss above. This magnetochiral dichroism model utilizes the light and a parallel magnetic field from a supernova to process the previously created amino acids. A single supernova would not suffice because it would have the same problem as it would for the SNAAP model: the size of the red giant produced as one stage of the stellar evolution would extend beyond the region that could be served by the magnetic field of the nascent neutron star, a requirement of that model. However, a Wolf-Rayet star or a binary system obviates that issue, thus providing several sites including some of the ones described above, that could also pertain to the magnetochiral dichroism model.

The authors thank L. Nittler, F. Thielemann, H. Schatz, and L.D. Barron for helpful comments and suggestions. M.A.F.'s work was supported by the National Astronomical Observatory of Japan, and by a WMU Faculty Research and Creative Activities Award (FRACAA). T.K. was supported partially by Grants-in-Aid for Scientific Research of JSPS (15H03665, 17K05459).

Software: Gaussian (Frisch et al. 2016).

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