A POSSIBLE NEW SOLUTION TO THE FAINT YOUNG SUN PARADOX: THE ROLE OF SUPER SOLAR FLARE CORONAL MASS EJECTIONS ON DUST DYNAMICS IN EARLY PLANETARY WARMING.  
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1. Background: The assumed Earth-like habitability of exoplanets is often based on their position relative to their host stars, specifically within the so-called 'Goldilocks Zone' where solar luminosity is expected to be suitable for maintaining liquid surface hydrospheres [1]. However, these habitable zones are dynamic, evolving with changes in stellar infrared output over time, as demonstrated by Earth's 'Faint Young Sun Paradox (FYSP)'. This paradox contrasts the theoretical prediction of a globally glaciated state under an early Sun with approximately 70% of its current luminosity against geological evidence indicating a liquid hydrosphere on Earth at that time [2]. This discrepancy is primarily reconciled by suggesting enhanced greenhouse effects from gases like CO2 and CH4 [3], with their warming impact likely boosted by pressure broadening [4] and interactions with H2O vapor. The paradox is deepened by evidence of an early Mars with Earth-like hydrospheric features, including a northern ocean, ice sheets, and extensive fluvial systems [5]. We are exploring potential solutions to the FYSP that are independent of traditional luminosity considerations. This abstract introduces one such hypothesis currently being tested through various modeling approaches.

2. The Late Heavy Bombardment as a Densifier Mechanism of the Zodiacal Cloud

From approximately 3.9 to 3.8 billion years ago, the inner solar system underwent a period of intense asteroidal bombardment known as the Late Heavy Bombardment (LHB), leading to the heavily cratered landscapes still visible on Mercury, the Moon, and Mars [6]. Debate persists about the physical mechanisms behind the LHB, but it is widely thought to have been initiated the Jupiter-Saturn resonance crossing event during the migration of the giant planets, an event which is believed to have destabilized the planetesimal disk resulting in a sudden increase in the impact rate in the inner Solar System [6, 7]. Though not precisely quantified, the volumes of planetary mass ejected during the LHB were likely colossal, as indicated by the vast dimensions of impact basins such as the Martian northern plains [8] and the substantial thinning of Mercury’s crust from an impact event [9]. We propose that the ejected debris likely densified the zodiacal cloud. This proposition is reasonable given that the Lunar Dust Experiment on the LADEE (Lunar Atmosphere and Dust Environment Explorer) mission observed significant increases in the lunar dust cloud density following minor impact events [10]. The contribution of the Late Heavy Bombardment to the zodiacal cloud's dust likely included primary ejecta from planetary impacts along with secondary sources, encompassing material from debris collisions and phenomena such as outgassing and fragmentation within asteroids and comets. We are currently developing numerical models to determine the size distribution and material volumes ejected during the LHB, having as initial conditions the work of Kegerreis et al. [11].

3. Super Solar Flare Coronal Mass Ejections and Hypervelocity Acceleration of Zodiacal Dust Materials: The concept of dust ionization and depletion has been theorized for two decades [12] and was recently confirmed by observations from the Parker Solar Probe [13] during its passage through one of the most intense coronal mass ejections (CMEs) on record. The early Sun was characterized by frequent daily super solar flares [14], with events reaching kinetic energies of up to 1033 ergs [15] and producing CMEs with velocities of ≥1,000 km/s [14]. The bombardment of Earth by these high-energy particles could have transformed molecular nitrogen, carbon dioxide, and methane into potent greenhouse gas nitrous oxide, contributing to early paleoclimate warming [14]. Recent observations of short-timescale variations in the infrared emission of circumstellar disks suggest that CMEs can remove dust grains on timescales as short as a few days [16], suggesting that interplanetary dust can be accelerated to hyper-velocities by the high-energy particle streams. We suggest that the CMEs accompanying super solar flares early in the solar system’s history could have transferred considerable kinetic energy to the LHB-densified zodiacal dust, generating hyper-velocity dust flows away from the sun. *We are currently designing the simulations required to produce quantified parameters using a magneto-plasma / neutrals code, which self-consistently considers the momentum transfer between the plasma and neutrals [17].

3. Super Solar Flare Coronal Mass Ejections and Hypervelocity Acceleration of Zodiacal Dust Materials: We propose that fast-moving, ionized dust, upon being captured by the magnetic fields of Mars and Earth and funneled toward their polar regions, could
transform its kinetic energy into thermal energy during deceleration, significantly heating the atmosphere. For context, considering just a ton of dust influx at 100 km/s, the kinetic energy \( KE = 0.5 \times m \times v^2 \); results in in 500 trillion joules or 500 terajoules (TJ). This value exceeds the energies released by 'Little Boy' (63 TJ) and 'Fat Man' (88 TJ) from World War II. It is worth noting that contemporary studies estimate at ~15,000 tons of cosmic dust descend upon Earth annually [18]. We are developing models to examine how substantial atmospheric heat dissipation might have influenced early planetary climates, potentially addressing the FYSP. This approach is informed by the K-Pg boundary impact, where reentering ejecta produced intense thermal radiation, offering parallels for understanding early climate warming mechanisms [19].

4. Effects of a More Dynamic Ionosphere: The Earth's early ionosphere, shaped dynamically by factors like solar ionizing radiation, the interplanetary magnetic field, and solar wind, significantly impacted the magnetosphere. This interaction potentially led to magnetic reconnection at the dayside magnetopause [20], causing ohmic (Joule) heating in ionospheric plasma currents. Such heating likely molded the ionosphere and thermosphere [21], influencing the atmospheric temperature, ionization, density.

5. Galactic Cosmic Rays and a Highly Charged Ionosphere: Galactic Cosmic Rays (GCRs) could have intensified the ionization of early planetary ionosphere, leading to stronger electric fields in the lower atmosphere. This might have enhanced the efficiency of charged aerosols and particles as cloud condensation nuclei, boosting cloud formation. Increased cloudiness would facilitate dynamic hydrological cycles with frequent precipitation, cleansing the atmosphere of particulates. Consequently, a clearer atmosphere would emerge, permitting more solar radiation penetration and potentially affecting local weather and climate dynamics of early inner solar system planets.

6. Hypervelocity Vaporization on Planetary Atmospheres: During hypervelocity entry into planetary atmospheres, rapid dust vaporization of dust, leading to the dominance of vaporization over particulate retention [18], so it is unlikely that this process would have generated dusty atmospheres. We expect that this process will release diverse vapor compounds into the atmosphere. For example, silicate and organic vapors from clathdrites, volcanic-like gases such as sulfur dioxide and carbon monoxide from achondrites, and metallic vapors from iron meteorites, with stony-iron types adding a combination of metallic and silicate gases. Cometary and icy bodies would sublimate, releasing water vapor, CO\(_2\), methane, and various other organics. This complex gaseous mixture, engaging in intricate photochemical reactions, could have significantly augmented the greenhouse effect.

7. Impact of High-Energy Solar Particle Influx on Polar Seawater Vaporization: Our proposed process could have imparted substantial kinetic energy to seawater molecules at the poles, facilitating vaporization by disrupting the intermolecular hydrogen bonds. The resultant elevated emission of water vapor, a significant greenhouse gas, into the atmosphere could have led to pronounced tropospheric warming and fostered rainfall leading to the wet precipitation of aerosols and atmospheric particulate matter.

8. Implications: The early Martian hydrology indicates paleoclimatic conditions that could have supported a global hydrologic cycle and possibly an ocean for over 100 million years [5], with glacio-fluvial activity in the southern high-latitude regions [22] supporting our hypothesis of polar and circum-polar atmospheric warming and its effects on the early Martian climate. This concept also extends to exoplanets, suggesting that frequent CMEs from super solar flares could offer a climate-warming mechanism, enabling Earth-like habitable environments outside traditional Goldilocks zones, especially around young or faint stars. This has significant implications for understanding the habitability potential of exoplanets, potentially addressing the faint young sun paradox.