ANOMALOUS STELLAR ACCELERATION:
causes and consequences

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In 2018 Vitvazev and colleagues analyzed positions and motions of more than a million main sequence stars, most of which are within 500 light years of the Sun. Their analysis utilized the first data release from the European Space Agency's Gaia space observatory. Surprising results of their analysis were the facts that most stars in our galactic vicinity are considerably older that our Sun and stars apparently accelerate in their galactic revolution by ~1 km/s per billion years. In this paper some possible modes of stellar acceleration are suggested, discussed and evaluated, including unidirectional stellar electromagnetic flux, accelerated stellar winds, galactic cannibalism, coronal mass ejections, unidirectional stellar neutrino flux, and thermal nuclear fusion of stellar winds. We demonstrate that the accelerated unidirectional stellar wind and the unidirectional stellar neutrino jet in conjunction with the unidirectional photon jet ejected from the star and non-isotropic stellar wind can yield the stellar linear momentum change by ~6 x 10^{16} N that produces the stellar acceleration 3 x 10^{-14} m/s^2. Some of the stellar acceleration mechanisms considered in this paper may provide evidence for the technosignatures of advanced galactic civilizations.

Keywords: Stellar Acceleration, Stellar Wind, Stellar Electromagnetic Flux, Neutrino Flux, Technosignatures, Parenago's Continuity, SETI

1 INTRODUCTION: NEW OBSERVATIONS OF STELLAR KINEMATICS

As a successor to Hipparcus, an earlier European Space Agency (ESA) space telescope, the ESA Gaia space telescope was launched in December 2013 and is currently on-station at the Earth-Sun L2 Lagrange point, about 1.5 x 10^6 km from Earth. The goal of this mission is accurate determination of position and motions for ~1 billion stars in the Milky Way galaxy [1].

Three years after Gaia's launch, the Gaia Collaboration published Gaia Data Release 1 (DR1) [2]. This document discusses early observations by this spacecraft, which resulted in accurate proper motions and parallaxes for approximately 2 million stars.

In 2018, Vityazev and colleagues applied DR1 data to investigate Parenago's Discontinuity [3], an aspect of stellar kinematics [4]. Named after its discoverer, Soviet-era Russian astronomer Pavel Parenago and observed later by Roman [5,6] this phenomenon concerns a discontinuity in stellar galactic revolution velocities. Stars in the vicinity of our solar system with (B-V) color indices greater than around 0.61 (F9 or G1) revolve around the galaxy's center about 20 km/s faster than hotter, more massive stars.

Beginning in the 1990s, it became possible to obtain accurate astrometric data for nearby stars using space-based observatories. In 1997, Binney et al. [7] applied an exacting modeling procedure of stellar velocity dispersions to obtain kinematics results for 5,610 main sequence stars within 260 light years of the Sun using data obtained by the Hipparcos space telescope. Parenago's Discontinuity is clearly present in the Hipparcos data set.

Vityazev et al. [3] utilized a much more extensive data set than that of Binney et al. [7] – more than 1,260,000 main sequence stars and 500,000 red giants. Giant stars were excluded from their analysis because they are generally very distant. Parallaxes for very distant stars are not well determined, which reduces the accuracy of kinematics calculations. Most of the main sequence stars in the DR1 sample are within a sphere of radius > 500 light years centered on the Sun.

Parenago's Discontinuity for main sequence stars within this volume is clearly visible in the results plotted by Vityazev et al. [3], which indicates that the discontinuity is likely a galactic rather than a local phenomenon.

Because of the larger number of stars in the DR1 data set, Vityazev et al. [3] were able to investigate a feature visible in both the Hipparcos and Gaia DR1 Parenago plots. This is a strange bump in the curve of galactic revolution velocity versus (B-V) color index between (B-V) ≈ 0.55 and (B-V) ≈ 0.9, roughly equivalent to stellar spectral classes G1-K2 [8]. As is true for Parenago's Discontinuity, this bump is not apparent in plots of stellar velocity components in directions other than the direction of stellar galactic revolution.

After estimating that most stars in the DR1 sample are billions of years older that the Sun, Vityazev et al. [3] concluded that the reason for this bump is that stars apparently accelerate along the direction of stellar galactic revolution. The magnitude of this surprising effect is ≈ 1 km/s per billion years (3 x 10^{-14} m/s^2). In a billion years, this effect could alter a star's unaccelerated position by about 1.5 x 10^{16} km or 1,500 light years.

It must be understood that this interesting and unexpected result must be confirmed by other researchers to be considered as real. The purpose of this paper is the consideration of various possible physical processes that could account for this stellar acceleration, if it is confirmed.

The goal of this study is to evaluate possible stellar acceleration modes including unidirectional stellar electromagnetic flux, galactic cannibalism, stellar mass loss by thermonuclear fusion, accelerated stellar winds, high-speed coronal mass ejections, unidirectional stellar neutrino flux, and thermonuclear fusion of stellar winds that could account for the stellar acceleration

The paper is organized in the following way. Section 2 presents our theoretical approach. We present the stellar mass loss processes in Section 3. In particular, unidirectional or focused electromagnetic flux, galactic cannibalism, stellar mass loss by thermonuclear fusion, non-isotropic solar wind, accelerated unidirectional stellar wind, coronal mass ejections, unidirectional neutrino flux, and solar wind thermonuclear fusion are considered in subsections 3.1-3.8, correspondingly. Conclusions follow in Section 4.

2 THEORETICAL APPROACH

Two fundamental conservation laws provide the basic analytical tools of the analysis. These are the law of linear momentum conservation and the law of angular momentum conservation. It is also assumed, for simplicity, that all stars are in circular orbits around the galactic center.

In our analyses all stars considered are similar to the Sun, with a luminosity of $L_{\odot}$ = 3.9 x 10^{26} W and a mass of $M_{\odot}$ = 1.99 x 10^{30} kg [9]. Calculations are based upon the Sun's distance from the galactic center, about 26,000 light years or 2.6 x 10^{17} km, the Sun's approximate revolution velocity around the galactic center is 220 km/s and the period of one solar revolution around the galactic center around 225 million years [9]. Although this assumption is not entirely accurate since the Sun is brighter and more massive than most main sequence stars, it allows for the discussion of various suggested modes of stellar acceleration based upon solar data, which is of course more accurate in many cases than corresponding data regarding other stars.

Because the Sun's orbit around the galactic center is assumed to be circular, the Sun's galactic-orbital velocity V_s can be estimated by equating centripetal force and the gravitational attractive force between the Sun and the galactic center:

$$V_s = \sqrt{\frac{GM_g}{R_S}} \tag{1}$$

where M_g is the galactic mass interior to the Sun's galactic orbit, R_s is the distance between the Sun and the galactic center and G = 6.67 x 10^{-11} Nm^2/kg^2 is the gravitational constant. Substitution in Eq. (1) of the values of V_s and R_s reveals that the galactic mass interior to the Sun's galactic orbit is about 10^{11} solar masses.

The linear momentum P_s of the Sun-like star can be expressed as: $P_s = M_s V_s$. Therefore, we find that the star's linear momentum is approximately equal to P_s = 4.4 x 10^{35} kg m/s. The linear momentum of a star and all its emissions is a conserved property. If one considers the case of a star expelling a quantity of mass M_{ex} at a velocity V_{ex} during a time interval t, based on the linear momentum conservation, the change in a star's linear momentum caused by the ejection of a unidirectional jet of material can be expressed as:

$$M_S \frac{dV_S}{dt} = -V_{ex} \frac{dM_{ex}}{dt} \tag{2}$$

The system consisting of the star and unidirectional expelled material is an analogue to the system consisting of a rocket and its expelled fuel. The star's velocity change ΔV_s can be expressed using the familiar rocket equation first derived by Tsiolkovsky in 1903 [10]:

$$\Delta V_s = V_{ex} \ln \frac{M_S}{M_S - M_{ex}} \tag{3}$$

This change of the velocity of the star could be a source of the acceleration that stars experience during the lifetime. As mentioned above the analysis of the velocity field of main-sequence stars and red giants from the Gaia Astrometric Solution catalogue with heliocentric distances up to 1.5 kpc for various spectral types presented in Ref. [3] can infer that the average acceleration of a main sequence star in its galactic revolution is 3 x 10^{-14} m/s^2. A legitimate question arises: is Newton's second law valid for so small acceleration? At very small accelerations a deviation from Newtons second law could remain hidden in most laboratory scale experiments but might appear in astrophysical and cosmological observations [11]. Any deviation from Newton's second law would have profound consequences as it would imply a violation of conservation laws such as those of momentum and energy. In Refs. [11, 12] the authors have tested the proportionality of force and acceleration in Newtons second law for small accelerations. The tests reach well below the acceleration scales relevant to understanding several current astrophysical puzzles such as the flatness of galactic rotation curves, the Pioneer anomaly, and the Hubble acceleration. It was found that Newtons second law holds down to the lowest accelerations measurable within experimental errors, 3 x 10^{-11} m/s^2 [12]. Over two decades later in Ref. [11] the authors reported that they found no deviation from the proportionality in Newton's second law down to accelerations of 5 x 10^{-14} m/s^2, which is the smallest acceleration ever achieved in a scientific experiment. This acceleration is approximately 1,000 times smaller than the previous 1986 test [12].

Because the star's galactic orbit is assumed to be circular and the direction to the galactic center is perpendicular to the star's galactic orbit, the angular momentum of the star can be expressed as:

$$L_S = M_S V_S R_S \tag{4}$$

Substitution in Eq. (4) the values of M_s, V_s and R_s reveals that the star's angular momentum is approximately equal to L_s = 1.1 x 10^{56} kg m^2/s. As is the case for the linear momentum, the angular momentum of the system consisting of a star and its emissions is conserved. Therefore, $\frac{dL_S}{dt} = 0$. This conservation principle can be expressed as:

$$\frac{dL_S}{dt} = M_S R_S \frac{dV_S}{dt} + V_S R_S \frac{dM_S}{dt} + M_S V_S \frac{dR_S}{dt} = 0 \tag{5}$$

Assuming circular stellar galactic rotation and a constant stellar distance $\frac{dR_S}{dt} = 0$ from the galactic center from Eq. (5) one obtains:

$$M_S \frac{dV_S}{dt} = -V_S \frac{dM_S}{dt} \quad (6)$$

Let us estimate the left part of Eq. (6). Recalling that the star's velocity change is:

$$\frac{dV_S}{dt} \approx 3 \times 10^{-14} \frac{\text{m}}{\text{s}^2}$$

we obtain $M_S \frac{dV_S}{dt} = 6 \times 10^{16}$ N.

Therefore, the right side in Eq. (6) should be of the same order and this depends explicitly on the rate of the star expelling mass $\frac{dM_S}{dt}$.

There are a number of physical mechanisms responsible for expelling mass during the stars' life. These include but may not be limited to: unidirectional or focused electromagnetic (EM) flux, solar wind, accelerated solar wind, coronal mass ejections (CMEs), unidirectional neutrino flux, and solar wind thermonuclear fusion. Each mechanism can be treated as an exhaust velocity V_{ex} with a mass flow rate so that the acceleration of the star is analogous to a rocket thrust $F = V_{ex} M_s$. It is worth noting that from a terrestrial point of view, $F = 10^{16}$ N is an enormous force. It is about equivalent to the force exerted by two billion 10^6 kg rockets, each accelerating by 3*g*. But from the cosmic viewpoint, this force is inconsequential. It is more than 5 orders of magnitude less than the mutual gravitational force between the Earth and Sun.

3 STELLAR MASS LOSS PROCESSES

Stars never seem to be in a purely static state of mass conservation and stellar mass loss has a significant impact on stellar evolution. There are a number of possible mechanisms of stellar mass loss that could account for the stellar acceleration. Some are investigated in this section.

3.1 Unidirectional or Focused Stellar Electromagnetic Flux

As well as stars emitting copious quantities of electrically charged massive particles, they also emit electrically neutral particles with negligible mass such as neutrinos and massless photons. Let us first consider the star's mass loss due to electromagnetic radiation and emission of photons. It is known from quantum mechanics that a photon's linear momentum is equal to the ratio of its energy and the speed of light $p = \frac{E}{c}$ [13].

When considering the stellar mass loss produced non-isotropically, the equation for photon momentum can be easily applied to obtain:

$$\frac{dV_S}{dt} = \frac{P_S}{cM_S} \quad (7)$$

where P_s is unidirectional stellar emitted photon power in the direction of a star's acceleration and $c = 3 \times 10^8$ m/s is the speed of light in vacuum.

Assume that a portion of the Sun's EM output is emitted in a unidirectional or focussed jet. Substitution in Eq. (6) for solar mass, the speed of light, and the stellar acceleration value reported by Vityazev et al. [3] reveals that the approximate power of this luminous jet is $P_s = 1.8 \times 10^{26}$ W. This is less than 5% of the total solar luminosity of $L_\odot = 3.9 \times 10^{26}$ W. From an energetic viewpoint, a unidirectional or focused stellar jet is a reasonable explanation for the observed stellar acceleration. But ~ 5% annual variation in EM flux has never been observed for our Sun. Because the radiation pressure force of solar photons rising towards the photosphere exactly balances solar self-gravitation, it seems likely that a unidirectional photon jet ejected from the Sun opposite to the direction of solar galactic revolution around the galactic center would slightly alter the Sun's shape. This too has never been observed. Therefore, while the unidirectional photon jet ejected from the Sun can provide the stellar acceleration, it is not enough for the enormous average force $F = 3 \times 10^{16}$ N.

3.2 Galactic Cannibalism

Dwarf galaxies generally exist as satellites of large galaxies such as our Milky Way. At about billion-year intervals, large galaxies may absorb one of their small companions in a phenomenon called "galactic cannibalism" [9].

If a dwarf galaxy with a mass of 1% of our Milky Way spiral is absorbed by the Milky Way, the apparent mass of our galaxy within the Sun's galactic orbit might increase. Application of Eq. (1) reveals that the galaxy-orbiting velocity components of existing stars might therefore increase.

This effect could explain the acceleration of stars over 1 billion-year time intervals if stars simply blinked into existence out of the void. But because the molecular nebulae that serve as stellar nurseries will be accelerated by galaxy mergers in the same way as pre-existing stars, it can be safely rejected as a possible cause of stellar acceleration.

3.3 Stellar Mass Loss by Thermonuclear Fusion

During its ~10 billion-year main sequence lifetime, a Sun-like star's mass is not constant. One factor reducing stellar mass is the stellar wind – a variable stream of electrically positive and negative ions ejected from the star. The second factor is thermonuclear fusion deep in the star's interior that constantly converts hydrogen nuclei (protons) to helium nuclei (alpha particles) and energy through pp reaction cycle or carbon-nitrogen-oxygen (CNO) cycle.

An omni-directional stellar wind will have little effect upon a star's velocity. In such a case wind components accelerating and decelerating the star will balance.

In the case of our Sun, it has been estimated that the total mass loss is $9.13 \times 10^{-14}\, M_\odot$/yr [14]. The annual solar mass loss to the solar wind is about $2.5 \times 10^{-14}\, M_\odot$/yr [15]. Therefore, the annual rate of solar mass loss due to thermonuclear fusion is:

$$\frac{dM_\odot}{dt} \sim 6.62 \times 10^{-14} M_\odot/\text{yr}$$

or about 4.2×10^9 kg/s.

The next step is to evaluate each of the three terms in the angular momentum conservation equation (5). Substituting the values of M_s, R_s, $\frac{dM_S}{dt}$ and $\frac{dV_S}{dt}$, one can evaluate the first and the second terms.

The first term $M_s R_s \frac{dM_S}{dt}$ ~1.56 × 10^{37} kg^2 m/s and the second term $V_s R_s \frac{dM_S}{dt}$ ~ -2.4×10^{35} kg m^2/s^2, which is almost two orders of magnitude less than the first term. Evaluating the third term $M_s V_s \frac{dR_S}{dt}$ is more difficult since approximate values of dR_s/dt are not readily available. However, recent observational results indicate that young galaxies are more compact than older ones [16]. This means that the term $M_s V_s \frac{dR_S}{dt}$ will tend to be positive. It therefore is reasonable to assume that fusion-related stellar mass loss is not a likely explanation for the observed stellar acceleration.

3.4 Non-Isotropic Stellar Wind

The solar wind, on average, is an isotropic stream of ionized particles emitted by the Sun. At the Earth's orbit 1 Astronomical Unit (AU) from the Sun, the average solar wind velocity is ~ 400 km/s [17]. At 1 AU from the Sun, the solar wind velocity can vary between 300 and 800 km/s. The annual solar wind loss is ~ 2.5 x 10^{-14} $M_\odot$/yr or about 1.7 x 10^9 kg/s [15].

In exact calculations of stellar acceleration caused by a non-isotropic stellar wind, the velocity of the jet escaping from the Sun's gravitational influence would be slightly less than the values cited above because the solar escape velocity at 1 AU is about 42 km/s. But assuming that a Sun-like star emits all its stellar wind at a constant effective velocity of 800 km/s in a direction exactly opposite to that star's direction of galactic revolution, the star's linear momentum change per second is about 1.4 x 10^{15} N, only a small fraction of the observed stellar linear momentum change. Clearly, a non-isotropic stellar wind cannot account for the observed stellar acceleration.

3.5 Accelerated Unidirectional Stellar Wind

Consider the case of a dual-purpose Dyson/Stapledon megastructure constructed around a star [18]. Confirmation of the existence of such a megastructure would constitute evidence for the existence of a Kardashev Level 2 or higher civilization [19]. A fraction of the star's radiant output is used to accelerate a fraction of the star's stellar wind as a unidirectional jet.

Assume that about 50% of the star's stellar wind (8 x 10^8 kg) is collected every second. This is accelerated to a velocity that allows a linear momentum change of 6 x 10^{16} N. From the law of linear momentum conservation (2), it is easily demonstrated that V_{ex} ~ 7 x 10^7 m/s, or about 0.24*c*.

For greater accuracy of course, a relativistic correction must be applied. But it is clear from this example that a circumstellar megastructure used to collect and accelerate a fraction of the star's stellar wind as a unidirectional jet is a viable alternative to produce the observed stellar acceleration.

3.6 Coronal Mass Ejections

Coronal mass ejections (CME) are processes that periodically eject large quantities of ionized material from the corona into the interplanetary medium at high velocities. Even for the well-observed case of solar CMEs, many questions remain about how they originate and evolve. They may be associated with disturbances in the coronal magnetic field [9]. The corona is the outer, very tenuous layer of the Sun's atmosphere. Only visible during a total eclipse of the Sun or with the aid of a coronagraph, this irregular layer extends from just above the thin chromosphere to one or two solar radii. (The solar radius is $R_\odot$ ~ 7 x 10^5 km). Composed of ~ 3 x 10^6 K plasma, the typical mass density of this layer is ~10^{-12} kg/m^3 [9]. Assuming a spherical corona extending from 7 x 10^5 to 1.4 x 10^6 km from the Sun's center, the coronal mass can be approximated as 10^{16} kg.

Typical CME ejection velocities range from 160 km/s during the period of solar minimum activity to 450 km/s during solar maximum activity. During solar minimum, the frequency of these events is ~ 0.1-0.3 CMEs/day. During solar maximum, the frequency is ~ 2-3 CMEs/day. A typical CME ejects 3 x 10^{12} kg/day into the interplanetary medium [20].

Some CMEs are considerably more energetic than the average. CME velocities as high as 3,000 km/s have been detected by spacecraft monitoring solar weather [21].

The following analysis considers three CME variations that might account for the observed stellar acceleration. These are average frequency CMEs at average velocities, average frequency CMEs at expansion velocities of 3,000 km/s and the extreme case of the entire corona being ejected.

3.6.1 Unidirectional Average Frequency CMEs at Average Velocities

Consider a Sun-like star that ejects an average of 3 CMEs per day at an expansion velocity of 450 km/s. The average CME mass is 3 x 10^{12} kg. All CMEs are emitted in the same direction.

The CME mass-ejection rate is ~10^8 kg/s. The acceleration force on the star caused by unidirectional CME emission is ~5 x 10^{13} N, which is three orders of magnitude less than the force accelerating the star of ~6 x 10^{16} N, according to the above discussion of the observational results described by Vityazev et al. [3].

3.6.2 Unidirectional Average Frequency CMEs at 3,000 km/s Velocities

In this case, unidirectional CME frequency and mass are identical to the values in the previous example. But the emission velocity is increased to 3,000 km/s.

The CME-induced stellar acceleration force is ~3 x 10^{14} N. It is still two orders of magnitude less than the required value to explain the stellar acceleration phenomenon.

3.6.3 Coronal-Mass Unidirectional CMEs Ejected at 3,000 km/s

To evaluate this possibility, it is first necessary to estimate the necessary unidirectional mass ejection rate at a velocity of 3,000 km/s to produce the required 6 x 10^{16} N stellar acceleration force. Applying Newton's second law, the total CME ejection mass is ~2 x 10^{10} kg/s.

This mass ejection value is approximately five orders of magnitude less than the mass of the solar corona. Therefore, the star's corona must be ejected about once every few terrestrial day at 3,000 km/s in the direction opposite the star's galactic revolution direction to produce the required force.

The solar energy per second that must be devoted to this process is ~10^{23} W, about 0.03% of the Sun's luminous output. During each year, the star's mass is reduced by 3 x 10^{-13} $M_\odot$/yr during this process. This CME scenario therefore is a possibility (even though it has never been observed), for active stars if not the Sun.

Recent progress has been made in estimating stellar CME properties and mass ejection rate by using the Sun to normalize a correlation between the ultraviolet and X-ray energy released in flares with CME masses and kinetic energies [22,23]. Ref. [24] extended an existing semi-analytic model of stellar wind mass-loss rates [23] and predicted CME mass-loss rates. The tabulated masses for the CMEs given in the database are likely to be highly uncertain. Nevertheless, including those masses for poor and very poor events would have increased the total CME mass to 1.248 x 10^{16} kg/yr [24] or ~4 x 10^{8} kg/s. At the same time one can use for the estimation of the CMES an approximate equation produced for almost completely non-overlapping time periods for the CME rate

$$\frac{dM_{CME}}{dt} \approx 5.6 \times 10^{-18} (S+7)\ M_{\odot}/\text{yr}\ [24]$$

where S is the recently revised month-averaged sunspot number from the World Data Center. In this case we obtain ~2.3 x 10^{9} kg/s. For this model one can assume that the CME rate can vary from ~4 x 10^{8} kg/s to ~2.3 x 10^{9} kg/s. Therefore, the CME rate can be over one order higher than above estimations done for ~10^{8} kg/s. Within the assumptions of the calculations for 10^{8} kg/s rate, thrusting due to CME gave a stellar linear momentum change less than the required 6 x 10^{16} N. However, our estimation based on Ref. [24] for CME rate ~4 x 10^{8} kg/s to ~2.3 x 10^{9} kg/s indicates that mass ejection rates may be 10-100 times higher and further analysis of CME thrusting may show that it also has the potential to meet the outlined requirements.

3.7 Unidirectional Neutrino Flux

As well as producing electromagnetic photons, thermonuclear reactions deep in stellar interiors produce non-reactive, electrically neutral, negligible-mass particles called neutrinos (ν) [25]. The operational neutrino-detection array [26-28] has measured neutrino energies between 10^{-3} meV and 10^{3} PeV [29]. Neutrinos and antineutrinos come in various "flavors" and neutrino mass can vary between 0 and 50 meV. For comparison, the rest mass of an electron is about 511 KeV [30].

There are two varieties of solar neutrinos. The first are thermally produced fluxes of neutrinos and antineutrinos with energies in the KeV range. The second is MeV-range neutrinos. The higher energy flux is what is expected from thermonuclear processes; the lower energy neutrinos might originate in the solar core. About 3% of the Sun's energy output is in the form of neutrinos [31]. The Sun emits 2.3% of its nuclear energy production in the form of MeV neutrinos [25].

These arise from the series of fusion reactions directly converting 4 protons to a helium nucleus, 2 neutrinos and 26.73 MeV of energy. Side thermonuclear reactions in the stellar interior that produce additional neutrinos include the reaction of a helium-3 nucleus with a proton, the reaction between helium-3 and helium-4 and the reaction between a beryllium-7 nucleus and an electron.

Although the proton-proton chain is the dominant energy-production method in Sun-like stars, about 1% of the Sun's energy output comes from the carbon-nitrogen-oxygen cycle [32-34]. This cycle is the dominant energy source in stars more massive than the Sun and those that have left the main sequence. In the CNO cycle, carbon is a catalyst that greatly speeds proton burning. It is combined with a proton in the first reaction in the CNO cycle and produced along with a helium-4 nucleus in the final CNO reaction. Two neutrinos are generated in the CNO cycle [35].

For simplicity, it is assumed here that all neutrinos are massless and there is no distinction between Majorana and Dirac neutrinos – Marjorana particles are identical to their antiparticles. It is also assumed that all neutrinos are emitted in a unidirectional jet. All proton-proton chain reactions release on average 0.267 MeV neutrinos, which implies a solar neutrino production of ~1.83 x 10^{38} s^{-1}, which results in a total neutrino power release of 4.89 x 10^{37} MeV/s, about 2.1% of the solar luminosity. Consideration of the unidirectional neutrino flux is quite problematic. One of the purposes of the Super-Kamiokande experiment [26,27] is to reveal the neutrino properties through the observation of solar neutrinos, atmospheric neutrinos and man-made neutrinos. While neutrino beams here on earth are created with intermediary particles that can be focused, doing this on a stellar scale seems questionable, we are considering that the total solar neutrino radiant power does not exceed 3% of total solar radiant power. Therefore, the neutrino power in the assumed unidirectional jet is 1.2 x 10^{25} W. Assuming that the relationship between the energy and momentum for massless photons also applies to massless neutrinos, the linear momentum change produced by the unidirectional neutrino jet approximates the required linear momentum change.

For stellar neutrino production to contribute to the apparent acceleration of main sequence stars along their galactic revolution trajectories, at least a portion of the emitted neutrinos must be aligned in a unidirectional jet. This requirement implies that terrestrial observers will observe a variation in neutrino flux with time. Although searches for such a variation have been attempted, none have been detected using current technology neutrino detectors [36]. It should also be noted that production of a focused neutrino beam on the stellar scale is very far in advance of any technology that can be imagined by contemporary terrestrial scientists.

3.8 Solar Wind Thermonuclear Fusion

Svoronos in Ref. [37] has proposed a high-performance stellar engine that is physically possible although technologically very difficult. This approach would fuse protons ejected in the solar wind enhanced by a star-lifting megastructure to produce helium nuclei and energy. Ejected as a unidirectional jet, the produced accelerated plasma could accelerate the star by 0.001c or 300 km/s after about 5,000 years.

One difficulty with this proposal is the very low proton-proton reaction cross section, as presented in Bussard's classic paper [38] on the proton-fusing interstellar ramjet. Recognizing this issue, Svoronos suggests application of the CNO catalytic fusion cycle because this catalytic reaction cycle is far easier to initiate than proton-proton fusing [37]. A technological difficulty with this approach, one shared by Whitmire's catalytic ramjet [39] is the necessity to retain carbon, nitrogen and oxygen atoms in the reaction chamber rather than ejecting them with the exhaust.

It should be pointed out that this process need not be exothermic. Stellar radiant output could conceivably be utilized by an advanced technology to provide energy to initiate the thermonuclear reactions in the CNO cycle.

To determine the effectiveness of this possibility in accelerating stars, we apply Einstein's mass-energy equivalence principle to estimate the energy ε per unit reacting mass M available to accelerate exhaust helium nuclei produced in the CNO fusion cycle:

$$\mathcal{E}/M = \beta\epsilon\eta c^2 \qquad (8)$$

where β is the burn fraction of reacting protons consumed in the CNO cycle, ε is the efficiency of mass-energy conversion, and η is the efficiency of energy transfer to the exhaust.

The burn fraction is taken as $\beta = 0.15$, similar to that of the BIS Daedalus conceptual interstellar fusion rocket [40,41]. The mass-energy conversion efficiency in the stellar interior is about $\varepsilon = 0.007$ [42]. It is assumed here that 50% of the released energy is transferred to the unidirectional exhaust jet. Substituting in Eq. (8) the values of β, ε η one obtains $\mathcal{E}/M = 4.7 \times 10^{13}$ J/kg. From the classical kinetic energy equation, the exhaust velocity is ~10^7 m/s. For this concept to apply to the application considered here, megastructure-induced star lifting is required to enhance the star's stellar wind, as suggested by Svoronos [37].

It is common knowledge that deuterium/deuterium and deuterium/helium-3 thermonuclear reactions for electrical power and spacecraft propulsion are almost within our technological capabilities. But because the cosmic concentrations of deuterium and helium-3 nuclei are less than 10^{-4}, a star's stellar wind must be greatly enhanced for these reactions to have application to stellar acceleration [43].

Further work might consider application of other stellar engine concepts to supply the required stellar acceleration. It is not impossible that terrestrial astronomers could obtain observational evidence for the existence of such accelerated megastructures.

4 CONCLUSIONS

In our study, we consider the stellar mass loss processes such as unidirectional or focused electromagnetic flux, galactic cannibalism, stellar mass loss by thermonuclear fusion, non-isotropic solar wind, accelerated unidirectional stellar wind, coronal mass ejections, unidirectional neutrino flux, solar wind thermonuclear fusion that can lead to the stellar acceleration reported in an evaluation of stellar kinematics from the first Gaia data release [3]. Stars apparently accelerate in their galactic revolution by 3×10^{-14} m/s^2. For stars like the Sun, this acceleration requires ~6×10^{16} N acceleration force.

In our analyses, all stars considered are similar to the Sun. This assumption is not entirely accurate since the Sun is brighter and more massive than most main sequence stars. However, this assumption allows consideration of various suggested modes of stellar acceleration based upon solar data, which is of course more accurate in many cases than corresponding data regarding other stars.

Our analyses demonstrate that the coronal mass ejections-induced stellar acceleration still varies far less than the required value to explain the stellar acceleration phenomenon. It is also reasonable to assume that stellar mass loss via thermonuclear fusion mass loss is not a likely explanation for the observed stellar acceleration. The galactic cannibalism can be rejected as a possible cause of stellar acceleration, and the acceleration due to the solar wind thermonuclear fusion also becomes unrealistic.

On the other side, the unidirectional photon jet ejected from the Sun can provide the stellar acceleration, but it is not enough for the enormous average acceleration force $F = 6 \times 10^{16}$ N. A non-isotropic stellar wind cannot account for the observed stellar acceleration because it provides only ~1.4×10^{15} N, a small fraction of the observed stellar linear momentum change. Our estimation based on Ref. [24] for CME rate indicates that the CME rates may be 10-100 times higher than we considered and further analysis of CME thrusting is important. Nevertheless, these three mechanisms can contribute a small fraction to the stellar linear momentum change.

As follows from our analyses the momentum change produced by the unidirectional neutrino jet approximates the required 6×10^{16} N stellar acceleration force and accelerated unidirectional stellar wind allows a linear momentum change of 6×10^{16} N as well. Thus, the latter two mechanisms in conjunction with the unidirectional photon jet ejected from the star and non-isotropic stellar wind can produce the stellar linear momentum change by ~6×10^{16} N that produces the stellar acceleration 3×10^{-14} m/s^2.

One should not assume that the eight mechanisms suggested and evaluated here in any way exhaust the field of possibilities. It is too soon in this effort to rule out any explanation for this apparent phenomenon. In this admittedly speculative paper, we have presented and evaluated a number of physical mechanisms that might explain the anomalous stellar acceleration reported in an evaluation of stellar kinematics from the first Gaia data release [3]. Hopefully, other experts in stellar kinematics will endeavor to verify or falsify this apparent stellar acceleration. Until verification or falsification of the apparent stellar acceleration is accomplished, scientists and others should keep an open mind regarding causative agencies for this apparent phenomenon. As we further explore our solar system, we must remain open to other possibilities. Some of the methods of stellar acceleration suggested above might provide evidence for the technosignatures of advanced galactic civilizations.

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