Ode to Planet Earth[1]

Graeme D. Buchan[2]

"Speak to the Earth, and it shall teach thee". Job 12, v .8.

ABSTRACT

"Good planets are hard to find", as the saying goes. This paper gives an 'extra-terrestrial' overview of the 'awesome' (literally) features of our Planet, which conspire to produce its finely-tuned, life-enabling environment. This is the first in a series of 'resource appreciation' papers. We protect what we value: these papers aim to encourage readers to *value* Nature's resources, and therefore protect them. The sequel paper is 'Ode to H_2O' (Buchan, 1996), which reverences the wonder properties of the first pillar of life – water.

Introduction

Imagine yourself as a cosmic traveller encountering planet Earth. You see that, unlike its fellow planets, it is enveloped in a thin and delicate life-supporting *biosphere*, made up of atmosphere, oceans, rocks and soils. If Earth were a chilled apple, this biosphere would be about as thin as the moisture film formed by breathing on it, yet it supports millions of life species.

In this article, I describe a) the Sun factors (its temperature and distance from Earth), b) Earth's own features, and c) the subtle roles of the Moon, which miraculously combine to produce our planet's rich, life-enabling environment. Using some simple scientific analysis, I examine the many single factors that combine to produce our "finely tuned" planet.

SUN FACTORS

Consider the temperature and radiation strength of our Sun, and our distance from it. To appreciate the importance of these factors, we can estimate the change in Earth's conditions (especially its average surface temperature T_{Earth}) with imagined but plausible changes in Sun-Earth conditions (See Appendix).

Solar Temperature

The Sun's surface temperature, T_{Sun}, is about 6,000 Kelvin (i.e. 6,000 degrees above absolute zero). This has two important consequences. First, its radiation spectrum (Figure 1) peaks within the benign range of wavelengths supporting photo-biological activity, including photosynthesis in plants that convert about 1% of the Sun's energy reaching Earth's surface into biologically stored energy. Second, only 9% of its output power is the potentially harmful ultraviolet (UV) radiation. Now imagine the Sun to be only 10% hotter (6,600 K) – not a bold change, because star temperatures range from about 3,000 K to 30,000 K (Henbest, 1988). Some simple physics (see Appendix) shows that T_{Earth}, at present 288 K (equivalent to 15 °C), would also be about 10% warmer at 317 K, or 44 °C. Also, the Sun's output of UV radiation would approximately double. These changes would produce an environment too

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hostile for life as it exists. Conversely, lowering T_{Sun} by 10% would cause Earth to freeze at a mean temperature of about -14°C!

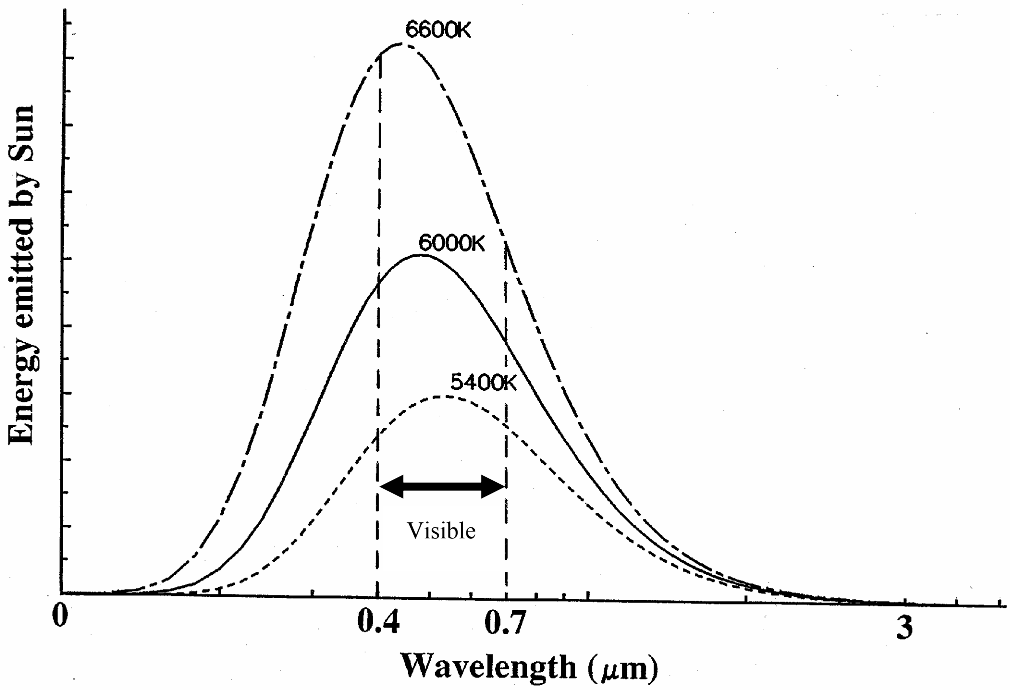

FIGURE 1. **The Sun's radiation spectrum**, shown for its actual radiating temperature (c. 6,000 K), and for imagined temperatures 10% hotter (6,600 K) and 10% cooler (5,400 K). The visible range, stimulating the photochemistry of the eye, is 0.4 to 0.7 μm. This is also the range of 'photosynthetically active radiation' (PAR) stimulating photosynthesis in plants. UV is to the left of the visible.

Sun-Earth Distance

Suppose our solar system had developed with Earth nudged a mere 10% further from the Sun. See Fig. 2. (Mars, our outer neighbour, is about 50% further out than Earth). Simple physics (see Appendix) shows that T_{Earth} drops by 15 degrees to about 0°C. During the last ice age, which ended 10,000 years ago, mean surface air temperature was only 5°C lower than at present (Budyko et al., 1988). If we were 10% closer to the Sun (Venus is about 30% closer), then T_{Earth} would rise to 30°C. In both cases Earth would be inhospitable for human life.

EARTH FACTORS

Having considered our dependence on the Sun, this section focuses on Earth itself. For example, how does it hold down its atmosphere while floating in the near-vacuum of space? Why is that atmosphere so important for moderating surface climate? Why is Earth the only "watery planet?" Why is its rotation crucial for climate? Why does the Earth have land surfaces at all, instead of being totally ocean-bound? Is the proportion of land to ocean critical? Does the Moon play any role?

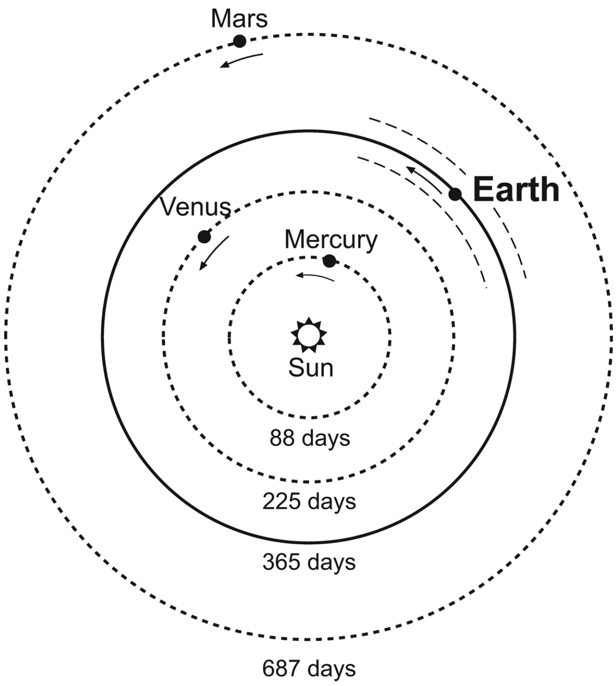

FIGURE 2. **Orbits of the four inner planets**
- showing imagined shifts of Earth's orbit to 10% further from and 10% closer to the Sun. The numbers (in days) are the times taken by the planets to orbit the Sun. (Note: The orbits are actually not perfect circles, but slightly deformed circles, i.e. ellipses).

Grip of Gravity

The ability of a planet to hold down fast-moving objects (like gas molecules) is described by its so-called *escape velocity*, which for Earth is 11.2 km/sec. Anything launched faster at Earth's surface would (with no air friction) escape out to space. Now, at Earth's average temperature of 15°C, air molecules such as nitrogen and oxygen (N_2 and O_2) move with average speeds of only about 0.5 km/sec (i.e. 1800 km/hr, about twice the speed of a jet airliner. Think – these are beating against your skin !). Hence they are successfully retained by Earth's grip. By contrast, most of the lighter and faster hydrogen and helium gases have long since escaped to space. The combination of Earth's mass, size, and temperature enables it to hold onto its atmosphere. Not only that, its surface gas density is sufficiently high to enable the rapid exchange of gases required by higher, oxygen-breathing lifeforms. By contrast Mars, with about ½ of Earth's radius, has a surface gravity about three times weaker, and a much thinner atmosphere with a surface pressure of only 0.6 % of our own (Wayne, 1991). Even more extreme, both Mercury and our Moon have no atmospheres.

"Warmhouse" Earth

Earth continuously gains energy from the stream of solar radiation, and loses infrared radiation that escapes out to space (See Figure 3). The gain and loss must be in balance, otherwise Earth would be rapidly warming or cooling. This simple idea gives us a model for calculating Earth's mean temperature (see Appendix). The model shows that a "naked" (airless) Earth would mostly freeze with a mean temperature of only -18°C! Why is Earth's surface warmer than this? The answer is that the atmosphere acts like an insulating mantle with two main effects: (a) Atmospheric gases, mainly water vapour and CO_2, allow sunlight in but help to trap infrared energy radiated back from Earth's surfaces - a warming effect. (This is in fact the natural – and *essential* – 'greenhouse effect'); and (b) Clouds form, and reflect more of the sun's rays back to space – a cooling effect. (Clouds also contribute to the warming effect by radiating infrared energy down to Earth.)

The warming effect easily wins out, raising Earth's average surface temperature by 33 degrees to 15°C. Thus Earth's life-enabling climate relies on the natural greenhouse gases to raise the mean temperature from a frozen -18°C, to a life-friendly 15°C. Human activity is raising the levels of *added* greenhouse gases, shifting the natural equilibrium.

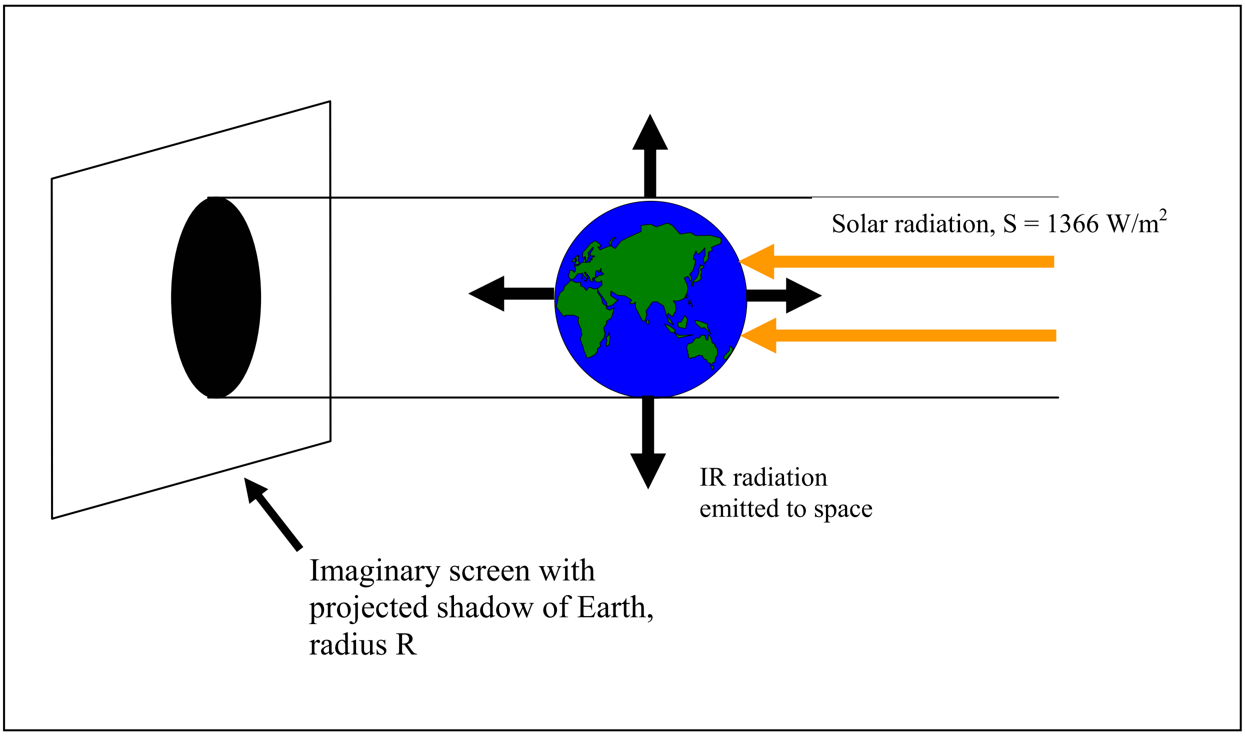

FIGURE 3. **Energy balance of Planet Earth**. Solar radiation (S = 1366 W m^{-2}), shown by incoming arrows, is intercepted over a circle (the 'shadow' area πR^2 on the imaginary screen). Balancing this gain is a loss of infrared (IR) radiation (outgoing arrows), emitted from the *whole* surface of the sphere, area 4 πR^2.

Oxygen: Provider and Protector

Oxygen (19% of our atmosphere) is the miracle atom. First, its 'hunger' for electrons makes it chemically reactive, so it 'oxidises' foods and provides energy for our bodies (in the process called respiration). Second, the electron-attracting O in H_2O is also the main secret behind the wonder properties of water (Buchan, 1996).
But wait – there's more: oxygen in the atmosphere also turns out to be a very effective but delicate filter against the harshest, high-energy part of the sun's UV spectrum. UV rays are absorbed partly as they enter the outer atmosphere, but also in the *ozone layer* in the middle atmosphere. There are two misconceptions about this 'layer'. First, it is not thin, but is spread over altitudes about 15 to 50 km. Second, ozone (O_3) is not our only protector. Ozone reduces, but does not completely block, the UV-B, the cause of sunburn, suntans, and other

biological effects (Giese, 1976). However oxygen (O_2) also absorbs UV, in the much more damaging UV-C waveband. Thanks to absorption by O_2 and other gases, no UV-C reaches Earth's surface. Without Earth's UV-C screen, higher, land-based life would not be possible. In summary, oxygen and ozone together act like a natural sunblock on the face of Earth, protecting life on its 'complexion' below.

Water

We owe water many debts (Buchan, 1996). First, it is the basis of life. Second, without water vapour (Earth's main greenhouse gas) our planet would be over 20°C colder – a snowball in space! Third, water vapour in the atmosphere and liquid water in the oceans act like two giant energy conveyors, pumping heat from lower to higher latitudes. So why is Earth such a wet planet, compared to the "almost complete dryness of our sister planets, Venus and Mars" (Szesztay, 1991)? Our planet owes its abundant water resources to its near-surface temperatures, which are cool enough to provide a *cold trap*. Imagine ascending into the atmosphere: temperature drops rapidly, reaching values as low as about -55°C at the top of the troposphere (about 11 km up). Air as cold as this has negligible capacity to hold vapour and, consequently, water is "trapped" in the lower atmosphere. Otherwise, the H_2O would slowly leak up into or above the ozone layer, to be broken down by UV radiation, and then free H-atoms would escape into interplanetary space.

More Screening

Our atmosphere shields us from the Sun's harshest UV rays. It also protects life from two other bombardments from outer space (Faughn et al., 1991). First, Earth's interior, a circulating brew of molten minerals, acts like a giant dynamo generating Earth's magnetic field. This field acts as a protective screen, trapping charged particles (*cosmic rays*) that stream from the Sun. Second, space is peppered with solid objects, from small dust-sized particles to larger meteors. Most objects encountering Earth are burned up by friction with our atmosphere, which fortunately is dense enough for this task.

Spinning Earth

Consider the curious but vital role of Earth's rapid rotation. A person at the equator is being spun on a giant 'roundabout', at a speed of about 0.47 km/sec – about the same speed as gas molecules, and 17 times faster than a 100 km/hr speed limit! This rotation has two effects:
1) It helps smooth Earth's day-night temperature swings. (Compare Mercury, which has a very leisurely rotation period of 59 days. Its surface temperature ranges from a peak of 500°C in full sunshine, to below -170°C on the dark side [Friedlander, 1985]).
2) The rotation appears to produce an extra force (the *Coriolis force*) on anything that moves. The result of this is fascinating. Look at a weather map (e.g. Figure 4), with its isobar lines that trace out places with equal atmospheric pressure. Contrary to what you expect, the air doesn't move directly *across* the isobars from high to low pressure. Instead, it moves *along* the isobars at right angles to the way pressure wants to push it! This has a huge effect on climate. If Earth did not rotate, pressure differences would quickly cancel out – "Winds would hardly exist if the Earth did not rotate" (McIntosh & Thom, 1981). Yet winds are vital for atmospheric mixing processes. They prevent excessive heating of the ground surface, shift heat from warmer to cooler regions, and carry water vapour and rain from oceans onto land surfaces. Similarly, Earth's rotation helps drive ocean currents, such as the Atlantic Gulf Stream, which act as giant heat conveyor belts in Earth's climate.

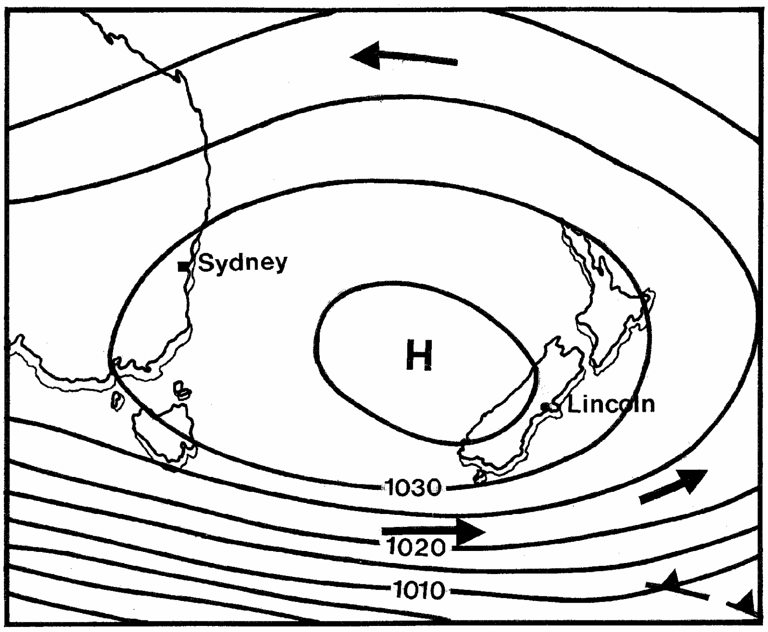

FIGURE 4. **Persistence of winds**. This weather chart for 13 August 1987 shows a fine-weather anticyclone (high pressure) between Australia and New Zealand. The curves are isobars, showing pressure in millibars. The arrows show the direction of the wind, which, contrary to expectation, is approximately *parallel to* (not across) the isobars.

Land Versus Ocean

Why does Earth, the watery planet, have dry land at all? Imagine piling up sand or rocks on the beach. Nature, which prefers lowering energy, would tend to collapse and smooth the pile. Similarly, if Earth's surface crust were totally uniform in composition, we would expect to see an almost perfectly spherical planet, smoothly enveloped in a single ocean, with no piled-up land surfaces. The material in Earth's surface crust, however, is not all of the same density. Material forming the continents is light, composed of rocks with a density only about 2.7 times that of water. Historically, this material came to 'float' above denser underlying material. "As it happened, however, there was only enough continental material to cover about a quarter of the Earth's surface" (Trefil, 1986). If there had been no lighter continental material, or conversely much more of it, the result would have been a smoother Earth surface, with little or no dry land.

The Strange Roles of the Moon

Does the Moon help make Earth life-friendly? Curiously, yes. First, it provides a night-light in the sky. Second, it drives the pulse of the tides that wash our shores and provide an environment for seashore and estuary life. However, as well as ocean tides, the Moon (and Sun) also drive *land tides* in Earth's solid crust. These solid tides prevent the build-up of stresses in Earth's surface, by triggering more frequent (and thankfully smaller!) earthquakes than would otherwise occur.

Did you know?
About 50 earthquakes worldwide are recorded every day.
If the Moon did not "tug" on mother Earth's 'skin', there would be fewer but BIGGER quakes!

But the third and most important effect concerns the tilt of Earth's spin axis. This tilt (currently 23 degrees) gives us the seasons. In the N hemisphere summer, that hemisphere is tilted towards the Sun. At the opposite (winter) point on Earth's orbit, the N hemisphere is tilted away from the Sun. The Moon, through its gravitational pull on Earth, has stabilised the tilt of Earth's axis. Without this, Earth's tilt angle would (over cycles of tens of thousands of years) have wandered from large to small, causing (at large angles) the seasons to swing violently from extra hot summers to intensely cold winters (Ward and Brownlee, 2000).

Summary

Earth is a special and beautifully balanced planet. It bathes in the starshine of a Sun at the right temperature and at the right distance. It has the proper mass, size and temperature to hold down its atmosphere, with a surface gas concentration high enough to support higher life-forms. Its atmosphere is a beautiful blend of gases, with transparent 'windows' and filtering 'curtains' in the right parts of the electromagnetic spectrum. The atmosphere acts as a vapour trap, making Earth the 'watery planet' and protects us from bombardments from outer space. Its rotation evens out solar heating and it sustains winds and ocean currents essential to climate and mixing processes. Its waltzing partner, the Moon, has steadied Earth's spin axis, preventing violent extremes in our seasons.

How can we degrade such a gift?

APPENDIX

A simple model for estimating Earth's average temperature can be obtained by considering how Earth gains and loses energy in space (see Budyko et al., 1987; Friedlander, 1985; Lorius et al., 1990). The model can also show us how sensitive that temperature is to imagined changes in conditions. Figure 3 shows that Earth traps solar energy as if it were a circular disk projected on a screen. This gain is exactly balanced by the loss of infrared energy radiated back out to space. Because Earth is rotating reasonably rapidly, we assume it has uniform temperature, T_{Earth} and therefore uniform infrared loss over its whole surface (area = $4\pi R^2$ for a sphere of radius R). This simple model gives an equation for calculating T_{Earth} :

Solar radiation energy absorbed = infrared energy radiated to space.

$$\pi R^2 (1 - a) S = 4 \pi R^2 \sigma T_{Earth}^4$$

The *albedo*, a, is the fraction of the Sun's radiation reflected back to space, about 30%. S is the *solar constant* (1366 W m^{-2}). The laws of nature tell us that a surface emits radiation in proportion to the fourth power of its temperature, and σ is a constant of nature, defining how rapidly that radiation is emitted.
The above equation predicts a value of 255 K, or -18°C, for T_{Earth}. This is in fact the correct 'radiation' temperature of the *outer atmosphere*, confirmed by measurements made from

satellites in space. The actual average temperature of Earth's *surface* is 15°C, 33 degrees warmer. The above model enables estimation of the sensitivity of Earth temperature to changes in Sun temperature, T_{Sun}. Because the Sun's radiation S is proportional to T_{Sun}^4, we can deduce that T_{Earth} is approximately proportional to T_{Sun}.

Interestingly, the renowned Soviet climatologist Budyko and his colleagues (1987) proposed that Earth's current climate is not the only stable option for present Sun-Earth conditions. They speculate on two other possibilities:
1) A frozen "white Earth", locked in a complete glaciation at temperatures of -50 to -70°C, because its albedo would then be increased to Antarctic-like values of 0.6 to 0.7.
2) Conversely, if large quantities of CO_2 were released into the atmosphere from the vast stores of carbon in Earth's rocks and oceans, a "runaway" greenhouse effect might elevate surface temperatures to very high levels.

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