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Dark energy and the anthropic principle

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ABSTRACT

The Hubble constant is split into two terms $H = H_1 + H_2$, where H_1 is a decreasing function due to the Big Bang and the subsequent gravitational interaction that slows the expansion of the Universe and H_2 is an increasing function that corresponds to dark energy which accelerates this expansion. For $T = 13.7$ Gyr we prove that $H_2(T) > 5$ m/(yr AU). This is a quite large number and thus the impact of dark energy, which is spread almost everywhere uniformly, should be observable not only on large scales, but also in our Solar system. In particular, we show that Earth, Mars and other planets were closer to the Sun 4.5 Gyr ago. The recession speed ≈5.3 m/yr of the Earth from the Sun seems to be just right for an almost constant influx of solar energy from the origin of life on Earth up to the present over which time the Sun's luminosity has increased approximately linearly. This presents further support for the Anthropic Principle. Namely, the existence of dark energy guarantees very stable conditions for the development of intelligent life on Earth over a period of 3.5 Gyr.

1. Introduction

The effect of cosmological expansion on local systems (such as the Solar system) has a long history dating back to the paper (McVittie, 1933). Coincidentally, 1933 is also the year when Fritz Zwicky suggested the existence of dark matter (Zwicky, 1933). At present we know that the expansion of our Universe accelerates (Glanz, 1998). This fact is based on the 10–15% lower luminosity of very distant supernovae of type Ia that shine into a larger space than if the expansion would be decelerating (see Perlmutter et al., 1997, 1999; Riess et al., 1998). The observed acceleration is due to dark energy that is distributed almost uniformly in the Universe. Therefore, as we shall prove below (see (2) and (5)), dark energy has an essential influence on the current value of the Hubble constant $H_0 = 65\ \mathrm{km\ s^{-1}\ Mpc^{-1}} = 20\ \mathrm{km\ s^{-1}\ Mly^{-1}}$ that characterizes the speed of this expansion (slightly higher values $\approx 70\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$ can also be found in the literature, see e.g. Larson et al., 2010). Let us recalibrate H_0 to the Earth–Sun distance, i.e., 1 AU = $1.49597870691 \cdot 10^{11}$ m (Pitjeva and Standish, 2009). Taking into account that the Sun's photons travel to the Earth in about 500 s, we find that

$$H_0 = 65\ \mathrm{km\ s^{-1}\ Mpc^{-1}} = 0.02\ \mathrm{m\ s^{-1}\ ly^{-1}} \\ = 0.02 \cdot 500\ (\mathrm{AU})^{-1}\ \mathrm{m\ yr^{-1}} = 10\ \mathrm{m\ yr^{-1}}\ (\mathrm{AU})^{-1}. \tag{1}$$

This number is quite large and we shall see below that the impact of the dark energy can also be detected in the Solar system. We present some geophysical, heliophysical, climatological, geochronometrical, astrobiological, and astronomical observational arguments to support this conjecture that enables us to explain a number of classical paradoxes such as the Faint Young Sun Paradox, the very large orbital momentum of our Moon, formation of Neptune and the Kuiper belt, rivers on Mars, the Tidal Catastrophe Paradox of the Moon, etc. Actually, an accuracy of order of about $H_0 = 1.5$ milliarcsecond cy^{-1} has been reached nowadays in planetary motion reconstruction such as the precessions of the planetary perihelia (see e.g. Fienga et al., 2010; Folkner, 2010; Pitjeva, 2010), and there are several attempts to measure some dynamical effects as small as H_0 effects in the Solar system (Iorio, 2005a, 2010a).

2. The Hubble constant as the sum of two independent terms

The Hubble constant $H = H(t)$ can be written as the sum of two functions of a very different origin (see Fig. 1)

$$H(t) = H_1(t) + H_2(t), \tag{2}$$

where

$$H_1(t) \approx C/t \quad (C - \mathit{constant}) \tag{3}$$

is decreasing with time t from $(0, T)$ and is due to the Big Bang and the subsequent gravitational interaction that slows down the expansion, and

$$H_2(t) := H(t) - H_1(t)$$

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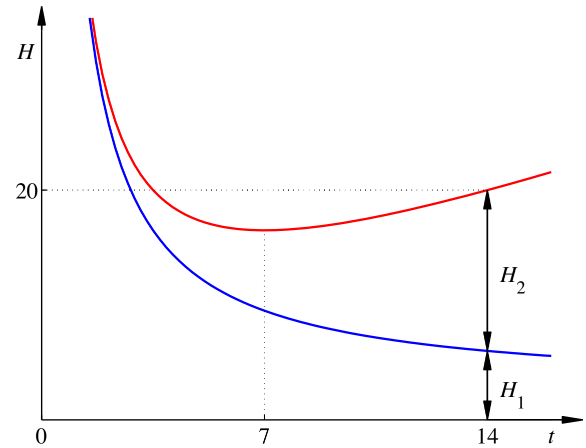

Fig. 1. Time behavior of the Hubble constant $H(t) = H_1(t) + H_2(t)$ measured in km s^{-1} Mly^{-1}. The time t is given in Gyr. This figure has just illustrative purposes, since all data are only approximate.

is an increasing function that corresponds to dark energy, which on the other hand accelerates the expansion by its antigravity effects, $H_0 = H(T)$, and

$$T = 13.7 \text{ Gyr}$$

is the age of Universe.

Both terms in (2) have very roughly the same order at present time

$$H_1(T) \sim H_2(T). \tag{4}$$

They have only an "averaged" character, i.e., all local irregularities are ignored. The increasing character of H_2 shows why the slowing expansion turned into an accelerating one approximately 7 Gyr ago.

We will illustrate the influence of the term H_2 corresponding to dark energy on the expansion of the Solar system by several sophisticated testable hypotheses below. All of them can be justified by a recession speed greater than one half of that given in (1).

Assuming the equality in (3) as many classical cosmological models suggest (see e.g. Misner et al., 1997, p. 735) we will now prove mathematically that

$$H_2(T) > H_1(T), \tag{5}$$

i.e., the term H_2 dominates over H_1 after $T = 13.7$ Gyr from the Big Bang. Since $H(t)$ is increasing during the last 7 Gyr (which is confirmed by astronomical observations), we find by (2) that (5) holds:

$$\begin{aligned} H_2(T) &= H(T) - H_1(T) > H(T/2) - H_1(T) > H_1(T/2) - H_1(T) \\ &= 2H_1(T) - H_1(T) = H_1(T). \end{aligned}$$

At the same time we see that the difference

$$H_2(T) - H_1(T) = H_2(T/2) + [H(T) - H(T/2)] \tag{6}$$

is positive and thus the inequality (5) is valid also if the equality $H_1(t) = C/t$ holds only approximately (see (3)). Let us emphasize that inequality (5) was derived for any size of the constant C from (3) (not only for its usual value $C = 2/3$) and independently of the behavior of the functions $H_1(t)$ and $H_2(t)$ during the first $T/2$ Gyr. From (1) and (5) we get

$$H_2(T) > 5 \text{ m/(yr AU)}. \tag{7}$$

Moreover, several real-world examples below (see e.g. (11) and (15)) also indicate that this inequality holds.

From (1) we observe that 1 m^3 of the space rises in average 0.2 mm^3 per year, namely,

$$\left(1 + \frac{10}{150 \cdot 10^9}\right)^3 \approx 1 + 3\,\frac{10}{150 \cdot 10^9} = 1 + 0.2 \cdot 10^{-9}.$$

According to (5), a larger part of this amount is due to dark energy. To demonstrate its influence in the Solar system we must either measure very precisely (e.g. the Earth–Moon distance), or we have to consider extremely long time intervals, where all small deviations from Newtonian mechanics are accumulated and then possibly observed. An extremely small deviation $\varepsilon > 0$ during one year may cause after one billion years a quite large and detectable value of $10^9\varepsilon$ which is then interpreted as dark energy. Thus we should never identify any physical model with reality, since the above argument can be applied to any non-Newtonian model as well.

An extremely small time derivative of $H(t)$ for $t = T$ on the scale of the Solar system is derived in Carrera and Giulini (2010, p. 175) yielding a tiny outward acceleration of $2 \cdot 10^{-23}$ m/s^2 at Pluto's distance of 40 AU. Similar very small values are given in Cooperstock et al. (1998, p. 62) and Mashhoon et al. (2007, p. 5041). However, the big value of the Hubble constant itself as given in (1), which implies the large expansion rate (7), is surprisingly not considered in these papers. On the other hand, a more realistic expansion rate of 0.57 H_0 in the Solar system derived from growth pattern on fossil corals is proposed in Zhang et al. (2010).

The perihelion precession of elliptic orbits due to the force induced by the cosmological constant is investigated in Adkins and McDonnell (2007), Adkins et al. (2007), Cardona and Tejeiro (1998). Effects of the cosmological constant on the local dynamics of the Solar system (and binary pulsars) have also been studied by many authors (see e.g. Iorio, 2006a, 2008; Islam, 1983; Jetzer, Sereno, 2006; Kagramanova et al., 2006; Kerr et al., 2003; Kraniotis and Whitehouse, 2003; Rinder, 2001; Sereno and Jetzer, 2006, 2007; Wright, 1998 and the references therein). These papers contain various upper and lower bounds on the cosmological constant in the interval 10^{-52}–10^{-37} m^{-2} which have been derived from the motions of bodies in the Solar system.

3. Was Mars closer to the Sun when it had liquid water?

The total solar power incident per unit perpendicularly to rays at the top of the Earth's atmosphere (corrected to 1 AU) is equal to the *solar constant*,

$$L_0 = 1.36 \text{ kW m}^{-2}. \tag{8}$$

Since the Sun is a star on the main sequence, its luminosity increased approximately linearly with time during the last 4.5 Gyr. See also Bertotti et al. (2003, p. 177) and Kump et al. (1999), where more accurate descriptions are attainable.

Hydrologists estimated from the number of craters in dry river valleys that Mars had liquid water on its surface 3–4 Gyr ago. Shortly after the origin of the Solar system (4.5 Gyr ago) the luminosity of the Sun was only 70% of its current value (see Fig. 2). Con-

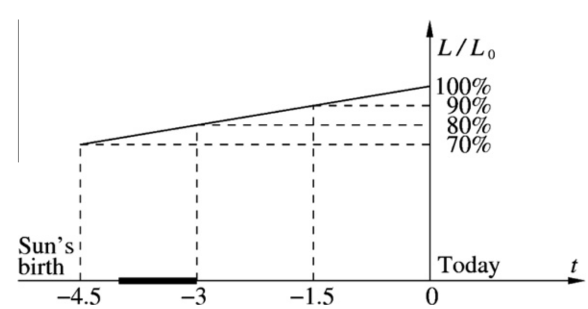

Fig. 2. Relative luminosity L/L_0 of the Sun from the origin of the Solar system up to the present. The time t is given in Gyr.

sequently, 3−4 Gyr ago the Sun's luminosity was about 75% of its current value. Since the solar power decreases with the square of the distance from the Sun, the corresponding luminosity would only be

$$L_{\mathrm{Mars}} = 0.75 L_0 \frac{150^2}{225^2} = \frac{L_0}{3} \qquad (9)$$

provided Mars had been 225 million km farther away from the Sun as it is now. However, a value L_{Mars} three times smaller than L_0 is not able to guarantee an averaged temperature suitable for hundreds of large rivers whose dry riverbeds are now between −40° and 40° of Martian latitude (see Google Mars Maps). Imagine that we would have a permanent two thirds eclipse of the Sun on the Earth. Then surface water even at the equatorial regions of the Earth would be completely frozen although the greenhouse effect is about 15 °C at present. Let us emphasize that a decrease of solar luminosity larger than 5% would cause total glaciation of the Earth. The huge decrease of 66.6% as given in (9) thus excludes the existence of liquid water on Mars if it would not be much closer to the Sun.

Due to measurements of the missions Viking I and II, Pathfinder, Spirit, etc., we know that the current annually averaged temperature on Mars is deeply below the freezing point (about −63 °C). When the Sun's luminosity was only 75% of the present value, the greenhouse effect was surely essential (Bertotti et al., 2003, p. 178; Sagan, Mullen, 1972), but not big enough that it could explain such a large gap in temperatures necessary for the existence of rivers and ocean on Mars.

According to Hartmann (2003, p. 415), an initial atmosphere on Mars had one-third to two-thirds of the surface atmospheric pressure as Earth has today. Moreover, the albedo of Mars' surface was higher than the current value of 0.25, since there were water clouds feeding many rivers. Ice and snow were not only present at polar caps, but also at other regions, which increased the albedo, too.

The above arguments show that Mars had been closer to the Sun by several tens of million km when it had liquid water. For instance, if there were to be equality in (4), then one half of the averaged recession speed given in (1) recalculated to the Mars-Sun distance (i.e. 5 · 225/150 = 7.5 m/yr) would correspond to a shift of about 30 (=4 · 5 · 225/150) million km from the Sun during the last 4 Gyr. However, due to the crucial inequality (5), Mars could be much less than 195 = 225 − 30 million km from the Sun when there were rivers and ocean. Its current secular recession speed will be determinable when laser retroreflectors are installed on Mars or Phobos (Turyshev et al., 2010).

Mars has been the setting for a recent test of general relativity. The gravitomagnetic Lense-Thirring force of Mars essentially secularly shifted the orbital plane of the Mars Global Surveyor spacecraft (Iorio, 2006b).

4. Lunar orbit anomaly

The first observed discordance between the acceleration of the Moon's mean longitude utilizing Ephemeris Time and Atomic Time has been reported in van Flandern (1975)). By four laser retroreflectors installed by the Apollo missions 11, 14, 15 and Lunokhod 2 on the Moon 40 years ago, it has been found that the mean distance D = 384,402 km between the Earth and the Moon increases by about 3.8 cm per year (Dickey et al., 1994; Williams and Boggs, 2009). Tidal forces can explain only 55% of this value, i.e., 2.1 cm per year, see Williams (2000, p. 55) for geological constraints arising from paleontological clocks. This phenomenon is usually referred as the Tidal Catastrophe Paradox (Verbund, 2002). However, the remaining part

$$\Delta = 0.45 \cdot 3.8 \approx 1.7 \text{ cm per year} \qquad (10)$$

could be due to dark energy that determines the part H_2 of the Hubble constant. In Zhang et al. (2010, p. 4016) a very similar averaged value $\Delta \approx 1.6$ cm/yr during the last 500 Myr is independently obtained by measurements of growth patterns on fossils corals. This method uses geochronometrical techniques first introduced in Wells (1963). The large value in (10) is based on the following facts.

The inertial moment of the Earth is $I = 8.036 \cdot 10^{37}$ kg m^2 (Burša and Pěč, 1993) and the Earth's rotation slows down mainly due to tidal forces of the Moon (cca 68.5%), but also of the Sun (cca 31.5%). By a thorough analysis of historical records of solar eclipses (Said and Stephenson, 1996) we know that the length of a day increases by $1.7 \cdot 10^{-5}$ s per year during the last 2700 years. The decrease of the Moon's angular momentum is negligible. From this, the above values, and the conservation of the total momentum of the Earth–Moon system, we can then derive that $\mathrm{d}D/\mathrm{d}t = 0.674 \cdot 10^{-9}$ m/s (for a detailed calculation see Křížek (2009, pp. 1034–1037)). However, the observed value corresponding to the real recession speed of 3.8 cm per year is much higher, namely $\mathrm{d}D/\mathrm{d}t = 1.2 \cdot 10^{-9}$ m/s. Putting these values together, we obtain that $1.7 \approx 3.8(1.2 - 0.674)/1.2$ which is the speed given in (10). Hence,

$$H_2(T) \approx 1.7\ H_0/2.56 = 0.66\ H_0, \qquad (11)$$

taking into account that the Hubble constant as given in (1) recalibrated to the Earth–Moon distance is H_0 = 2.56 cm yr^{-1} D^{-1}. The value in (11) is in very good agreement with formulae (2), (4), and (5). In Zhang et al. (2010) a similar expansion rate of 0.57 H_0 is obtained. Therefore, the unexplained part (10) of the total recession speed 3.8 cm/yr is indeed comparable with the part $H_2(T)$ of the Hubble constant H_0. Dark energy may thus explain the Tidal Catastrophe Paradox. Other anomalies (like an anomalous increase of the eccentricity of the lunar orbit) are reported in Anderson and Nieto (2010), Iorio (2011b,c), Williams and Boggs (2009).

Let us finally estimate the amount of dark energy that the Moon continuously receives. For simplicity assume that the Moon ($m = 0.735 \cdot 10^{23}$ kg) has a circular orbit with radius $r = 384.4 \cdot 10^6$ m around the Earth ($M = 5.976 \cdot 10^{24}$ kg). According to Kepler's third law $r^3/P^2 = MG/4\pi^2$, where P is the period and G the gravitational constant, the total mechanical energy can be expressed as

$$E(r) = \frac{m}{2}\left(\frac{2\pi r}{P}\right)^2 - \frac{mMG}{r} = -\frac{mMG}{2r}.$$

From this and (10) the annual increase of total energy is

$$E(r+\Delta) - E(r) = 1.7 \cdot 10^{18}\ \mathrm{J}, \qquad (12)$$

which corresponds to a power of 53 GW.

5. Fast satellites

At present we know 19 satellites of Mars, Jupiter, Uranus, and Neptune (see Table 1) that are below the corresponding stationary orbit with radius

$$R = \left(\frac{GmP^2}{4\pi^2}\right)^{1/3}, \qquad (13)$$

where m is the mass of a planet, and P is its sidereal rotation. We will call them *fast*, since their orbital period is smaller than P. The tidal bulges continuously reduce their potential energy and orbital periods to keep the total orbital momentum constant. Thus, according to Newtonian mechanics they should approach their mother planets along spiral trajectories and very slightly accelerate the planet's rotation (Bertotti et al., 2003, p. 489). From a statistical point of view it is very unlikely that all these satellites would be captured, since all of them move in the same direction on circular orbits with

Table 1
Radii of fast satellite orbits and the corresponding values proportional to tidal forces per kg.

Planet	Fast satellite	r [km]	m/r^3 [kg/m^3]
Mars	Phobos	9377	778.6
Jupiter	Metis	127,974	905.9
	Adrastea	129,000	884.4
Uranus	Cordelia	49,751	705.1
	Ophelia	53,763	558.8
	Bianca	59,166	419.2
	Cressida	61,767	368.5
	Desdemona	62,658	353.0
	Juliet	64,358	325.7
	Portia	66,097	300.7
	Rosalind	69,926	254.0
	Cupid	74,392	210.9
	Belinda	75,256	203.7
	Perdita	76,417	194.6
Neptune	Naiad	48,227	913.2
	Thalassa	50,075	815.8
	Despina	52,526	706.8
	Galatea	61,953	430.8
	Larissa	73,548	257.5

almost zero inclinations. Therefore, they have been mostly in their orbits approximately 4.5 Gyr even thought some may be parts of larger disintegrating satellites.

Denoting r to be the radius of a given satellite's orbit, tidal forces (per 1 kg of the satellite mass) are proportional to m/r^3, where m is the mass of a planet (Bertotti et al., 2003, p. 96). From Table 1 we observe all fast satellites have this ratio on the same decimal order as Phobos – some larger, some smaller. According to classical mechanics, the approaching speed of Phobos (which was probably captured) to Mars should be about 1.8 cm per year. Assuming a similar speed of 1–2 cm per year for the other fast satellites, we find that all of them should be 45,000–90,000 km closer to their mother planet during the 4.5 Gyr of their existence. However, this contradicts the fact that the radii R of the respective stationary orbits of Uranus and Neptune are 82,675 and 83,496 km. For the time being, their fast satellites are on very high orbits with radii $0.58R$–$0.92R$. Moreover, the radii of stationary orbits (see (13)) were smaller in the past, since the rotations of the planets were faster. Recalibrating the Hubble constant to R corresponding to Uranus or Neptune, we find that $H_0 \approx 0.55$ cm yr^{-1} R^{-1}. Due to the averaged character of this value, the real antigravity forces can yield a shift on the order of 1 cm per year. Hence, it is again dark energy that acts in the opposite direction than gravity, and thus prevents the fast satellites from crashing onto their mother planets. We again see that dark energy acts not only on large scales, but also on small scales.

A similar argument can be applied to the extrasolar planet WASP-18b which need not quickly spiral into its mother star cca 1 Gyr old, even though it is below the stationary orbit (see Southworth et al., 2009). From the evolution of its orbital parameters we could verify the above hypothesis about dark energy within 10 years.

6. Was Earth also closer to the Sun?

The total surface area of our Earth is about half a billion square kilometers, which surely represents a very large natural biochemical laboratory for the origin of life. Life on Earth could also be transported from asteroids or comets whose total surface area is several orders higher. Anyway, life on Earth exists continually for at least 3.5 Gyr and this requires relatively stable conditions during this very long time period. However, the luminosity of the Sun increases approximately linearly (see Fig. 2) and 3.5 Gyr ago it was only 77% of its present value. It is known that a decrease of luminosity of only a few percent caused ice ages in the past. A decrease larger than 5% would cause total glaciation of the whole planet. A decrease or increase of the solar constant (8) up to 5 % corresponds to a ring – the so called *ecosphere* – with radii $(0.95)^{1/2}$ AU and $(1.05)^{1/2}$ AU that represent a very narrow interval 145.8–153.3 million km. This leads to the paradox which is usually referred as the Faint Young Sun (see Bertotti et al., 2003, p. 177; Lang, 2001). The greenhouse effect, higher level of radioactivity, impacts of comets, and more volcanism 3.5 Gyr ago are not able to explain this paradox.

Assume for a moment that the averaged recession speed of the Earth from the Sun is (Křížek, 2009, p. 1038)

$$v = 5.3 \text{ m per year}, \tag{14}$$

which is in a good agreement with (1), (2), (4), (5), and corresponds to the relation

$$H_2(T) \approx 0.53 H_0. \tag{15}$$

Since the luminosity decreases with the square of distance, the speed (14) ensures that the Earth would receive an almost constant energy flux comparable with (8),

$$L(t) = \frac{(0.77 + 0.23t/\tau)L_0 r^2}{(\sqrt{0.77}r + vt)^2} \approx 1.36 \pm 0.005 \text{ kW m}^{-2} \tag{16}$$

for every t from the whole interval $(0, \tau)$, where $\tau = 3.5$ Gyr and $r = 1.496 \cdot 10^{11}$ m = 1 AU. This would, of course, guarantee very stable conditions for the development of life on the Earth. The speed in (14) is optimal in the sense that any other slightly different speed would not yield an almost constant value of the rational function in (16) on the time interval 3.5 Gyr. Therefore, it is probable that the real average recession speed of the Earth from the Sun was close to the value given in (14). Hence, the initial distance of the Earth from the Sun could be about $130 \cdot 10^6$ km $\approx (0.77)^{1/2}$ AU. The Earth was contained all this time in the ecosphere that slowly expanded as sketched in Fig. 3. Outside this region photosynthesis would stop. Dark energy may thus explain the Faint Young Sun Paradox due to formulae (14) and (16).

According to geochemical analysis, the ancient surface temperature on the Earth was much higher than now. Therefore, the real recession speed was probably slightly higher than that in (14), since the Earth's surface temperature 3 Gyr ago may have reached 70 °C (Knauth and Epstein, 1976) and the temperature of the oceans 3.5 Gyr ago was about 80 °C (Lineweaver and Schartzmann, 2003). Note that there were oceans on the Earth already 4.35 Gyr ago. A larger recession speed than that in (14) nicely fits to (6) and (7) which were derived by independent arguments.

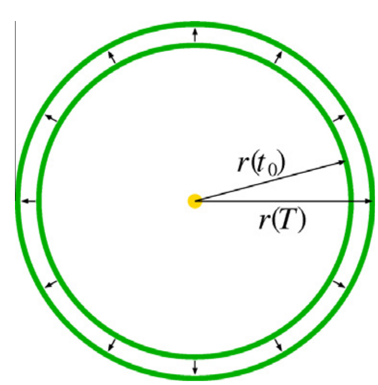

Fig. 3. Schematic illustration of the expansion of the ecosphere during the last 3.5 billion years, where $r(t_0) = 1.3 \cdot 10^{11}$ m, $r(T) = 1.5 \cdot 10^{11}$ m and $t_0 = T - 3.5$ Gyr.

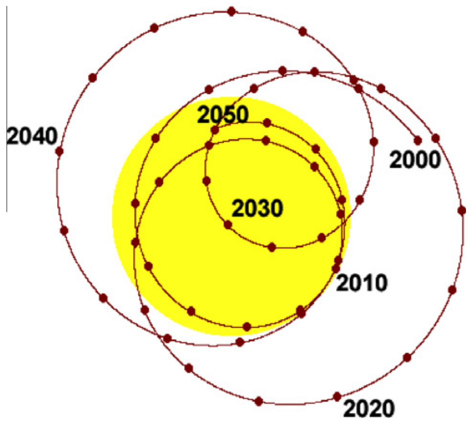

Fig. 4. The position of the Solar system barycenter with respect to the Sun during the period 2000–2050. The diameter of the Sun is about 1400,000 km.

Two more proofs of a larger recession speed than that in (14) were also independently obtained in the groundbreaking paper (Zhang et al., 2010) by a detailed analysis of growth patterns on fossil corals. From their Fig. 4 that contains daily pattern data we find that during the last 500 Myr the Earth–Sun distance increased about 3 million km. This yields an average recession speed of 6 m/yr which is in perfect agreement with (14). From their Fig. 3 which contains lunar pattern data we get a similar average recession speed of 7 m/yr which slowly decreases. By Zhang and Kelley (2011) the Earth's semi-major axis was 146 million km at the beginning of the Phanerozoic Eon, i.e. 0.53 Gyr ago. Hence, the corresponding average recession speed of the Earth from the Sun is $(149.6 - 146)/0.53 = 6.79$ m/yr. Variations in the number of solar days per year are examined in Zhang et al. (2011).

Similarly as in (12) we find from (14) that the annual increase of the total energy is $9.4 \cdot 10^{22}$ J which corresponds to a continuous power of 2976 TW of dark energy that would shift the Earth 5.3 m per year further from the Sun.

According to Schröder and Smith (2008), the Earth will leave the habitable zone within 1 Gyr due to the 10% increase of solar luminosity. The recession speed (14) however guarantees very stable conditions for several Gyr in the future. For instance, after the next 3.5 Gyr from now the luminosity of the Sun will be about 1.32 kW m^{-2} if it behaves as in (16).

7. Anthropic principle

According to the Anthropic Principle (Carter, 1974; Barrow and Tipler, 1986), there are very delicate balances between fundamental physical constants. These fine-tuned constants permitted the emergence of life.

From Fig. 1 we observe that the Hubble constant $H(t)$ and also $H_2(t)$ did not change too much during the last 3.5 billion years. By the previous section it seems that the magnitude of the repulsive term $H_2(t)$ is just right for a recession speed that yields an almost constant flux of solar energy close to (16) over this very long time period. Dark energy thus represents a further support for the (weak) Anthropic Principle. The magnitude of $H_2(t)$ lies in a relatively narrow interval that enabled the origin of intelligent life.

If the recession speed of the Earth from the Sun (and thus also $H_2(t)$) were to be too small compared to (14), then there would be only a short period with suitable conditions for the evolution of life. The averaged temperature of Earth's surface would grow quite rapidly due to the increasing character of Sun's luminosity as indicated in Fig. 2. On the other hand, if the recession speed of the Earth were to be much larger than (14), then the energy flux function $L(t)$ would be essentially decreasing which does correspond to fossil findings.

Unfortunately, the real recession speed cannot be verified by direct measurements of the Earth–Sun distance. From Kepler's third law and (14) we can easily find that the change in orbital period of the Earth after one year would be only 1.5 ms. However, such a small time change cannot also be reliably detected, since the Solar system barycenter travels hundreds of thousands km per year due to the influence of large planets as marked in Fig. 4. Note that one (or two) additional leap-seconds are usually added every year to compensate for the slowing of Earth's rotation.

Let us still note that tidal forces from the Sun, solar wind, and decreasing mass of the Sun can explain a recession speed of only a few cm per year (see e.g. Iorio, 2010a; Noerdlinger, 2008). Consequently, they are negligible with respect to (14).

The increase of the Earth–Sun distance of about 15 cm per year was obtained in Krasinsky and Brumberg (2004). However, this conclusion was derived under a nonrealistic assumption that classical Newtonian mechanics describes the Solar system absolutely exactly. The existence of dark energy was not taken into account at all. The authors calculated the time derivative d(AU)/dt from Keplerian elements considering altogether 62 unknown parameters and assuming the infinite speed of gravitational interaction. Later Pitjeva (2010) obtained the same value 15 cm per year for more than 260 parameters using Newtonian mechanics as well. The secular increase of the Astronomical Unit is investigated also Anderson and Nieto (2010) and Iorio (2005b). It can be explained (Iorio, 2011c) by postulating that there exists a small radial extra-acceleration depending on H_0. Anthropic constraints on the cosmological constant from the Sun's motion through the Milky Way are given in Iorio (2010c) (see also Iorio, 2009a).

8. Further arguments for the influence of dark energy in the Solar system

According to Bertotti et al. (2003, p. 534)), there is a strong evidence that the Kuiper belt of comets had been formed much closer to the Sun in the region with larger velocities. Assuming the equality in (4), we find that one half of the value given in (1) can explain a shift of about 10 AU during the last 4.5 Gyr due to dark energy. For the architecture of the Kuiper belt and its origin we refer to Iorio (2007, 2011a), Lykawka and Mukai (2008) and Matese and Whitmire (2011).

It is an open problem how Neptune could be formed as far away as 30 AU from the Sun, where all movements are very slow (Bertotti et al., 2003). Dark energy can again explain this paradox. Assuming one half of the speed given in (1), we find that Neptune could be formed 4.5 AU closer to the Sun than it is now. Indeed,

$$4.5 \cdot 10^9 \ [\mathrm{yr}] \cdot 5 \ [\mathrm{m/(yr\ AU)}] \cdot 30[\mathrm{AU}] = 4.5 \cdot 150 \cdot 10^9 \ [\mathrm{m}] \\ = 4.5 \ [\mathrm{AU}].$$

This value could be even much larger due to (7). By Kepler's third law the corresponding delay for Neptune and also for Uranus would be about 50 milliarcsecond cy^{-1}. Note that such a small anomalous unexplained shifts are already observed (Standish, 1993).

The influence of dark energy over longer duration left further footprints in the Solar system (Křížek and Brandts, 2010). They are recorded in the physical characteristics of other bodies. For instance, the rotation of Mercury is very slow (59 days) due to larger tidal forces when this planet was closer to the Sun. Tidal forces decrease cubically with distance. Thus, if Mercury were, e.g. 10 million km closer to the Sun 4.5 Gyr ago, then the tidal forces would be twice as large as today.

Since the Earth could be about 125 million km further away from the Sun 4.5 Gyr ago due to (14), Venus (whose current distance from the Sun is 108 million km) had to be also closer to the Sun. Otherwise their orbits would be unstable. Moreover, Mercury and also Venus have no moon, since the corresponding lunar orbits would be unstable closer to the Sun.

A paradoxically very large orbital momentum of the Earth–Moon system (Bertotti et al., 2003, p. 534) can also be explained by dark energy which causes an additional shift in the recession speed of the Moon from the Earth that is not due to tidal forces, see (10).

According to Zhang and Kelley (2011), dark energy is merely another side of dark matter. Note that dark matter is not able to explain the observed secular increase of the Moon's orbital eccentricity and the observed acceleration of orbits of some of the Galilean satellites of Jupiter (Iorio, 2010d). An anomalous behavior of the perihelion of Saturn also requires a thorough explanation (Iorio, 2009b).

9. Conclusions

The Hubble constant can be split into two functions $H = H_1 + H_2$ of a very different origin. The term H_1 corresponds to gravitational interaction, whereas H_2 to dark energy. We showed that H_2 is larger than H_1 at present (see (5)). Therefore, dark energy may contribute, for instance, to a relatively large recession speed 3.8 cm/yr of the Moon from the Earth that cannot be explained by mere tidal forces (that cause only 2.1 cm/yr). Also the magnitude of the recession speed of the Earth from the Sun seems to be influenced by dark energy. Moreover, this speed is just the right amount for there to be an almost constant influx of solar energy from the origin of life on Earth up to present over which time Sun's luminosity has increased approximately linearly. This represents further support for the Antropic Principle. In another words, the magnitude of H_2 lied in a narrow interval that enabled the origin of intelligent life.

For the time being we do not know the source of dark energy that is needed for the accelerated expansion of the Universe. It may come partly from a finite speed of gravitational interaction that causes gravitational aberration which is much smaller than the aberration of light, but positive due to causality (see Křížek, 1999, 2009). Another source of dark energy could be time-varying fundamental physical constants (see e.g. Iorio, 2010b; Sisterna and Vucetich, 1990).

Note that dark energy has no large effects on the Pioneer spacecrafts, since they have flown only a very short time. The observed deceleration $8.5 \cdot 10^{-10}$ m/s^2 is probably caused by other effects, such as interplanetary dust (producing zodiacal light), asymmetric thermal radiation of the heat from the spacecrafts, and the Hubble drug (Zhang, 2011; Zhang and Lei, 2011).

Classical Newtonial mechanics is not suitable especially for long-term simulations due to inaccuracies in the model. It assumes the infinite speed of gravitational interaction, whereas in reality this speed is surely finite which causes aberration effects that are not taken into account. Moreover, the standard n-body problem does not possess Lyapunov stability and thus, small changes due to unexact initial conditions, numerical integration and round-off errors produce another source of large errors in the final stage.

We showed that dark energy acts not only on large scales but also on small scales. It essentially contributes to the migration of planets and their moons, it also causes that many star clusters dissolve (Kroupa, 2007), it helps to reduce the frequency of collisions of galaxies and stars, etc. It has also helped to create suitable habitable conditions on the Earth for several billion years.

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