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The Faint Young Sun Paradox Revisited

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Abstract

We propose a plausible solution to the long-standing paleoclimatology puzzle known as the *Faint Young Sun Paradox* through a combined two-fold hypothesis that involves the conservation of the radiation balance between the Earth and the Sun, alongside the concept of an Expanding Earth Hypothesis (EHH). As solar luminosity increases, the Earth could maintain stable temperatures by adjusting the height of its atmosphere. This adjustment implies two possibilities depending on whether the solid Earth's radius is changing: 1) If the radius increases, the Earth would accrete matter from its surroundings (specifically from the solar wind), leading to an increase in the mass of its atmosphere. 2) If the radius decreases, the Earth would naturally expel matter from its atmosphere, resulting in a decrease in its effective mass. We demonstrate that if, as current ITRF observations suggest, the Earth's landmass is expanding globally at a modest rate of approximately $0.45 \pm 0.05\ \mathrm{mm{\cdot}yr^{-1}}$, and if the Earth's atmosphere has a vertical height of about one-third of the Earth's radius (approximately 2860 km from the surface), it becomes plausible to explain the presence of liquid water on the Earth's surface around 3.20 ± 0.70 Gyr ago during the *Archaean eon*, when the Sun was about 75% as luminous as it is today. Additionally, this framework can account for the current radial expansion rate of the Earth. Ultimately, we view the Earth system as an *auto-self-regulating incubator*, where this self-regulating mechanism arises from the Earth's atmosphere automatically adjusting its height in response to changes.

Keywords

Expanding Earth Hypothesis, Faint Young Sun Paradox, Solar Gravitational Anomalies

1. Introduction

In 1972, the renowned American astronomer, cosmologist, astrophysicist, astrobiologist, author, and one of history's greatest science communicators of all time—Carl Edward Sagan (1934 - 1996), along with his colleague George Mullen, brought attention to an apparent paradox regarding the evolution of the Sun and the supposed presence of liquid water on Earth's surface. This issue was highlighted for the first time in the world-renowned journal *Science* [1].

As noted by Donn *et al.* [2], Sagan and Mullen [1] were the first to popularize this problem within the broader scientific community. They pointed out that according to the then-newly established stellar evolutionary models, which describe stars like our Sun—models that remain valid today [see e.g., [3] [4]]—the Sun's energy output during the Archaean eon (approximately 3.80-to-2.50 Gyr ago) should have been around $\sim 0.75 L_{\odot}$. This output was considered insufficient to sustain liquid water on Earth's surface, contradicting geological evidence that suggests liquid water was indeed present [see e.g., Refs. [5] [6]].

This discrepancy raises the question of how a *Faint Young Sun* could have warmed the Earth enough to allow liquid water to exist, despite its apparently inadequate energy budget. Consequently, it is believed that the Earth should have had only frozen water, making the emergence of diverse life forms highly unlikely. This paleoclimatological dilemma is now commonly referred to as the *Faint Young Sun Paradox* (hereafter FYS-Paradox) [see e.g., Refs. [7]-[19], for various expositions of this paradox].

To address this apparent riddle, Sagan and Mullen [1] proposed that the Earth's atmosphere during the Archaean eon must have been rich in carbon dioxide (CO_2), suggesting that the resulting *Greenhouse Effect* [see e.g., Refs. [20] [21]] was responsible for warming our early planet. However, geological evidence indicates that atmospheric CO_2 concentrations during the Archaean and Proterozoic eons were likely too low to prevent the surface from freezing [see e.g., Refs. [6] [18] [22]].

The FYS-Paradox becomes even more intriguing when considering Mars, which we now know was once covered by oceans for extended periods during its early history [see e.g., Refs. [23]-[25]]. Mars receives only about half the incoming solar energy that Earth does [see e.g., Ref. [9]], raising further questions about how it could have supported liquid water under such conditions.

In closing this introductory section, we provide a synopsis of this reading, which is organized as follows: In the subsequent §(2), we discuss the proposed solutions to the FYSP. In §(3), we discuss the expanding Earth hypothesis. In §(4), we present a standard exposition of the derivation of the solar radiation balance equation. Following that, in §(5), we introduce a new concept of the effective radius of the Earth. Next, in §(6), we provide an improved *Solar Radiation Balance Equation* (SRB-Equation), where we also discuss the concept of a changing albedo for a radially expanding Earth and how this affects the SRB-Equation. In §(7), we examine the model of the Earth from the perspective of an effective average global temperature, maintaining a constant effective average global temperature, and the proposed solution to the FYS-Paradox is presented. Finally, in §(8), we offer a general discussion and draw conclusions from our findings.

2. Proposed Solutions

Proposed solutions to the *FYS-Paradox* include, but are not limited to:

1. ***Greenhouse Effects*** [see e.g., Refs. [16] [17] [19] [26] [27]] present a scenario where an enhanced greenhouse effect—*driven by carbon dioxide or methane*—coupled with geothermal heat from an initially much warmer terrestrial core, a significantly lower Earth albedo, and life developing in a cold environment under a 200 m thick ice sheet, among other factors, could explain past climatic conditions.

However, Kasting [18] notes that many of these greenhouse effect models have serious shortcomings. For instance, the greenhouse effect from methane appears to be self-limiting, and the geological record does not indicate sufficient carbon dioxide to support a significantly enhanced greenhouse effect in the past.

Furthermore, Rosing *et al.* [6] argue that an examination of Archaean sediments is inconsistent with the hypothesis of high greenhouse gas concentrations. They suggest that the moderate temperature range of Earth's system over the eons may instead be attributed to a lower surface albedo, resulting from reduced continental area and a lack of biologically induced cloud condensation nuclei. This would have led to greater absorption of solar energy, compensating for the lower solar output.

2. ***Astrophysical Influences*** [see e.g., Refs. [6] [14] [28] [29]]. For instance, Rosing *et al.* [6] [14] hypothesize that a lower Earth albedo, resulting from considerably less continental area and a lack of biologically induced cloud condensation nuclei, played a significant role in moderating surface temperatures during the Archaean eon. They further suggest that this lower albedo allowed for environmental conditions above the freezing point of water, thereby reducing the necessity for extreme greenhouse gas concentrations to resolve the FYS-Paradox. In a similar vein—*though from a different perspective*—our proposed model also incorporates a lower albedo for the early Earth, which we argue results from a smaller Earth that gradually expands over time.

3. ***Active Young Sun Hypothesis*** [30]. Using κ^1-*Ceti* as a comparison for the young Sun, Karoff [30] argues that not only was the young Sun significantly more effective at protecting the Earth's environment from galactic cosmic rays than the present-day Sun, but it also exhibited flare and coronal mass ejection rates up to three orders of magnitude greater than those of today.

Through the mechanism known as the *Forbush Effect*—named after American astronomer, physicist, and geophysicist Scott Ellsworth Forbush (1904 - 1984), who studied galactic cosmic rays in the 1930s and 1940s—Karoff [30] contends that these immense coronal mass ejection rates of the young Sun could have had a profound impact on the young Earth's climate. Specifically, a young, faint but active Sun producing a higher frequency of coronal mass ejections would have resulted in fewer cosmic rays reaching Earth. This reduction in cosmic rays would lead to less cloud cover, allowing for greater sunlight penetration and thereby creating a warmer environment for nascent life to thrive.

4. ***Massive Young Sun Hypothesis*** [see e.g., Refs. [9] [15] [31]]. In this scenario, a somewhat more massive young Sun with a significant mass loss rate $\left(\gtrsim 10^{-11} M_{\odot}\,\mathrm{yr}^{-1}\right)$ sustained for two to three billion years is assumed. Such a massive young Sun, bright enough to prevent both the terrestrial and Martian oceans from freezing, is thought to resolve the paradox. For instance, Martens [9] finds that a large and sustained mass loss is consistent with the well-observed spin-down rate of Sun-like stars and may indeed be necessary for it.

However, according (*e.g.*) to Wood *et al.* [32], Gaidos *et al.* [33], and Guzik *et al.* [34], such large mass loss rates contradict both solar evolutionary models calibrated using helioseismology [34] and measurements of stellar winds around Solar-type stars [32] [33]. This discrepancy highlights the challenges in reconciling the proposed mass loss rates with established astrophysical models.

5. ***Closer Earth Hypothesis.*** From an astrometric perspective, a plausible solution is that the Earth may have been significantly closer to the Sun, at approximately ~95.6% [10] of its current heliocentric distance. This proximity would enable the Earth to receive the necessary radiation intensity to sustain liquid water on its surface. Over time, as solar luminosity increases, the Earth-Moon system would need to slowly recede from the Sun at a precise rate to maintain stable temperatures.

In this scenario, Iorio [10] posits that the change in the mean heliocentric distance of the Earth, $\delta r_{\oplus}(t)/r_{\oplus}(t)$, must be correlated with the change in solar luminosity, $\delta L_{\odot}(t)/L_{\odot}(t)$, as follows:

$$\frac{\delta r_{\oplus}(t)}{r_{\oplus}(t)}=\frac{\delta L_{\odot}(t)}{L_{\odot}(t)}. \tag{1}$$

However, according (*e.g.*) to Pitjeva [35] [36], Standish [37], and Krasinsky *&* Brumberg [38], the currently measured recessional rate of the Earth from the Sun of (7.00 - 15.00) cm/yr is insufficient [10] [11] to support the concept of a Closer-Earth-to-the-Sun scenario that could explain the presence of liquid water during the Archaean eon, as this would necessitate a rate as high as ~180 cm/yr, or 30-70 times the currently measured recessional rate. Assuming a steady recessional rate of (7.00 - 15.00) cm/yr since the Archaean eon, it follows that:

$$\frac{\delta r_{\oplus}(t)}{r_{\oplus}(t)}=(3.00\text{ - }1.00)\times 10^{-5}. \tag{2}$$

In comparison, $\delta L_{\odot}(t)/L_{\odot}(t)$ is four orders of magnitude larger than $\delta r_{\oplus}(t)/r_{\oplus}(t)$. This indicates that the secular drift of the Earth from the Sun at (7.00 - 15.00) cm/yr cannot account for the sustenance of liquid water during the Archaean eon up to the present day. If a closer Earth is indeed the solution to the FYS-Paradox, then an additional mechanism would be necessary to explain the continued recession of the Earth from the Sun [10] [11].

Before concluding this subsection, it is worth noting that several recent studies have explored the possibility that the expansion of the Solar System may be linked to cosmological expansion driven by dark energy [39] [40]. In these frameworks, the secular increase in the Earth-Sun distance is not merely a tidal effect but could be influenced by changes in the cosmic gravitational field. Such a scenario, if valid, would imply that the Earth's gravitational field—and consequently its internal structure and radius—might also evolve over cosmic timescales. Thus, the Expanding Earth Hypothesis, as proposed in the present work, may find a deeper theoretical foundation within cosmological models that couple local gravitational dynamics to the expansion of the Universe. While a detailed exploration of this connection lies beyond the scope of the present paper, we acknowledge its potential relevance and encourage future investigations along these lines.

Extensive reviews on this topic have been conducted, with relatively recent contributions from Iorio [11] [10] and Feulner [41]. The FYS-Paradox not only remains an *Open Question*, but also constitutes an active area of research where a solution is eagerly sought [see e.g., Refs. [7]-[19]]. In this endeavor, we propose a completely new solution to this long-standing and intriguing riddle. Our approach focuses on *Astrophysical Influences*, framing the Earth system as an auto-self-regulating incubator that adjusts its albedo in response to changes in solar luminosity.

As already mentioned earlier, the Archaean eon occurred approximately t_A ~(3.80 to 2.50) Gyr ago. For the sake of convenience in calculations, we need a single value for t_A instead of a range. Therefore, we will take the average of the Archaean eon period: t_A ~(3.80 to 2.50) Gyr, which is calculated as (3.80 + 2.50) Gyr/2 = 3.15 Gyr. The upper and lower limits (the range or 'error') will be based on the average of the difference $t_A \sim (3.80 - 2.50)\,\mathrm{Gyr}$, resulting in (3.80 - 2.50) Gyr/2 = 0.65 Gyr. Thus, we define $t_A = (3.20 \pm 0.70)\,\mathrm{Gyr}$ as representative of the time when the Archaean eon occurred, with the upper and lower limits indicated by the 'error' bars—the error bar covers the range [$t_A^{initial} = 2.50\,\mathrm{Gyr}$, to $t_A^{final} = 3.80\,\mathrm{Gyr}$] of the Archaean eon.

At this point, it is important to state that in this work, we will demonstrate (and propose) a solution based on the currently observed radial expansion rate of the solid Earth, as reported in the peer-reviewed literature [42]-[44]. We will assume that this rate has remained steady throughout the ages. With this radial expansion of the Earth, we can explain the stable temperatures for the Earth system by positing that since the Archaean eon, the Earth as a system:

> *has maintained a state of radiation balance between the energy it receives and the energy it emits. This fundamental assumption, that the radiation balance within the Earth system is conserved, will be referred to as the* ***Solar Radiation Balance Equilibrium Hypothesis*** *(RBE-Hypothesis).*

With steady temperatures achieved over the eons *via* the RBE-Hypothesis, we can account for the diversity of life observed today on Earth, which traces back to as far as the Archaean eon.

3. Expanding Earth Hypothesis

The esteemed German polar researcher, geophysicist, and meteorologist Alfred Lothar Wegener (1880 - 1930) was the first to propose the controversial idea of the *Expanding Earth Hypothesis* (EEH). This bold hypothesis emerged when Wegener observed that the various continental landmasses of the Earth, or continental plates, fit together almost seamlessly like pieces of a perfect jigsaw puzzle. He argued that these continents are gradually drifting across the Earth's surface, attributing this movement to the solid Earth expanding radially outward on a global scale.

However, Wegener faced significant challenges in identifying a viable energy source to drive this hypothesized expansion, leading to considerable resistance from the scientific community [see e.g., Refs. [45]-[48]]. As a result, his ideas were largely dismissed. Despite this, Wegener's theories captivated the imaginations of many curious minds [see e.g., Refs. [49]-[53]]. It was not until the 1950s, with discoveries such as paleomagnetism providing strong support for continental drift, that Wegener's concepts began to gain traction, forming a substantial foundation for the modern model of plate tectonics [46]. While the notion of continental drift was ultimately accepted and is now regarded as a cornerstone of modern geophysics, the idea of an expanding Earth has been vehemently rejected and continues to face skepticism today [see e.g., Refs. [54]-[56]].

Nevertheless, while the majority of scientists today vehemently deny the concept of an expanding Earth, we will demonstrate that this idea presents an intriguing solution to the FYS-Paradox. Interestingly, in light of this, evidence for an expanding Earth appears to be surfacing in the '*not-so-distant horizons*' of observational science [42]-[44] [57]-[62]. Efforts are being made to explore whether the Earth is indeed expanding, with several initiatives aiming to bring this idea to the forefront of scientific discourse, such as those by Scalera [63]-[66].

For instance, Wu *et al.* [58] conducted direct measurements using data from the International Terrestrial Reference Frame (ITRF), a crucial reference for precision orbit tracking, navigation, and global change monitoring. This data integrates information from Satellite Laser Ranging (SLR), Very Long Baseline Interferometry (VLBI), Global Positioning System (GPS), and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), with its current origin primarily derived from SLR. Contrary to the expectations of EEH proponents, Wu *et al.* [58] found no significant change in the Earth's mean radius, reporting an uncertainty of 0.20 $\text{mm}\cdot\text{yr}^{-1}$ at the 1σ level of statistical significance. On a more optimistic note, Shen *et al.* [42] [44] also claim to have found evidence of an expanding Earth.

Specifically, similar to Wu *et al.* [58], Shen *et al.* [44] utilized ITRF-2008 space-geodetic data collected over more than 10 years from globally distributed stations (including GPS, VLBI, SLR, and DORIS). Their calculations suggest that the Earth is expanding at a rate of approximately $+0.24 \pm 0.04$ $\text{mm}\cdot\text{yr}^{-1}$. This implies a change in the Earth's radius from the Archaean eon to the present day of:

$$\frac{\delta R_{\oplus}(t_0)}{R_{\oplus}(t_0)} = +0.10 \pm 0.02, \tag{3}$$

indicating that, if Shen *et al.* [44]'s findings are accurate, the Earth has experienced a 10% radial increase since the Archaean eon. Here and after, the symbol δ in Equation (3) will be understood to represent changes since the Archaean eon.

Furthermore, based on the *Earth Gravitational Model 2008*, Shen *et al.* [44] identified secular variation rates of the second-degree coefficients estimated through SLR and Earth mean-pole data, revealing that the principal inertia moments of the Earth are gradually increasing. This observation underscores the notion that the Earth is indeed expanding, at least over recent decades. They found expansion rates ranging from approximately +0.17 ± 0.02 mm·yr^{-1} to +0.21 ± 0.02 mm·yr^{-1}, aligning with space geodetic evidence. Consequently, Shen *et al.* [44] concluded that the Earth has been expanding at a rate of about +0.20 mm·yr^{-1} over the past decade.

In a subsequent study, Shen *et al.* [42] reported even more favourable results for the expanding Earth theory. Using ITRF-2008 data spanning 20 years, they revised their previous estimate to about +0.24 ± 0.50 mm·yr^{-1}. Their findings indicated that sea level is rising at a rate of approximately +3.20 ± 0.40 mm·yr^{-1}, of which +1.84 ± 0.50 mm·yr^{-1} is attributed to melting ice on land. Additionally, they found that oceanic thermal expansion due to temperature increases over the past half-century is estimated at about +1.00 ± 0.10 mm·yr^{-1}.

Shen *et al.* [42] noted that this sea level rise is not entirely balanced by the effects of ice melting and thermal expansion, presenting an open question in their study. However, they inferred that the oceanic portion of the Earth is expanding at a rate of approximately +0.40 mm·yr^{-1}. By combining the expansion rates of both land and oceanic components, they concluded that, at least over the last two decades, the Earth has been expanding at a rate of approximately +0.35 ± 0.47 mm·yr^{-1}. Furthermore, they posited that if the Earth expands at this rate, it could satisfactorily account for the observed sea level rise. Notably, this expansion rate of about +0.35 ± 0.47 mm·yr^{-1} is ~145% (nearly one and a half times) larger than their previous estimate of +0.24 ± 0.05 mm·yr^{-1}, representing a significant advancement for proponents of the EEH.

Based on the published work of Shen *et al.* [42]-[44], it seems that those who have long declared the demise of the EEH may need to reconsider their stance. For our purposes, we will focus on the landmass expansion, adopting the published value of about +0.45 ± 0.05 mm·yr^{-1} from Shen *et al.* [43] as representative of the current global expansion rate of the Earth. This result corresponds to:

$$\frac{\delta R_{\oplus}(t_0)}{R_{\oplus}(t_0)} = +0.23 \pm 0.07. \tag{4}$$

At this juncture, we believe we have not only motivated but also justified the validity of the EEH as a working hypothesis.

Thus, in concluding this section, we would like to emphasize that, according to the Expanding Earth and Solar Radiation Balance Equilibrium model proposed herein, the measured solid Earth expansion rate reported by Shen *et al.* [43] in Equation (4) aligns well with the notion of a young, faint Sun that was ~75% of its current luminosity during the Archaean eon, along with an Earth that possessed liquid water and maintained steady global mean surface temperatures of 288.15 K until the onset of the Anthropocene epoch[1].

4. Radiation Balance Equation

As is well known and previously mentioned, the mean global temperature of the Earth's surface has remained remarkably constant over geological epochs. This stability is primarily inferred from isotopic analyses of the Mg/Ca ratio in foraminiferal tests, alkenones[2], and particularly from δ^{18}O measurements [68]. Even the significant cooling during the *Ice Age*[3] resulted in a temperature change of only about $\lesssim 1\%$, equating to approximately 3 K in global average surface temperature, occurring over thousands of years. While seasonal temperature fluctuations can be substantial in specific locations, they correspond to very minor changes in the overall mean global temperature.

To sustain this long-term temperature stability, the Earth must radiate an energy flux into space that is sufficient to balance the incoming solar energy. This implies that, to a good degree of approximation, the Earth has been, and likely continues to be, in radiative equilibrium with the solar radiation it receives. This concept is relatively straightforward to understand.

Table 1. Effective and Actual Temperatures of Mercury, Venus, Earth & Mars: Column (1)-(6) gives the name of the planet, its radius, orbital semi-major axis, its albedo, the actual global average temperature $T_a(t_0)$, the expected global average temperature $T_{pl}(t_0)$ in-accordance with Equation (11), and the last column (7) gives the difference $\left[T_a(t_0) - T_{pl}(t_0)\right]$ in actual and expected global average temperatures of the listed planets.

Planet	Radius ($R_\oplus$)[a]	Semi-major axis (1AU)[a]	Albedo[b]	$T_a(t_0)$ (K)[c]	$T_{pl}(t_0)$ (K)	$T_a(t_0) - T_{pl}(t_0)$ (K)
Mercury	0.38	0.39	0.12	440.15	433.53	6.62
Venus	0.95	0.72	0.75	737.15	231.53	505.62
Earth	1.00	1.00	0.29	288.15	255.62	32.53
Mars	0.53	1.52	0.16	208.15	215.99	-7.84

Notes.—Adapted from: [a]https://nssdc.gsfc.nasa.gov/planetary/factsheet/index.html.
[b]http://astronomy.swin.edu.au/cosmos/A/Albedo .

By absorbing incoming Solar radiation, the Earth warms up, resulting in a corresponding rise in temperature. If the Earth lacked an atmosphere or oceans, like the

[1]The Anthropocene epoch is a proposed epoch marking the present time, beginning in the mid-20th century, when human activities began to significantly impact ecosystems and climate.

[2]Alkenones are long-chain unsaturated methyl and ethyl n-ketones produced by certain phytoplankton species from the class Prymnesiophyceae [67].

[3]The Ice Age is thought to be a prolonged period of reduced temperatures in Earth's climate, leading to the expansion of continental ice sheets, polar ice sheets, and mountain glaciers. Evidence for ice ages is categorized into geological, chemical, and paleontological types.

Moon, the sunlit side would become very warm, while the dark side would be much colder than our current experience. The slight warmth on the dark side would come from the minimal heat stored in the ground from sunlight during the previous day—similar to conditions in a cloud-free, landlocked desert climate on Earth.

Furthermore, according to the Stefan-Boltzmann Law [69] [70], all heated objects emit electromagnetic radiation, especially when surrounded by empty space. This radiation is known as outgoing radiation. As long as the incoming radiative flux exceeds the outgoing radiation, the object will continue to warm, causing its temperature to rise. This increase in temperature leads to a corresponding rise in outgoing radiation (as per the Stefan-Boltzmann Law, outgoing radiation increases at a faster rate than temperature). Eventually, the object will reach a point where it emits as much radiation as it receives, establishing a state of radiative equilibrium. The fact that the Earth has maintained and continues to maintain quasi-steady temperatures indicates that it is, in one way or another, in a state of equilibrium with the life-giving and life-sustaining solar radiation it receives.

Now, in-order to compute this state of radiation balance, let: $L_{\odot}(t) = 4\pi\sigma R_{\odot}^{2}(t)T_{\odot}^{4}(t)$, be the Solar luminosity at time t, with σ_0 being the usual Stephan-Boltzmann constant, $R_{\odot}(t)$ the Solar radius at time t, $T_{\odot}(t)$ the Solar temperature at time t; and let $r_{\oplus}(t)$ be the mean distance of planet Earth (or any given planet) from the Sun at time t. The total Solar flux: $F_{\odot}(r,t)$, arriving at the spherical shell of radius r centred about the Solar center is such that:

$$F_{\odot}(r,t) = \frac{L_{\odot}(t)}{4\pi r^{2}(t)} = \sigma_0\left(\frac{R_{\odot}(t)}{r_{\oplus}(t)}\right)^{2} T_{\odot}^{4}(t). \tag{5}$$

The total Solar energy arriving at Earth per second [Power: $P_{\oplus}(t)$] can be calculated by multiplying $F_{\odot}(r,t)$ by the cross-sectional area (not the total surface area!) of the solid Earth $\left[\pi R_{\oplus}^{2}(t)\right]$, *i.e.* the area of Solar beam intersected by the solid Earth. That is to say, $P_{\oplus}(t) = \pi F_{\odot}(r,t) R_{\oplus}^{2}(t)$.

Not all Solar radiation intercepted by the Earth is absorbed by the Earth system—a good fraction of it is reflected back into space. The fraction of incident Solar radiation reflected is defined as the *albedo* and denoted by the symbol A, and the fraction absorbed by the Earth at time t is therefore $\left[1 - A_{\oplus}(t)\right]$. The effective power $P_{\oplus}^{\mathrm{abs}}(t)$ absorbed by the Earth system is therefore given by:

$$P_{\oplus}^{\mathrm{abs}}(t) = \pi\left[1 - A_{\oplus}(t)\right] F_{\odot}(r,t) R_{\oplus}^{2}(t). \tag{6}$$

According to the Stefan-Boltzman Law, the total energy emitted by the solid Earth per unit area is given by $\epsilon_{\oplus}\sigma_0 T_{\oplus}^{4}(t)$, where, $\epsilon_{\oplus}$ is the emissivity[4] of the

[4]The emissivity of the Earth shall here be assumed to be unity [71, 72, cf.,]. Taken to the letter, this is obviously not correct because emissivity is defined as the ratio of the energy radiated from a material's surface to that radiated from a blackbody (a perfect emitter) at the same temperature, wavelength and under the same viewing conditions. This ratio varies from 0 to 1, with ($\epsilon = 1$) for a perfect blackbody and ($\epsilon = 0$) for a perfect absorber. The emissivity is dependent on the type of surface and many climate models set the value of the Earth's emissivity to 1. However, a more realistic value is ~0.96 [e.g., [71] [72]].

solid Earth. The emitting total area is the surface area of the solid Earth, $4\pi R_{\oplus}^{2}(t)$, therefore, the total energy emitted by the solid Earth per second is:

$$P_{\oplus}^{\mathrm{emit}}(t) = 4\pi\epsilon_{\oplus}\sigma_0 T_{\oplus}^{4}(t) R_{\oplus}^{2}(t). \tag{7}$$

This energy balance requires that (*Incoming Radiation* = *Outgoing Radiation*) so that when averaged over eons, we will have:

$$P_{\oplus}^{\mathrm{abs}}(t) = P_{\oplus}^{\mathrm{emit}}(t), \tag{8}$$

thus:

$$4\pi\sigma_0 T_{\oplus}^{4}(t) R_{\oplus}^{2}(r,t) = \pi\left[1 - A_{\oplus}(t)\right] F_{\odot}(r,t) R_{\oplus}^{2}(t). \tag{9}$$

This deceptively simple looking Equation (9) is the trivial *Solar Radiation Balance Equation*. It can be solved for the average temperature, $T_{\oplus}(t)$, at which the Earth must emit radiation to bring the energy budget into balance. This temperature is called the effective temperature of the planet. *i.e.*:

$$T_{\oplus}(t) = \left(\frac{\left[1 - A_{\oplus}(t)\right] F_{\odot}(r,t)}{4_0}\right)^{1/4}. \tag{10}$$

This Eq. (10) can further be re-written so that it reads:

$$\begin{aligned} T_{\oplus}(t) &= \left(\frac{1 - A_{\oplus}(t)}{4\varepsilon_{\oplus}\sigma_0} \frac{L_{\odot}(t)}{4\pi r_{\oplus}^{2}(t)}\right)^{1/4} \\ &= \left(\frac{\left[1 - A_{\oplus}(t)\right] S_{\odot}(t)}{4\varepsilon_{\oplus}\sigma_0}\right)^{1/4}, \end{aligned} \tag{11}$$

where: $S_{\odot}(t) = L_{\odot}(t) / 4\pi r_{\oplus}^{2}(t)$, is the *Solar constant* or *Solar irradiance* at time t, and this important quantity is measured by satellites orbiting above the Earth's atmosphere at 1.00 AU, and its current accepted value is: $1360.80 \pm 0.50\ \mathrm{W} \odot \mathrm{m}^{-2}$ [73].

As can be read off from column (3) of **Table 1**, an application of Equation (11) to the Earth system, the effective temperature of the Earth is found to be: ~255.52 K, and this temperature is: ~32.53 K, below that which is actually measured for the mean global temperature, which is: ~288.15 K. The: ~32.53 K, discrepancy between theory and observation is usually attributed to the fact that effects such as the greenhouse effect are not included in the derivation of Equation (11). From this same **Table 1**, it is seen that even for the other planets—Mercury, Venus and Mars, there exists discrepancy between theory and observation. As is the case with the Earth system, the reason given for this discrepancy is that the derivation of Equation (11) does not include all the processes at play. All in an effort to improve on Equation (11), we shall in the subsequent section, give a critic of the derivation of the Solar Radiation Balance Equation (11).

5. Critic to the Radiation Balance Equation

In the derivation of the RB-Equation (10), a significant issue arises: the fact that the Earth has an atmosphere is not taken into account. Our discussion of this enduring fact will reference **Figure 1**. It is clear that we must state that:

> '*the fact that the Earth has an atmosphere is not considered in the derivation of the RB-Equation (10),*'

and this so—because, only the Light rays travelling through the region HCDG are included, while those in the regions ABCH and FGDE are overlooked.

We know that the Earth's atmosphere has a higher refractive index than the Solar interplanetary medium. From centuries of studying optical phenomena, it is evident that Light rays striking the boundary of the Earth's atmosphere will be refracted into it. Once inside, these rays become trapped, with only those scattered perpendicularly by the Earth in the region HCDG able to escape back into interstellar space.

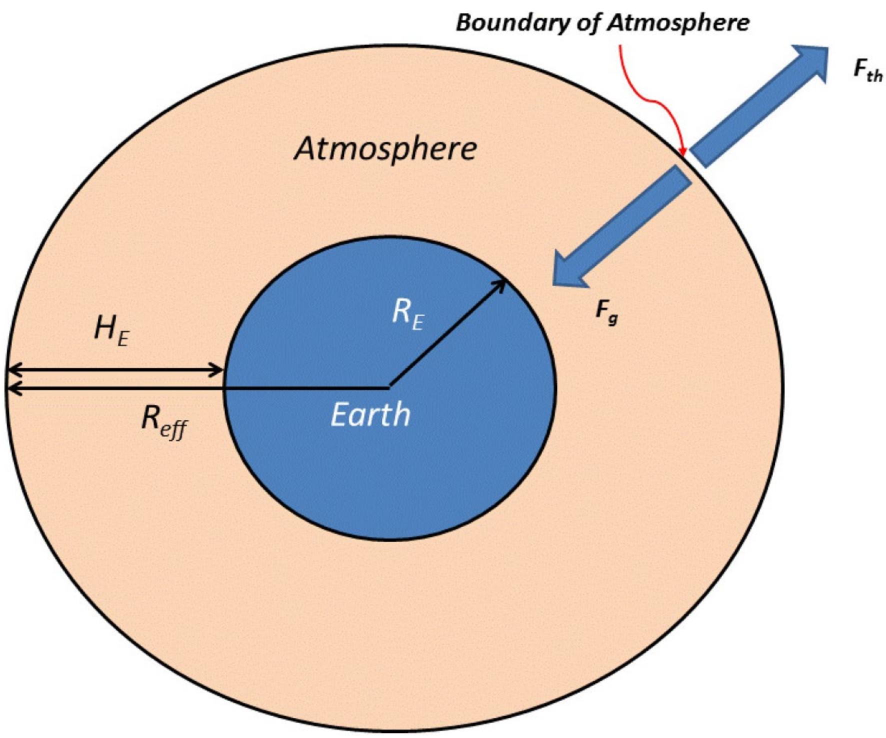

Figure 1. **Effective Radius of the Earth:** The boundary of the Earth's atmosphere is here defined as the surface where the Earth's gravitational force, $\boldsymbol{F}_{\mathrm{g}}$, acting on an atmospheric molecule exactly balances the thermal force, $\boldsymbol{F}_{\mathrm{th}}$, due to the atmospheric pressure on the molecule, *i.e.*: $\boldsymbol{F}_{\mathrm{g}} = \boldsymbol{F}_{\mathrm{th}}$.

5.1. New Definition of the Earth's Albedo

In this new model of the Earth's atmosphere described above, the albedo of the Earth is no longer the typical surface albedo we are accustomed to, which is based on the optical properties of the materials composing the Earth. Instead, the new albedo simply becomes the ratio of the solid Earth's cross-sectional area to that of its atmosphere, that is:

$$A_{\oplus}(t) = \frac{R_{\oplus}^2(t)}{R_{\mathrm{eff}}^2(t)}. \tag{12}$$

Thus, a new model of the Earth's atmosphere emerges, in which the atmosphere plays a central, critical, and pivotal role in sustaining stable mean global surface temperatures.

5.2. Effective Radius of the Earth System

If the Earth's atmosphere is not ignored but taken into account, then, the effective radiation capture radius $\left[R_{\text{eff}}(t)\right]$ of the Earth system in Equation (9) will not be equal to the radius of the solid Earth, but, will be equal to the radius of the solid Earth plus the size $H_{\text{atm}}^{\oplus}(t)$ of the Earth's atmosphere—*i.e.*:

$$R_{\text{eff}}(t) = R_{\oplus}(t) + H_{\text{atm}}^{\oplus}(t). \tag{13}$$

Figure 2 depicts this idea of an effective Earth radius that takes into account the Earth's atmosphere. Therefore, we need to make a correction for this because the atmosphere will certainly capture some radiation. In the next section, we construct a new model based on the criticism here given.

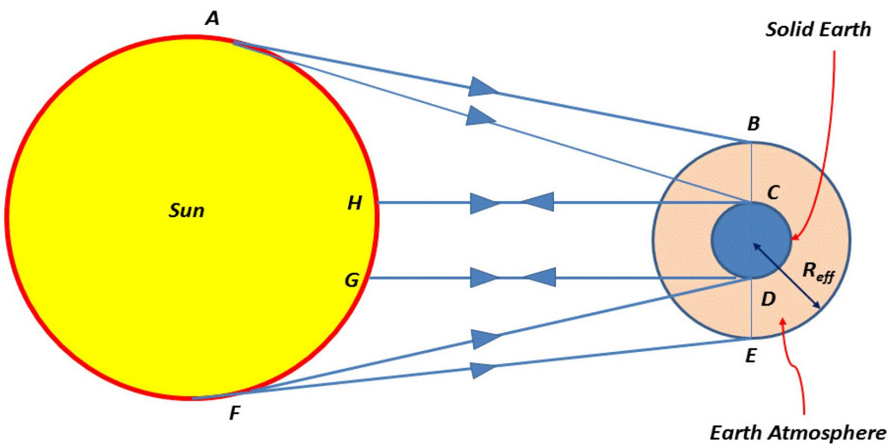

Figure 2. Diagram of Proposed Sunlight Capture of the Earth System: Sunlight hitting the Earth's atmosphere experiences partial reflection and refraction. The refracted rays are absorbed, while the reflected rays vanish into the void of space. Of the Light absorbed by the Earth's atmosphere, only the photons reflected back into space are those that are reflected perpendicularly to the Earth's surface in the region labelled as HCDG.

5.3. Boundary of Earth's Atmosphere

Once we talk of an atmospheric height, $H_{\text{atm}}^{\oplus}(t)$, the most immediate question becomes: What is the value of $H_{\text{atm}}^{\oplus}(t)$? The honest truth is that, the height of the Earth's atmosphere is not well known and most often the *Kármán line*, at ~100 km, [*i.e.*, $0.0157R_{\oplus}(t_0)$] is often used as the border between the atmosphere and outer space. This is so because atmospheric effects become noticeable during re-entry of spacecraft at an altitude of around ~120 km. This definition is accepted by the *Fédération Aéronautique Internationale*[5] (FAI). Be that as it may, from

[5]Founded on Saturday 14 October 1905 and headquartered in, Lausanne—Switzerland, the *Fédération Aéronautique Internationale*, is the *World Governing Body* for air sports. The FAI maintains world records for aeronautical activities including ballooning, aeromodeling, and unmanned aerial vehicles; and also for human spaceflight. *Official Website*: https://www.fai.org/

physics principles, we can and shall define a boundary for the Earth's atmosphere.

To that end, if—as is the case, the Earth system is a gravitationally bound system, the boundary of the Earth's atmosphere can then be defined as being the surface where the inward gravitational force, $F_{\mathrm{g}}(t)$, acting on a unit mass, $m_*(t)$, of the Earth's atmosphere is equal to the outward thermal force, $F_{\mathrm{th}}(t)$, emanating from the Earth's atmospheric thermal pressure, $P_{\mathrm{atm}}^{\min}(t)$: where $P_{\mathrm{atm}}^{\min}(t)$ is the atmospheric pressure at the said boundary—at time, t. The unit mass, $m_*(t)$, of air, is the usual *molar mass of air*, and, at present: $m_*(t_0) = 0.0289644\ \mathrm{kg \cdot mol^{-1}}$. Of the molar mass of air, if $m_{\mathrm{atm}}(t)$ is the total mass of the Earth's atmosphere and $N_{\mathrm{atm}}(t)$ is the total number of molecules making up this atmosphere, then: $m_*(t) = m_{\mathrm{atm}}(t)/N_{\mathrm{atm}}(t)$.

Now—we know that:

$$F_{\mathrm{g}}(t) = \frac{GM_{\oplus}(t)m_*(t)}{R_{\mathrm{eff}}^2(t)}, \tag{14}$$

where: G, is the usual Newtonian constant of gravitation. Further, we know that: $F_{\mathrm{th}}(t) = 4\pi R_{\mathrm{eff}}^2(t)P_{\mathrm{atm}}^{\min}(t)/N_{\mathrm{atm}}(t)$. In general, within the bounds of the Earth's atmosphere, the pressure: $P_{\mathrm{atm}}(h,t)$, at height: h, at an epoch time: t, is such that: $P_{\mathrm{atm}}(h,t) = P_{\mathrm{atm}}^{\mathrm{surf}}(t)\mathrm{e}^{-4h/H_0^{\oplus}}$, where: $P_{\mathrm{atm}}^{\mathrm{surf}}(t)$, is the surface pressure and: $H_0^{\oplus}(t) = k_{\mathrm{B}}T_{\oplus}(t)/4m_*(t)\mathrm{g}_{\oplus}^{\mathrm{surf}}(t)$, is a constant. This Law $\left[P_{\mathrm{atm}}(h,t) = P_{\mathrm{atm}}^{\mathrm{surf}}(t)\mathrm{e}^{-4h/H_0^{\oplus}}\right]$, is known as the *Law of Atmospheres* and is also known as the *Barometric Law* [e.g., [74]]. From the foregoing, it follows that:

$$F_{\mathrm{th}}(t) = \frac{4\pi R_{\mathrm{eff}}^2(t)P_{\mathrm{atm}}^{\mathrm{surf}}(t)\mathrm{e}^{-4H_{\mathrm{atm}}^{\oplus}(t)/H_0^{\oplus}}}{N_{\mathrm{atm}}} \tag{15}$$

In-order to calculate: $P_{\mathrm{atm}}^{\mathrm{surf}}(t)$, we know that the mass, $m_{\mathrm{atm}}^{\oplus}(t)$ of the Earth's atmosphere [see e.g., 75, p.13] is related to the Earth's mean global surface pressure, $P_{\mathrm{atm}}^{\mathrm{surf}}(t)$, and the Earth mean surface gravitational acceleration, $\mathrm{g}_{\oplus}^{\mathrm{surf}}(t)$, by the following formula:

$$P_{\mathrm{atm}}^{\mathrm{surf}}(t) = \frac{m_{\mathrm{atm}}^{\oplus}(t)\mathrm{g}_{\oplus}^{\mathrm{surf}}(t)}{4\pi R_{\oplus}^2(t)} = \frac{GM_{\oplus}^{\mathrm{SE}}(t)m_{\mathrm{atm}}^{\oplus}(t)}{4\pi R_{\oplus}^4(t)}. \tag{16}$$

Given that: $R_{\oplus}(t_0) \simeq 6.40\times10^6\ \mathrm{m}$, $\mathrm{g}_{\oplus}^{\mathrm{surf}}(t_0) \simeq 9.80\ \mathrm{m/s^2}$, and: $P_{\mathrm{atm}}^{\mathrm{surf}}(t_0) = 101.325\ \mathrm{kPa}$, one obtains for the mass of the Earth's atmosphere: $m_{\mathrm{atm}}^{\oplus}(t_0) \simeq 5.80\times10^{18}\ \mathrm{kg}$, where *here-and-after*, t_0 represents time in the present epoch. This result: $m_{\mathrm{atm}}^{\oplus}(t_0) \simeq 5.80\times10^{18}\ \mathrm{kg}$, is the widely accepted mass of the Earth's atmosphere [see e.g., [75]-[77]].

Now, substituting: $P_{\mathrm{atm}}^{\mathrm{surf}}(t)$, as given in Equation (16), into Equation (15), we will have:

$$\begin{aligned} F_{\mathrm{th}}(t) &= \frac{GM_{\oplus}^{\mathrm{SE}}(t)m_{\mathrm{atm}}^{\oplus}(t)R_{\mathrm{eff}}^2(t)\mathrm{e}^{-4H_{\mathrm{atm}}^{\oplus}(t)/H_0^{\oplus}(t)}}{N_{\mathrm{atm}}(t)R_{\oplus}^4(t)} \\ &= \frac{GM_{\oplus}^{\mathrm{SE}}(t)m_*(t)R_{\mathrm{eff}}^2(t)\mathrm{e}^{-4H_{\mathrm{atm}}^{\oplus}(t)/H_0^{\oplus}(t)}}{R_{\oplus}^4(t)}, \end{aligned} \tag{17}$$

where, as afore-stated: $m_*(t) = m^{\oplus}_{\rm atm}(t)/N_{\rm atm}(t)$, thus from the condition that at the boundary: $F_{\rm g}(t) = F_{\rm th}(t)$, it follows that:

$$\frac{R_{\oplus}(t)}{R_{\rm eff}(t)} = \left(\frac{M_{\oplus}(t)}{M^{\rm SE}_{\oplus}(t)}\right)^{1/4} {\rm e}^{-H^{\oplus}_{\rm atm}(t)/H^{\oplus}_0(t)}. \tag{18}$$

Considering the fact that: $M_{\oplus}(t)/M^{\rm SE}_{\oplus}(t) \sim 1$, it follows that:

$$R_{\rm eff}(t) \simeq R_{\oplus}(t)\,{\rm e}^{H^{\oplus}_{\rm atm}(t)/H^{\oplus}_0(t)}. \tag{19}$$

Out of interest, by making use of the definition of $R_{\rm eff}(t)$ given in Equation (13), Equation (19) can be re-written with $R_{\oplus}(t)$ as follows:

$$R_{\oplus}(t) = \frac{H^{\oplus}_{\rm atm}(t)}{{\rm e}^{H^{\oplus}_{\rm atm}(t)/H^{\oplus}_0(t)} - 1}. \tag{20}$$

In the next section, we shall now link the Earth's albedo to both the supposed expansion rate of the Earth and the changing luminosity of the Sun.

6. Remedy to the Radiation Balance Equation

In this section, we address the criticism we've raised regarding the currently accepted Solar-Earth radiation balance model used to derive the RB-Equation (10). This model fails to consider that the Earth possesses not just an atmosphere, but a radiation-capturing atmosphere. Before deriving the new RB-Equation, we will examine the newly defined albedo in §(6.1), which highlights that this geometry-defined albedo is sensitive to changes in Earth's radius and atmospheric height. Following this, in §(6.2), we will derive the new radiation balance equation for the Sun-Earth system based on the proposed model. In §(6.3), we will explore the implications of this new radiation balance equation, using it to establish a new value for Earth's albedo—specifically, an albedo that addresses the 32.53 K discrepancy between the theoretical (255.62 K) and observed (288.15 K) mean global temperatures.

6.1. Changing Albedo

If we are to embrace the concept of a gravitationally bound expanding solid Earth, with its atmosphere also expanding in response to the solid Earth's growth, then, according to Equation (12), the albedo $A_{\oplus}(t)$ will change too. It will change as follows:

$$\frac{\delta A_{\oplus}(t)}{A_{\oplus}(t)} = -2\left(\frac{\delta R_{eff}(t)}{R_{eff}(t)} - \frac{\delta R_{\oplus}(t)}{R_{\oplus}(t)}\right). \tag{21}$$

Since according to Equation (13): $R_{\rm eff}(t) = R_{\oplus}(t) + H^{\oplus}_{\rm atm}(t)$, it follows that:

$$\frac{\delta R_{\rm eff}(t)}{R_{\rm eff}(t)} - \frac{\delta R_{\oplus}(t)}{R_{\oplus}(t)} = \frac{H^{\oplus}_{\rm atm}(t)}{R_{\rm eff}(t)}\left[\frac{\delta H^{\oplus}_{\rm atm}(t)}{H^{\oplus}_{\rm atm}(t)} - \frac{\delta R_{\oplus}(t)}{R_{\oplus}(t)}\right]. \tag{22}$$

From Equation (19), we also have that:

$$\frac{\delta R_{\rm eff}(t)}{R_{\rm eff}(t)} - \frac{\delta R_{\oplus}(t)}{R_{\oplus}(t)} = \frac{\delta H^{\oplus}_{\rm atm}(t)}{H^{\oplus}_0(t)}\left[\frac{\delta H^{\oplus}_{\rm atm}(t)}{H^{\oplus}_{\rm atm}(t)} - \frac{\delta H^{\oplus}_0(t)}{H^{\oplus}_0(t)}\right] \tag{23}$$

Given that: $H_0^{\oplus}(t) = k_B T_{\oplus}(t)/4m_*(t) g_{\oplus}^{\text{surf}}(t)$, and assuming steady mean global surface temperatures over the *eons* for the Earth system, *i.e.*: $\delta T_{\oplus}(t) = 0$, we will have:

$$\begin{aligned} \frac{\delta H_0^{\oplus}(t)}{H_0^{\oplus}(t)} &= \frac{\delta m_{\text{atm}}(t)}{m_{\text{atm}}(t)} + \frac{\delta M_{\oplus}^{\text{SE}}(t)}{M_{\oplus}^{\text{SE}}(t)} + 2\left(\frac{\delta R_{\oplus}(t)}{R_{\oplus}(t)}\right) \\ &= -\kappa\left(\frac{\delta R_{\oplus}(t)}{R_{\oplus}(t)}\right), \end{aligned} \tag{24}$$

where in this Equation (22), we have assumed: $\delta M_{\oplus}^{\text{SE}}(t)/M_{\oplus}^{\text{SE}}(t) \sim 0$, and that: $\delta m_{\text{atm}}(t)/m_{\text{atm}}(t) = -(2+\kappa)\delta R_{\oplus}(t)/R_{\oplus}(t)$, and: κ is here some dimensionless parameter yet to be determined.

Now, substituting: $\delta H_0^{\oplus}(t)/H_0^{\oplus}(t)$, as given in Equation (24) into Equation (23), we will have:

$$\frac{\delta R_{\text{eff}}(t)}{R_{\text{eff}}(t)} - \frac{\delta R_{\oplus}(t)}{R_{\oplus}(t)} = \frac{H_{\text{atm}}^{\oplus}(t)}{H_0^{\oplus}(t)}\left[\frac{\delta H_{\text{atm}}^{\oplus}(t)}{H_{\text{atm}}^{\oplus}(t)} + \kappa\left(\frac{\delta R_{\oplus}(t)}{R_{\oplus}(t)}\right)\right]. \tag{25}$$

Further, equating the right handside of Equation (22) to the right handside of Equation (25), and re-arranging thereafter, we obtain:

$$\frac{\delta R_{\oplus}(t)}{R_{\oplus}(t)} = -\left[\frac{R_{\text{eff}}(t) - H_0^{\oplus}(t)}{\kappa R_{\text{eff}}(t) + H_0^{\oplus}(t)}\right]\frac{\delta H_{\text{atm}}^{\oplus}(t)}{H_{\text{atm}}^{\oplus}(t)}. \tag{26}$$

We can re-write this Equation (26), as:

$$\frac{\delta H_{\text{atm}}^{\oplus}(t)}{H_{\text{atm}}^{\oplus}(t)} = -\left[\frac{\kappa R_{\text{eff}}(t) + H_0^{\oplus}(t)}{R_{\text{eff}}(t) - H_0^{\oplus}(t)}\right]\frac{\delta R_{\oplus}(t)}{R_{\oplus}(t)}, \tag{27}$$

thus, substituting this into Equation (22), we will have:

$$\frac{\delta R_{\text{eff}}(t)}{R_{\text{eff}}(t)} - \frac{\delta R_{\oplus}(t)}{R_{\oplus}(t)} = -\frac{(1+\kappa)H_{\text{atm}}^{\oplus}(t)}{R_{\text{eff}}(t) - H_0^{\oplus}(t)}\frac{\delta R_{\oplus}(t)}{R_{\oplus}(t)} \tag{28}$$

We can re-write this Equation (29), as:

$$\frac{\delta R_{\text{eff}}(t)}{R_{\text{eff}}(t)} - \frac{\delta R_{\oplus}(t)}{R_{\oplus}(t)} = -\frac{(1+\kappa)\xi_{\oplus}(t)}{1 + \xi_{\oplus}(t) - H_0^{\oplus}(t)/R_{\oplus}(t)}\frac{\delta R_{\oplus}(t)}{R_{\oplus}(t)}, \tag{29}$$

where, $\xi_{\oplus}(t)$, is defined as:

$$\xi_{\oplus}(t) = \frac{H_{\text{atm}}^{\oplus}(t)}{R_{\oplus}(t)}. \tag{30}$$

From Equation (12), it follows from Equation (30), that:

$$A_{\oplus}(t) = \frac{1}{\left[1 + \xi_{\oplus}(t)\right]^2}. \tag{31}$$

thus, removing $\xi_{\oplus}(t)$ in Equation (29) through Equation (31), we will have:

$$\frac{\delta R_{\text{eff}}(t)}{R_{\text{eff}}(t)} - \frac{\delta R_{\oplus}(t)}{R_{\oplus}(t)} = \frac{(1+\kappa)\left[1 - \sqrt{A_{\oplus}(t)}\right]}{1 - H_0^{\oplus}(t)\sqrt{A_{\oplus}(t)}/R_{\oplus}(t)}\frac{\delta R_{\oplus}(t)}{R_{\oplus}(t)} \tag{32}$$

Now, assuming[6]: $\kappa \ll 1$ (or perhaps that: $\kappa \simeq 0$), and substituting this together with: $\delta R_{\text{eff}}(t)/R_{\text{eff}}(t) - \delta R_{\oplus}(t)/R_{\oplus}(t)$ [as given in Equation (32)], into Equation (21), we will have:

$$\frac{\delta A_{\oplus}(t)}{A_{\oplus}(t)} = \frac{2\left[1-\sqrt{A_{\oplus}(t)}\right]}{1-H_0^{\oplus}(t)\sqrt{A_{\oplus}(t)}/R_{\oplus}(t)}\frac{\delta R_{\oplus}(t)}{R_{\oplus}(t)}. \tag{33}$$

We now proceed to derive the new radiation balance equation.

6.2. New Radiation Balance Equation

Given the criticism directed at the RB-Equation (10), it is essential to consider the Earth's atmosphere in our calculations. Recognizing that the atmosphere contributes to the capture of some incoming solar radiation, the effective power, $P_{\oplus}^{\text{abs}}(r,t)$, absorbed by the Earth—instead of it being given by Equation (6), it will have to be given by:

$$P_{\oplus}^{\text{abs}}(r,t) = \pi\left[1-A_{\oplus}(t)\right]F_{\odot}(r,t)R_{\text{eff}}^2(t). \tag{34}$$

The difference between Equation (6) and Equation (34) is the effective radius. We have replaced $R_{\oplus}$ in Equation (6) with $R_{\text{eff}}(t)$ in Equation (34).

For the total energy emitted per unit effective surface area of the Earth, the left handside of Equation (7) will not change, so that the new energy balance will now be given by:

$$4\pi\epsilon_{\oplus}\sigma_0 T_{\oplus}^4(t)R_{\oplus}^2(t) = \pi\left[1-A_{\oplus}(t)\right]F_{\odot}(r,t)R_{\text{eff}}^2(t), \tag{35}$$

hence, Equation (35) reduces to:

$$4\epsilon_{\oplus}\sigma_0 T_{\oplus}^4(t) = \left[\frac{1-A_{\oplus}(t)}{A_{\oplus}(t)}\right]\frac{L_{\odot}(t)}{4\pi r_{\oplus}^2(t)}. \tag{36}$$

Further, Equation (36) reduces to:

$$T_{\oplus}(t) = \left(\frac{1-A_{\oplus}(t)}{4\epsilon_{\oplus}\sigma_0 A_{\oplus}(t)}\right)^{\frac{1}{4}}\left(\frac{L_{\odot}(t)}{4\pi r_{\oplus}^2(t)}\right)^{\frac{1}{4}}. \tag{37}$$

We can re-write this Equation (37), as:

$$T_{\oplus}(t) = \left(\frac{1-A_{\oplus}(t)}{4\epsilon_{\oplus}A_{\oplus}(t)}\right)^{\frac{1}{4}}\left(\frac{R_{\odot}(t)}{r_{\oplus}(t)}\right)^{\frac{1}{2}} T_{\odot}(t). \tag{38}$$

The obvious difference in the revised radiation balance Equation (37) and the original radiation balance Equation (10), is the factor $1/A_{\oplus}^{1/4}(t)$. This factor $\left[1/A_{\oplus}^{1/4}(t)\right]$, together with the fact that the new (geometric) albedo changes [Equation (33)] with respect to a change in the solid Earth's radius and as-well as a change in the atmospheric height, is all that we need in-order for a plausible

[6]This assumption that: $\kappa \ll 1$, implies that $H_0^{\oplus}(t)$ has not changed appreciably over time [*i.e.*: $\delta H_0^{\oplus}(t)/H_0^{\oplus}(t) \sim 0$], it has remained constant. This assumption is not unreasonable. We will prove this in the complimentary reading.

solution to the *FYS-Paradox*. Before we can do that, we will first have to solve the said 32.53 K-discrepancy between the theoretical (255.62 K) and observed (288.15 K) mean global temperature.

6.3. Implications

In Equation (37), we have a new RB-Equation whose albedo is no longer the surface albedo that is determined by the physical and chemical composition of the material making up the solid Earth. The new (geometric) albedo [Equation (12)] is now the ratio of the effective blocking surface area $\left[4\pi R_{\oplus}^{2}(t)\right]$ to that of the total cross-sectional $\left[4\pi R_{\mathit{eff}}^{2}(t)\right]$ of the Earth system. In-order to determine the new albedo, we have know the height, $H_{\text{atm}}^{\oplus}(t_0)$, of the Earth's atmosphere. At present, we have no way of determining this and even if there was a way, it would be difficult in practice. However, be that as it may, we could—in theory—determine, $H_{\text{atm}}^{\oplus}(t_0)$, by assuming that the present day value of the Earth's geometric albedo [as defined in Equation (12)] is just right to give the Earth system the observed 288.15 K- mean global surface temperature. So doing, we obtain:

$$A_{\oplus}(t_0) = 0.48, \tag{39}$$

from which we obtain: $\xi_{\oplus}(t_0) = 0.45$, hence:

$$H_{\oplus}(t_0) = 0.45 R_{\oplus}(t_0) = 2860 \text{ km}. \tag{40}$$

What is interesting about the geometric albedo [Equation (39)] here obtained, is that it is not far off from the measured geometric albedo for the Earth system. According to Mallama *et al.* [78]'s most recent measurement, the geometric albedo of the Earth is ~0.43. Mallama *et al.* [78]'s measurement is a measure of the ratio of a planet's actual brightness as seen from the Light source to that of an idealized flat, fully reflecting, diffusively scattering disk with the same cross-section. It can only embolden one's confidence to know that our calculated geometric albedo is very close (~12% difference) to that derived from measurements where our calculated albedo has been derived on the simple requirement that our unknown albedo, must yield the observed mean global surface temperature of 288.15 K.

Therefore, if one accepts the above suggestion to resolving the already thought to be resolved 32.53 K-discrepancy between the theoretical (255.62 K) and observed (288.15 K) mean global temperature obtained using the old Equation (11), then, what follows in the next section will be much more acceptable as a solution to the *FYS-Paradox* because the values that we have here derived, fit *hand-in-glove* like a jigsaw puzzle, with the currently measured values of the expansion of the solid Earth.

7. Earth as a Delicate Incubator

Life is not only precious but also delicate, requiring steady and predictable conditions to flourish. This is underscored by the fact that the Ice Age was triggered by a seemingly minor drop of less than 1% in mean global temperature, corresponding to approximately 3 K. What if there were a similar increase of less than 1%? Could this not lead to an era of heat waves similar to what we are currently experiencing? The fragility of life is further highlighted by evidence suggesting that the Earth has maintained stable temperatures over the last 3.20 ± 0.70 billion years. Had conditions been even slightly different, the diversity of life we see today might not have existed.

This raises the question: *How has the Earth managed to sustain steady average global temperatures over such an extended period?* Clearly, some subtle mechanism must have been at work, ensuring that these stable temperatures are maintained. To explain this intriguing phenomenon of the Earth's 'mysterious' ability to sustain steady average global temperatures for such a long time, we propose what we believe to be a reasonable hypothesis.

7.1. Radiation Balance Equilibrium Hypothesis

It is neither outrageous nor outlandish, but rather logical and imaginative, to consider that the Earth has maintained a state of radiation balance with the Sun at each point in time since the Archaean eon. Accepting this as a foundational premise, we can elevate Equation (8) to the status of a hypothesis. This hypothesis posits that the balance between the Sun's radiation and the energy output of the Earth system is a conserved state, expressed as:

$$\delta P_{\oplus}^{\text{abs}}(t) = \delta P_{\oplus}^{\text{emit}}(t). \tag{41}$$

What Equation (41) implies is that any change (whether positive or negative) in Solar output power will be met with an equal and opposite compensatory change in the energy radiated back by the Earth system. This dynamic is facilitated by the Earth's malleable albedo, which can adjust to accommodate new levels of radiation.

We shall refer to this crucial relationship as the *Radiation Balance Equilibrium Hypothesis* (RBE-Hypothesis). In the next subsection, we will evaluate this equation further to explore its implications and the mechanisms that allow the Earth to maintain this delicate balance.

7.2. Consequence

From the foregoing, steady average global temperatures imply steady average effective global surface temperature $T_{\oplus}(t)$, *i.e.*, $\delta T_{\oplus}(t) = 0$, thus applying the RBE-Hypothesis to Equation (36), it directly leads to:

$$\frac{\delta L_{\odot}(t)}{L_{\odot}(t)} - 2\left(\frac{\delta r_{\oplus}(t)}{r_{\oplus}(t)}\right) = \frac{A_{\oplus}(t)}{1 - A_{\oplus}(t)} \frac{\delta A_{\oplus}(t)}{A_{\oplus}(t)}. \tag{42}$$

Substituting: $\delta A_{\oplus}(t)/A_{\oplus}(t)$, as given in Equation (33) into Equation (42), we will have:

$$\frac{\delta L_{\odot}(t)}{L_{\odot}(t)} = \frac{2\left(1 - \sqrt{A_{\oplus}(t)}\right)}{\left[1 - A_{\oplus}(t)\right]\left[1 + \xi_{*}^{\oplus}(t)\sqrt{A_{\oplus}(t)}\right]} \frac{\delta R_{\oplus}(t)}{R_{\oplus}(t)} - 2\left(\frac{\delta r_{\oplus}(t)}{r_{\oplus}(t)}\right), \tag{43}$$

where in Equation (43), we have set: $\xi_*^{\oplus}(t) = H_0^{\oplus}(t)/R_{\oplus}(t)$. Since: $H_0^{\oplus}(t_0) = k_B T_{\oplus}(t_0)/4m_*(t_0)g_{\oplus}^{\rm surf}(t_0)$, and given that $g_{\oplus}^{\rm surf}(t_0) = 9.80\ \rm m/s^2$, $T_{\oplus}(t_0) = 288.15\ \rm K$, $m_*(t_0) = 0.0289644\ \rm kg \cdot mol^{-1}$: it follows that: $H_0^{\oplus}(t) = 4.23\ \rm km$, hence:

$$\xi_*^{\oplus}(t_0) = 6.61 \times 10^{-4}. \tag{44}$$

Alternatively, we can re-write Equation (43) in-terms of $\delta R_{\oplus}(t)/R_{\oplus}(t)$, where we will have:

$$\frac{\delta R_{\oplus}(t)}{R_{\oplus}(t)} = \frac{\left[1 - A_{\oplus}(t)\right]\left[1 + \xi_*^{\oplus}(t)\sqrt{A_{\oplus}(t)}\right]}{2\left(1 - \sqrt{A_{\oplus}(t)}\right)}\left[\frac{\delta L_{\odot}(t)}{L_{\odot}(t)} - 2\left(\frac{\delta r_{\oplus}(t)}{r_{\oplus}(t)}\right)\right]. \tag{45}$$

This Equation (45), connects the Earth's mean radial expansion rate $\left[\delta R_{\oplus}(t)/R_{\oplus}(t)\right]$, its geometric albedo $\left[A_{\oplus}(t)\right]$, atmospheric height $\left[\xi_*^{\oplus}(t) = H_{\rm atm}^{\oplus}(t)/H_0^{\oplus}\right]$ and secular recession from the Sun $\left[\delta r_{\oplus}(t)/r_{\oplus}(t)\right]$, together with the Solar luminosity rate $\left[\delta L_{\odot}(t)/L_{\odot}(t)\right]$ in the case of an expanding Earth that maintains steady average global temperature—in short, an *Incubator Earth*. Now, after all the preparation, in the next subsection, we will present our suggested solution to the *FYS-Paradox*, where the Earth system is cast as an *auto-self-regulating incubator*.

7.3. Implications

What Equation (45) [or Equation (43)] implies is that, if the Earth were a delicate incubator of life as supposed in the previous section—*i.e.*, a delicate incubator that maintains steady average global temperatures *via* steady average effective global surface temperature $T_{\oplus}(t)$ defined in Equation (43), *i.e.*: $\delta T_{\oplus}(t) = 0$, then, the Earth can do so for a steadily changing Solar luminosity by responding to this change in Solar luminosity *via* global radial expansion (or contraction) of the Earth. Actually, the expansion of the Earth is a natural means of *auto-self-regulating* the mean global temperatures.

Now, applying the values of: $\delta r_{\oplus}(t_0)/r_{\oplus}(t_0)$ [Equation (2)], $A_{\oplus}(t_0)$ [Equation (39)], and, $\xi_*^{\oplus}(t_0)$ [Equation (44)], into Equation (45) for the case: $\delta L_{\odot}(t_0)/L_{\odot}(t_0) = +0.25$, we find that:

$$\frac{\delta R_{\oplus}(t_0)}{R_{\oplus}(t_0)} = +0.21 \tag{46}$$

and in-turn, this implies a present day Earth expansion rate $\left[R_{\oplus}(t_0)\right]$ of:

$$R_{\oplus}(t_0) = +0.43 \pm 0.09\ \rm mm \cdot yr^{-1}. \tag{47}$$

This calculated radial expansion rate of the solid Earth is consistent, within the uncertainties, with the published measurements of Shen *et al.* [42], who reported a combined land and oceanic expansion rate of +0.35 ± 0.47 mm·yr^{-1}. The agreement between our theoretical prediction and the observational data, while not conclusive given the large uncertainty, suggests that the Expanding Earth Hypothesis merits further investigation as a potential solution to the FYS-Paradox.

This convergence of findings is humbling, as it communicates a profound truth about the physical and natural reality we experience: the very life we cherish—*and often take for granted*—exists on a *knife-edge balance*, sustained by the intricate *Laws of Nature*. This delicate equilibrium underscores the importance of understanding the mechanisms that maintain stability in our environment, reflecting the interconnectedness of all life with the forces that govern our planet.

8. General Discussion

Given the ongoing controversy regarding whether the Earth is expanding, we want to clearly state that, despite our strong belief in the Expanding Earth Hypothesis [as expressed in Refs., [79] [80]], this reading does not advocate for either the position of expansion or non-expansion. Instead, we argue that the idea of an expanding Earth holds a valid and potentially significant place within the complex array of possible solutions to the long-standing paleoclimatology puzzle known as the Faint Young Sun Paradox. If anything, our suggestion is novel in terms of addressing this issue. In the literature we have reviewed, we have not encountered any solutions to this problem that incorporate the Expanding Earth Hypothesis; thus, this reading represents a first in that context.

The proposed model depicts the expanding Earth as an auto self-regulating incubator that maintains stable average global temperatures by self-adjusting the boundary of the atmosphere. If the Earth is indeed expanding, as various observations [see e.g., Refs. [42]-[44], [57]-[62]] seem to strongly suggest, then, the boundary of the Earth's atmosphere must also change in response to this solid Earth expansion.

Currently, the exact boundary of the Earth's atmosphere is not well-defined and this serious shortcoming complicates the validation of the proposed model. The *Kármán line*, often used to define the boundary of the Earth's atmosphere, is commensurate with a solid Earth expansion rate of approximately ~+2.60 ± 0.60 $\text{mm}\cdot\text{yr}^{-1}$. This rate is about seven times higher than the latest measured Earth expansion rate of ~+0.35 ± 0.47 $\text{mm}\cdot\text{yr}^{-1}$ reported by Shen *et al.* [42], making the *Kármán line* an unfavourable boundary for the proposed model in light of these observations.

If—*for whatever reason imaginable*—we are to accept the present proposed model as valid, then, the expansion rate suggested by Shen *et al.* [42] would necessitate an atmospheric height of around 9860 km. Invariably, this implies, predicts or points to the falsifiable idea that within the range: $120\text{ km} < h_{\oplus}\left(t_0\right) \leq 2860\text{ km}$, there ought to be a very thin atmosphere that may very well be challenging to detect as a result of its rarefied nature.

9. Conclusions

1. *In-principle*, the Expanding Earth Hypothesis can explain the so-called Faint Young Sun Paradox *via* an auto-self-regulating mechanism where the height of

the Earth's atmosphere re-adjusts and in-turn the albedo changes in such a manner that it maintains constant average global temperatures for so long as the Earth is expanding and the Sun is getting brighter and brighter with time.

2. In accordance with the proposed expanding Earth evolutionary model, the published expansion measurements of Shen *et al.* [42] [44] (e.g., a global expansion rate of $+0.35 \pm 0.47\ \text{mm}\cdot\text{yr}^{-1}$) are consistent with the model's requirements. Our calculated expansion rate of $+0.43 \pm 0.09\ \text{mm}\cdot\text{yr}^{-1}$ falls within the observational uncertainty. If future measurements confirm a more precise expansion rate near the upper end of the current uncertainty, the model would require that the height of the Earth's atmosphere be approximately 2860 km, implying that in the region $120\ \text{km} < h_{\oplus}(t_0) \leq 2860\ \text{km}$, there may exist a very thin atmosphere that has so far escaped detection.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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