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Life in the Cosmological Future: Resources, Biomass and Populations

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The amounts of life that can be realized in any ecosystem are determined by the resources of materials and energy, the requirements of the biomass, the rates of usage or wastage, and the life span of the habitat. In the Solar System, carbonaceous asteroids and comets are accessible resources, and meteorite-based microcosms showed that these materials could support microbial and plant life. Based on the measured nutrients, bioavailable materials in the carbonaceous asteroids can yield a biomass of 10^{18} kg, and the total materials of the comets can yield a biomass of 10^{25} kg. The total amount of life in a habitat of finite duration, such as the Solar System, may be measured in terms of time-integrated biomass. In these terms, the potential amount of future life about the Main Sequence Sun can be 10^{34} kg-years, largely exceeding the 10^{24} kg-years of past terrestrial life. Life about brown, red and white dwarf stars may be energy-limited and contribute 10^{46} kg-years in the future. The upper limits of life would in the universe would be obtained by converting all baryonic matter to biomass, and gradually converting the biomass to supporting energy. These projections of cosmo-ecology allow an immense 10^{48} kg-years of time-integrated biomass in the galaxy and 10^{59} kg-years in the universe.

Keywords: Astrobiology, cosmology, ecology, galaxy, solar system

1. Introduction

The future prospects of life have long been of interest, recently as part of astrobiology [1]. These prospects can be quantified by cosmo-ecology that combines the biological requirements of mass and energy with cosmological projections of available resources.

The long-term future of life depends on expansion in space. In fact, pioneers such as Konstantin Tsiolkovsky [2], Robert Goddard, Freeman Dyson [3-6], Robert Forward [7], John D. Bernal [8], Michael Hart [9], and many others proposed technologies to expand life in space. Scientific plans exist for mining the asteroids[10, 11], settling Mars [12-14] and space colonies that could house billions [15, 16]. The prospects for life in the late Solar System were examined [17, 18], and we proposed directed panspermia missions to expand microbial life to other solar systems [19-22]. Human expansion in the Solar System and beyond is now a recognised NASA objective [23].

Life will need new resources for expanding in space. Ecology addresses the relations between the biota and resources [24, 25]. Similarly, astroecology addresses the relations between potential biota and resources in space, and in general, between life and its cosmic environment [26-29]. In this respect, the present paper aims to quantify the possible amounts of future life as a function of the available resources.

As to potential space resources, experiments with meteorites confirmed that microorganisms and plants can grow on carbonaceous chondrite materials similar to those in asteroids and comets. The contents of soluble, bioavailable nutrients in these materials were measured [27-30]. These data allow estimating the maximum biomass and populations in this and other similar solar systems, using asteroids and comets. In more distant eras, life is likely to be energy-limited, and its quantity may be estimated using cosmological predictions [31]. However, present cosmological models have large uncertainties. The main objective here is to present approaches for quantifying prospective life. These methods may be applied to any future projections of cosmology.

The present paper will use time-integrated biomass, denoted as $\mathrm{BIOTA}_{\mathrm{int}}$ and measured in units of kg-years, to quantify life [30]. For example, a small animal or plant of 1 kg would contribute in one year 1 kg-year, and a human of 50 kg would contribute over a lifetime of 100 years 5,000 kg-years of time-integrated biomass (or 100 human-years, in units similar to labour measured in man-years).

The amount of potential biomass in any ecosystem, up to the galaxy, depends on:

- The amounts of resource materials;
- The concentrations of nutrients in the resource materials and in biomass;
- The rate at which the resource is used up, dissipated or wasted;
- Energy sources and living space that accommodate the biomass;
- The lifetime of the habitat.

In addition, if the biomass is constructed by technology, its extent will depend on the motivations that guide the technology. As to this factor, Tsiolkovsky discussed a cosmist philosophy [2], motivations for planetary terraforming were discussed [32], and an astroethics framework was proposed whose objective is to maximize life in the universe [20-22]. These goals can be quantified by the calculations of time-integrated biomass.

The objective of this paper is to quantify the *upper limits of organic gene/protein life that are allowed by the resources of matter and energy*. Whether, and how, these limits may be achieved is beyond this paper. Obviously, other constraints can impose lower limits, such as unsuitable environments or slow space travel. Also, the amounts of life in a self-defined future will depend on ethical motivation as much as on physical resources (see Appendix 4). The present paper addresses only the limits imposed by future resources, based on the cosmological forecasts of Adams and Laughlin [31].

2. Resources, Biomass and Populations in the Solar System

2.1 Can Asteroid Materials Support Life?

The Solar System can be colonized using current levels of technology. Advanced methods of space travel such as antimatter propulsion and interstellar hydrogen ramjets, or mining the gas planets and the solar wind, and elemental transmutation, may become possible but are uncertain.

With current levels of technology, the most readily accessible resources will be carbonaceous chondrite asteroids that contain organic compounds and water [10, 11, 15, 16]. For example, the CM2 meteorites contain about 2% organics and 10% mineral-bound water by weight. The organics contain a coal-like polymer and even amino acids and adenine [33-35].

Can life survive on these materials? To test this question, we measured essential nutrients in carbonaceous chondrite materials from meteorites that are similar to asteroids and comets. We also tested small planetary microcosms based on these materials and observed the growth of algae, bacteria and plant cultures. The results showed that the fertilities of Martian and carbonaceous chondrite materials are similar to agricultural soils [27-29]. The main constituents of these space materials are basically similar to terrestrial materials: silicates, organics and water. The results are therefore not surprising, but they have important implications: If life can exist on Earth, then life can find resources to expand throughout the universe.

2.2 Nutrients in Asteroids and Comets

The biomass $m_{x,biomass}$ that can be constructed from planetary materials depends on the concentration of each nutrient x in the resource materials and in biomass, equation (1).

$$m_{x,biomass} = m_{resource}\, c_{x,resource}/c_{x,biomass} \qquad (1)$$

Here $c_{x,,resource}$ (g/kg) is the concentration of element x in the resource material, $c_{x,biomass}$ (g/kg) is the concentration of element x in a given type of biomass and $m_{x,biomass}$ (kg) is the amount of biomass constructed from $m_{resource}$ (kg) of resource material. From these relations we can calculate the amount of biomass that could be constructed if x was the limiting nutrient and all other nutrients were unlimited. Table 1 lists some definitions used, and Tables 2 and 3 show the elemental concentrations in carbonaceous chondrite materials ($c_{x\ resource}$) and in biomass (c_x biomass). Table 4 shows several types biomass that could be constructed from 1 kg of carbonaceous chondrite materials, if each of the nutrients shown was limiting. These amounts can be multiplied by the 10^{22} kg material in the carbonaceous asteroids, or by 10^{26} in the comets [36], to calculate the biomass allowed by these resources, assuming that their composition is similar to the CM2 Murchison meteorite.

2.3 Biomass and Estimated Populations

Applications of the above data can be illustrated by calculating the populations that are allowed by asteroid and cometary materials.

The allowed biomass is defined by the lowest limiting element. In terrestrial ecology nitrogen, phosphate and potassium are often limiting. Table 4 shows that these elements yield the smallest amounts of biomass also using carbonaceous chondrite materials, where nitrogen is most limiting, and in a resource with the solar (cosmic) distribution of elements,

TABLE 1: *Some Terms Applied in Astroecology, and Units and Data Used in the Present Calculations*.

	Units	Quantity	Definitions and formulas
RESOURCES			
Carbonaceous asteroids	kg	10^{22}	
Comets	kg	10^{26}	
Limiting nutrient			The nutrient that allows the least amount of biomass
Nutrient concentrations and elemental contents	g/kg	See Table 2	The content (grams) of a nutrient element per kg of resource material
Usage or waste	kg/year	$k_{waste} M_{biomass}$	Amount of biomass used, or lost as waste, per year
Baryonic matter	kg	10^{41} (galaxy), 10^{52} (universe)	
BIOMASS			
Biomass constructed from asteroids/comets	g/kg	See Table 2.	The amount of biomass (grams) that can be constructed from 1 kg of resource materials according to element x
Biomass of human individual	kg/individual	50	
Supporting biota	kg/individual	0 (independent humans); 1,000 (supported humans)	biomass required to support a human individual
time-integrated biomass ($BIOTA_{int}$)	kg-years		$BIOTA_{int} = \int_{t_o}^{t_f} M_{biomass,t} dt$
time-integrated populations	human-years		
Elemental contents in biomass	g/kg		
Baryonic matter	kg	10^{41} (galaxy), 10^{52} (universe)	
POWER SOURCES AND REQUIREMENTS			
Luminosity	Watts		The power output of a star, i.e.. energy output per second
Luminosity – Sun	Watts	3.8×10^{26}	Mass: 10^{30} kg Life-time: 5×10^{9} years
Luminosity – red dwarf	Watts		
Luminosity - white dwarf	Watts	10^{15}	Life-time: 10^{20} years
Power requirement of biomass	Watts/kg	2 (human), 200 (bacteria), 100 used here; or 1,000/per person (industrial society)	Power from energy source, including conversion efficiency, required by one kg of biomass

where potassium is limiting. For example, using current-level or more advanced technology, the water-extractable or total nitrogen contents of 1 kg of asteroid/cometary materials would yield 0.00034 or 0.042 kg of bacteria, or 0.00025 or 0.031 kg of human (mammalian) biomass, or 0.00048 or 0.060 kg general biomass, respectively. Table 4 shows that the bioavailable soluble nitrate in the 10^{22} kg carbonaceous chondrite asteroids would allow constructing 4.8×10^{18} kg of average general biomass, and if optimized ecosystems can support 1 human per 1,000 kg biomass, this would allow a population of 4.8×10^{15} humans (the two-digit figures illustrate the results of the calculations, the actual uncertainty is larger). If a more advanced technology extracts all the elemental contents and also develops fully self-sufficient humans, the asteroid nitrogen would allow 6×10^{20} kg of general biomass or 3×10^{20} kg of mam-

TABLE 2: *Contents of Nutrient Elements, Total Organic Carbon, and Water in Meteorites and in Some Terrestrial Materials (gram/kilogram).*

	C	N	S	P	Ca	Mg	K	Water
EXTRACTABLE CONTENTS[a]								
Allende Meteorite	2.0[b]	0.004	0.36	0.0075	0.097	0.20	0.034	20[b]
Murchison Meteorite	1.8	0.008	7.6	0.005	3.0	4.0	0.34	100[b]
Agricultural soil	-	0.001	0.007	0.001	0.040	0.040	0.030	-
TOTAL CONTENTS								
Murchison Meteorite	18.6[b]	1.0[b]	32.4[b]	1.1[b]	13[b]	114[b]	0.28[b]	100[b]
SOLAR ABUNDANCE								
	3.94	0.95	0.40	0.0077	0.068	0.76	0.0043	9.71[c]

Notes: a. Elements extracted under hydrothermal extractions in pure water at 120 ^{o}C for 15 minutes. Calcium (Ca), magnesium (Mg) and potassium (K) are extracted as elements in ionized forms Ca^{2+}, Mg^{2+} and K^{+}; sulfur (S) is extracted as sulfate SO_4^{2-}, nitrogen (N) as nitrate NO_3^{-} and phosphorus (P) as phosphate PO_4^{2-} (Mautner, ref. 28). b. Total concentrations of carbon, water and other elements in Murchison (Jarosewich, ref. 33, Fuchs *et al.*, ref. 34.). c. Calculated on the basis of the concentration of oxygen as 8.63 g/kg in solar material and MW(H_2O/O) = 18/16, considering oxygen as the limiting factor in constructing water. The solar abundance of hydrogen in solar matter is 789 g/kg, which makes it not a limiting element for producing water.

TABLE 3: *Elements in Microbial, Algal, Plant and Mammalian Biomass (Gram Element per Kilogram Dry Biomass)[a].*

	C	H	O	N	S	P	Ca	Mg	K
Bacteria	538	74	230	96	5.3	30	5.1	7.0	115
Brown algae	345	41	470	15	12	2.8	11.5	5.2	52
Plants (angiosperm)	454	55	410	30	3.4	2.3	18	3.2	14
Mammals	484	66	186	128	16	43	85	1.0	7.5
Average biomass	462	59	329	67	7.4	15.5	21	3.0	34.4

Notes: a. From Bowen, ref. 41. The concentrations of C, H and O in brain tissue were not listed by Bowen and we assume them to be equal to concentrations in other mammalian tissue. Average biomass in the last row is the average elemental concentration in bacteria, brown algae, angiosperms, gymnosperms, mammalian tissue and mammalian brain biomass as given by Bowen (ref 41).

TABLE 4: *Full Wet Biomass That can be Constructed Using Each Extractable Element, or Using the Total Elemental Contents, of Carbonaceous Chondrite Meteorites/Asteroids[a] or From a Resource That Contains Elements With the Solar Distribution[a] (kg Biomass/kg Resource).*

	C	H	O	N	S	P	Ca	Mg	K
CARBONACEOUS CHONDRITES, EXTRACTABLE ELEMENTS[b]									
Bacteria	0.013	0.11	0.12	0.00034	5.7	0.0007	2.4	2.3	0.012
Mammals	0.015	0.11	0.13	0.00025	1.9	0.0005	0.14	16.0	0.018
Av. Biomass	0.016	0.11	0.12	0.00048	4.1	0.0013	0.57	5.3	0.04
CARBONACEOUS CHONDRITES, TOTAL ELEMENTS[b]									
Bacteria	0.14	0.010	0.12	0.042	24.4	0.15	10.2	65.1	0.11
Mammals	0.15	0.15	0.13	0.031	8.1	0.10	0.61	456	0.11
Av. Biomass	0.16	0.033	0.12	0.060	17.5	0.28	2.5	150	0.11
SOLAR DISTRIBUTION OF ELEMENTS									
Bacteria	0.029	7.8	0.012	0.040	0.30	0.001	0.054	0.43	0.001
Mammals	0.033	7.9	0.012	0.030	0.10	0.001	0.003	3.0	0.0023
Av. Biomass	0.034	8.1	0.012	0.057	0.22	0.002	0.013	1.0	0.0005

Notes: a. Based on the data in Tables 2 and 3 and equation (1). The wet biomass was calculated assuming a ratio of wet/dry biomass = 4.0, i.e., assuming that the content of each element except H and O in wet biomass is $c_{x,\text{wet biomass}} = 0.25c_{x,\text{dry biomass}}$. To account for the H and O in biological water, the calculations used $c_{H,\text{wet biomass}} = [c_{H,\text{dry biomass}}/4 + (1{,}000\text{x}2/18)]$ g/kg and for O, $c_{O,\text{ wet biomass}} = [c_{O,\text{ dry biomass}}/4 + (1000\text{x}16/18)]$ g/kg.
b. To calculate the total biomass (kg) that can be constructed from the extractable or total materials in 10^{22} kg asteroids, multiply the numbers in the top and middle Tables by 10^{22} kg, respectively. For the biomass constructed from 10^{26} kg cometary materials, multiply these data by 10^{26} kg.

TABLE 5: *Estimated Resources, Biomass and Time-Integrated Biomass ($BIOTA_{int}$) That can be Supported by the Principal Resources in Future Periods of Cosmology.*

Location	Materials and mass (kg)	Power (Watts)	Number in the Galaxy	Life-time (y)	Biomass (kg)[a,b]	$BIOTA_{int}$ (kg-y)[a,b]	$BIOTA_{int}$ in galaxy (kg-y)[a]
Earth to Present				$4x10^9$	10^{15} [c]	$4x10^{24}$ [c]	
Solar System	Asteroids, 10^{22}	$4x10^{26}$	10^{11}	$5x10^9$	$5x10^{18}$ [d] $(6x10^{20})$[e]	$3x10^{28}$ [d] $(3x10^{30})$[e]	$3x10^{39}$ [d] $(3x10^{41})$[e]
Solar System	Comets, 10^{26}	$4x10^{26}$	10^{11}	$5x10^9$	$5x10^{22}$ [d] $(6x10^{24})$[e]	$3x10^{32}$ [d] $(3x10^{34})$[e]	$3x10^{43}$ [d] $(3x10^{45})$[e]
Red Giants	Comets, 10^{26}	10^{30}	10^{11}	10^9	$6x10^{24}$ [e]	$6x10^{33}$ [e]	$6x10^{44}$ [e]
White Dwarfs		10^{15}	10^{12}	10^{20}	10^{13} [f]	10^{33}	10^{45}
Red Dwarfs		10^{23}	10^{12}	10^{13}	10^{21} [f]	10^{34}	10^{46}
Brown Dwarfs		10^{20}	10^{11}	10^{10}	10^{18} [f]	10^{28}	10^{39}
Galaxy	Baryons, 10^{41}	mc^2/t		10^{37} [g]	$<10^{41}$		10^{48} [h]
Universe	Baryons, 10^{52}	mc^2/t		10^{37} [g]	$<10^{52}$ [i]		10^{59} [h, i]

Notes: a. The figures are order-of-magnitude estimates and the digits shown indicate the results of the calculations but don't imply this degree of accuracy. b. Per solar system. c. Assuming the estimated present 10^{15} kg biomass (ref. 41) for the past $4x10^9$ years, as an upper limit. d. Biomass obtained using extractable elements in asteroids or comets, respectively, based on N as the limiting nutrient. e. Biomass obtained using total elemental contents of asteroids or comets, respectively, based on N as the limiting nutrient. f. Biomass based on power supply of 100 Watts/kg as the liming factor. g. Proton decay time estimated by Adams and Laughlin, ref. 31. h. Based on the dissipation of mass as bioavalaible energy. i. Amount in the universe.

malian biomass, contained in a population of $6x10^{18}$ self-supporting 50 kg humans,. Assuming a similar composition for cometary nuclei, these numbers may be multiplied by 100 or 10,000 for the biomass allowed by the 10^{24} kg Kuiper Belt comets and 10^{26} Oort Belt comets, respectively. Table 5 summarizes the biomass that can be constructed in the Solar System and in the other habitats discussed below. These large populations would allow diverse biological and cultural evolution.

2. 4 Ecosystems with Finite Time Time-Spans, and the Effects of Wastage

The total amount of life in time-limited ecosystems depends not only on the biomass at any given time, but also on the longevity of the ecosystem. The time-integrated biomass is calculated using equation (2) and is denoted by $BIOTA_{int}$ (Biomass Integrated Over Time Available).

$$BIOTA_{int} = \int_{t_o}^{t_f} M_{biomass,t} dt \qquad (2)$$

Here $M_{biomass, t}$ (kg) is the biomass at time t, and integration extends from start of life t_o to the final inhabited time t_f of the ecosystem. Convenient units are kg-years. The total human life in the ecosystem may be expressed similarly in human-years, similarly as labour is expressed in man-years.

If even a small amount of biomass could exist for infinity in a perfectly recycling ecosystem, then $BIOTA_{int}$ would be infinite. However, biology requires a cycling of materials and energy, which inevitably results in dissipation or wastage. For example, materials on planets may become irreversibly bound in regolith, or leak to vacuum from space habitats. Even a low rate of wastage can seriously affect the time-integrated biomass.

For example, assume as discussed above that the materials of the carbonaceous asteroids are processed into $3x10^{20}$ kg mammalian biomass in a population of $6x10^{18}$ humans. This population can be obtained from the current world population of six billion with a growth rate of 2% per year in only 1046 years, nearly instantaneously on cosmological time-scales. A technologically advanced society may achieve a highly efficient ecology where, for example, only one part in ten thousand, i.e., 10^{-4} of the biomass/year is dissipated. At this rate every kilogram of biomass yields 10^4 kg-years of time-integrated biomass until all of the mass is dissipated (see equation A7 in Appendix 2). The initial mammalian biomass of $3x10^{20}$ kg would then yield a time-integrated biomass of $3x10^{24}$ kg-years. If all the biomass constituted humans, the population will have lived $6x10^{22}$ human-years. These figures may be multiplied by a factor of 10^4 using cometary resources.

Even at this low rate of wastage, the initial population of $6x10^{18}$ would decrease to the last individual after only 432,382 years (see equation A5 in Appendix 2). An initial general biomass of $6x10^{20}$ kg would decrease to the last bacterium of 10^{-15} kg after 823,822 years, and life would cease much sooner than the habitable five billion years of the Solar System.

Can the integrated biomass be increased if the resources are used gradually? Equation A6 in Appendix 6 shows that $\mathrm{BIOTA_{int}}$ depends only on the biomass constructed $\mathrm{M_{biomass,\,0}}$ and on $\mathrm{k_{waste}}$, and it is independent of the rate of construction. However, constructing the biomass more slowly will result in a smaller steady-state biomass, proportionally smaller absolute dissipation, and a longer-lasting ecosystem. For example, we may use the asteroids to construct biomass over the next five billion habitable years under the current Sun, so that $6\text{x}10^{20}/5\text{x}10^{9} = 1.2\text{x}10^{11}$ kg is constructed per year. A waste rate of 0.0001 y^{-1} would result in a steady-state biomass of $1.2\text{x}10^{15}$ kg (Equation A3 in Appendix 2), which would be dissipated at the rate of $1.2\text{x}10^{11}$ kg y^{-1} during the five billion years of the Solar System. The maximum biomass at any time would be reduced by a factor of $5\text{x}10^{5}$ but still a substantial population of $1.2\text{x}10^{12}$ biomass-supported or $2.4\text{x}10^{13}$ self-sufficient humans could exist throughout the habitable lifespan of the Sun.

In summary, given a specific amount of resources, the integrated biomass can be maximized by minimizing its rate of dissipation. If this rate can be reduced sufficiently, all the constructed biomass can last for the duration of the habitat, in which case it pays to construct the biomass as fast as possible. However, if the rate of dissipation is significant vs. the lifetime of the habitat, the construction rate of the biomass and its steady-state amounts may be reduced. This will not increase the time-integrated biomass, but the reduced steady-state biomass and population can then last throughout the lifetime of the habitat.

2. 5 Energy

The maximum biomass sustained by a power source can be calculated using

$$\mathrm{M_{biomass} = P_{source}\ x\ (efficiency)/(power\ use\ per\ unit\ biomass)} \quad (3)$$

Here $\mathrm{P_{source}}$ is the total power output, which is $3.8\text{x}10^{26}$ Watts for the Sun, yielding a flux of 1.35 kW/m^2 at 1 AU. Plants can convert solar energy to chemical energy through photosynthesis. The maximum efficiency for biomass yield is 0.08 by sugar cane, and about 0.01 - 0.05 in agricultural fields. Current photocells convert solar power to electricity with about 0.1 efficiency. We consider an optimized efficiency of 0.1 for converting solar power for biological use.

The biological power use of humans is on the order of 100 Watts per person i.e., about 2 Watts per kg of biomass or 10 Watts per kg of metabolically active biomass. Including an efficiency factor of 0.1, this requires a supply of 100 Watts per kilogram of metabolically active biomass. The power use in industrial societies is on the order of 10,000 Watts/person or 200 Watts/kg human biomass or 1,000 Watts/kg of metabolically active biomass. Altogether, allowing for conversion efficiencies, we may consider a power requirement of 1,000 Watts/kg biomass.

With these requirements, the Sun can sustain with power $4\text{x}10^{23}$ kg of biomass, larger than the $6\text{x}10^{20}$ kg biomass constructed from the asteroids. However, coincidentally, the $4\text{x}10^{23}$ kg of biomass sustainable by solar energy is comparable with the estimated $6\text{x}10^{24}$ kg that can be constructed from the comets. This estimate uses the entire power output of the Sun captured in a Dyson sphere [4, 5]. Constructing such a sphere of a fleet of 0.1 mm thick collector solar sails in orbit at 1 AU would require on the order of $5\text{x}10^{21}$ kg material, near the upper limits of asteroid resources. A more realistic capture of 0.001 of the solar output would support a biomass of $4\text{x}10^{20}$ kg, comparable to the amount allowed by the asteroids. The energy and material resources of the Solar System can therefore allow comparable biomass in the Solar System.

While considering solar energy, note that the intensity of solar light (energy flux per unit area) is an important biological variable. This flux varies inversely with the square of the distance from the Sun. Can photosynthetic algae and plants grow in the reduced solar light flux at the asteroid belt and in the outer Solar System? Endolithic algae can grow inside rocks, and benthic species grow under water where only a small fraction of the solar radiation incident on the surface penetrates. The limit of photosynthesis was reported as about 4-10 nmole photons $m^{-2}\ s^{-1}$ or about 10^{-5} of the solar flux at Earth [37, 38]. As for plants, we tested the effects of reduced light intensity on asparagus tissue cultures [28]. Plants were grown at about one tenth of the natural solar irradiance, comparable to solar radiation at 3 AU in the asteroid belt.

Asparagus cultures were also grown on extracts of the Allende and Murchison meteorites at light flux about 80 times weaker than the solar irradiance on Earth, comparable to solar irradiance at 9 AU, about the distance of Saturn. The asparagus yields on the Allende extracts were reduced by a factor of 0.55 while those grown on the extracts of the Murchison meteorites increased by a factor of 1.25 compared with the cultures grown under 0.1 solar radiance [28]. The results suggest that solar light can support plant growth at the distance of Mars, the asteroid belt, and on the moons of Jupiter and Saturn. Low-level photosynthesis may be possible out to 300 AU, based on Raven *et. al.* [37, 38].

2.6 Living Space

The maximum population of about 10^{23} humans based on cometary resources may be distributed in the volume of a Dyson Sphere about the Sun, in a spherical shell at the distance of the Earth from the Sun with a radius of 1.5x10^{11} m. The inhabited volume may be centred closer or further from the Sun depending on the desired equilibrium temperature. Assume that each individual will require the spacious living volume of a cube 100 meters on each size within this zone, about the size of a 40 story high-rise building. The required volume of 10^{29} m^3 can be provided by spreading out the population at 1 AU in a shell with an area of 2.8x10^{23} m^2 and a thickness of 354 km, about the length of a small country. Larger populations can be accommodated by spreading the population in thicker shells in the habitable zone. The orbital mechanics of keeping the population in this zone need to be considered, but as for resources, Lewis showed that the metals in asteroids can easily provide the needed construction materials to house such large populations [10]. Therefore, living space and construction materials do not limit the population in the Solar System.

3. Galactic Ecology and Cosmic Ecology

3.1 Populations About Red Giant and White Dwarf Suns

The evolution of the Sun and other stars in trillions of future years can be predicted only by theory since observational astronomy covers only the first fourteen billion past years. This section will rely on the model presented by Adams and Laughlin [31].

After the current phase, the Sun will become a red giant and then a white dwarf star. The Earth will be destroyed during the red giant phase but the Solar System itself may remain habitable during this stage and during the 10^{20} year white dwarf phase of the Sun [31]. The population will only need to move closer or further from the Sun as its luminosity varies. The other estimated 10^{12} white dwarfs in the galaxy might also sustain life for 10^{20} years.

The luminosity of the Sun will increase on the order of 2,000 times during the Red Giant phase, which will end with an unstable period of thermal pulses when the luminosity may reach about 6,000 times its current value [39]. Stern considered life in this late “delayed gratification habitable zone” [18], and some ecological aspects will be addressed here.

The habitable zone about a star is defined by the temperatures at which life can survive. For example, it may be defined as the zone where the equilibrium temperature of a blackbody object is between 0 and 100^o C. We may also define a “comfort zone” where the equilibrium temperature is 25^o C.

The equilibrium temperature increases with the luminosity of the Sun and it decreases with the heliocentric distance (equation A14 in Appendix 3). When the luminosity of the Sun increases 2,000 times its present value, the habitable zone will be between 25 and 47 AU, and the comfort zone of 25 C will be about 39 AU. At a later stage when the luminosity of the Sun increases to 6,000 times of its present value, the habitable zone will be between 43 to 81 AU and the comfort zone will be about 68 AU. By this time the Sun will lose some of its mass, the planets will move further out [29], and Neptune, Pluto and the inner Kuiper Belt comets may move closer to the new habitable zones.

The location of the habitable zone will force the population to move to the area of the Kuiper Belt. There are an estimated 35,000 Kuiper Belt objects including Pluto with radii larger than 100 km and a total mass of about 10^{24} kg [36]. These cometary nuclei are rich in water, organics and inorganic nutrients. According to Table 5, their total elemental contents can support a biomass on the order of 6x10^{22} kg. A population can live on these resources for the 10^9 years during the red giant phase Sun, giving $\mathrm{BIOTA}_{\mathrm{int}}$ on the order of 6x10^{31} kg-years.

The resources of the Kuiper Belt will be available only if these cometary nuclei survive the red giant phase of the Sun. This question was also considered [17]. Briefly, ices in comets could evaporate if heated, but equations A12 – A14 in Appendix 3 show that objects further than 268 AU will remain below 150 K even when the Sun is most luminous. They may lose some volatiles from their surfaces and form a protective crust, similar to burnt-out comets. The Oort cloud comets at 40,000 AU will be much colder, at 12 K even when the Sun is the most luminous. The mass of the surviving Kuiper Belt and the Oort Cloud comets will therefore retain on the order of 10^{26} kg organics and water.

Can these resources be accessed? A velocity of 10^{-4} c can be obtained by current solar sails. Space travel at this speed to the comfort zone at 68 AU will last only

11 years and travel to 1000 AU to the Kuiper Belt will last 158 years. Such travel times are accessible for humans with somewhat extended life spans. It is comforting that human populations may survive the hottest periods of the Solar System in this manner. Travel to the colder Oort cloud at 40,000 AU would last 6,342 years and travel to nearby habitable stars may last millions of years, with uncertain feasibility [40].

Once past the red giant period, life may continue up to 10^{20} years using the power output of the white dwarf Sun, which will be reduced to the size of the Earth with a surface temperature of 63 K and a luminosity of 10^{15} Watts. This output will be powered by the capture and annihilation of dark matter, if this speculative process really occurs [31]. Populations can then move close to the white dwarf Sun and capture its power in a Dyson Sphere [3, 5] as suggested by Adams and Laughlin [31]. The low-temperature radiation may be focussed by mirrors or converted to electrical energy for heating, at the cost of considerable wastage.

At this stage power, rather than matter, may limit the viable biomass. Assuming a power requirement of 100 Watt/kg biomass, the white dwarf star can support a biomass of 10^{13} kg, possibly in the form of 10^{11} self-sufficient humans, for 10^{20} years. This yields a time-integrated $\mathrm{BIOTA}_{\mathrm{int}}$ of 10^{33} kg-years possibly consisting of 10^{31} human-years. The material for this biomass can be obtained from an asteroid or comet of about 10^{15} kg with a radius of about 6 km. Although comets will be dispersed by passing stars [31], a fraction will stay in the Solar System or may be preserved as Dyson Spheres.

The population may have to be reduced if it captures only part of the stellar energy or converts it with low efficiency. Using one percent of the stellar power, a population of a billion can each have access to 10 kW of power, at the living at standards of industrial societies.

By this scenario humans and a diverse biota can exist in our Solar System for an immensely long hundred million trillion years. The time-integrated biomass is a trillion times larger than the about 10^{15} kg biomass[41] x 10^{9} y = 10^{24} kg-years of life that has existed to date, and its lifespan more than a hundred billion times longer than of life on Earth to date.

3. 2 The Effects of Wastage

The above considerations assumed no wastage. However, on long time-scales even a minute rate of wastage can dissipate large amounts of materials, and if the resources cannot replace this loss, the steady-state biomass would have to be reduced to allow the ecosystem to last longer. Quantitatively, the relation is given by equation (4):

$$M_{\mathrm{biomass}} k_{\mathrm{waste}} t = M_{\mathrm{resource}} c_{x(\mathrm{limiting}),\ \mathrm{resource}} \tag{4}$$

The terms were defined above and in Table 1. The concentration of the limiting resource in the cometary materials, $c_{x(\mathrm{limiting}),\ \mathrm{resource}}$ is given by Table 4 as 60 g/kg for nitrogen. As an example, the 10^{22} kg of asteroid materials may need to sustain the biota and its wastage about the White Dwarf Sun for 10^{20} years. Equation (4) shows that the sustainable rate of wastage $k_{\mathrm{waste}} \times M_{\mathrm{biomass}}$ is then 6 kg/year. If the 10^{15} Watt power output of the White Dwarf Sun is all used, it can sustain 10^{13} kilogram of steady-state biomass. In this case, the rate of waste can be only $6\mathrm{x}10^{-13}$ fraction of the biomass per year. On the other hand, with a more realistic rate of waste of $10^{-4}\ M_{\mathrm{biomass}}\ \mathrm{y}^{-1}$ the steady-state M_{biomass} must be reduced to $6\mathrm{x}10^{4}$ kg allowing only a human population of a thousand. Even this small wastage reduces the biomass and population by a factor of $1.7\mathrm{x}10^{8}$ compared with that allowed by solar power, unless materials are provided from other sources to sustain the energy-limited 10^{13} kg biomass and its 10^{29} kg of waste over 10^{20} years. These examples illustrate the importance that advanced technologies should eliminate waste.

3.3 Resources and Populations in the Future Galaxy

A purposeful civilisation may colonize the galaxy in a billion years, perhaps impelled by the red giant Sun. The contribution of each type of star to the total amount of life in the galaxy $\mathrm{BIOTA}_{\mathrm{int,\ galaxy}}$ can be calculated using equation (5).

$$\mathrm{BIOTA}_{\mathrm{int,\ galaxy}} = \mathrm{BIOTA}_{\mathrm{int,\ star}}\, n_{\mathrm{star}} = M_{\mathrm{biomass,\ star}}\, t_{\mathrm{star}}\, n_{\mathrm{star}} \tag{5}$$

Here $M_{\mathrm{biomass,\ star}}$ is the sustainable steady-state biomass about a given star for t_{star} years, n_{star} is the number of these stars in the galaxy, and $M_{\mathrm{biomass,\ star}}\, t_{\mathrm{star}}$ expresses the integrated biomass $\mathrm{BIOTA}_{\mathrm{int,\ star}}$ about the given type of star. These terms of course have large uncertainties. Each type of star will also have a wide distribution of masses, luminosities, material resources and lifetimes, which can support a wide distribution of the time-integrated biomass. Again, using current cosmology [31], we can obtain numerical estimates that are summarized in Table 5.

The first environment will be red dwarf stars with luminosities of 0.001 to 0.0001 times that of the Sun, that is, on the order of 10^{23} Watts, which can support 10^{21} kg biomass. Given enough materials, the sustainable integrated $\mathrm{BIOTA_{int}}$ with a lifetime of 10^{13} years about red dwarfs is on the order of 10^{34} kg-years, and 10^{12} red dwarfs in the galaxy will allow a $\mathrm{BIOTA_{int}}$ of 10^{46} kg-years.

Brown dwarfs may also accommodate life. These small stars are lighter than 0.08 M_{Sun} but somewhat heavier than the gas planets. They radiate heat slowly due to gravitational contraction with a typical luminosity of 10^{20} Watts, which can support 10^{18} kg biomass for the 10^{10} year lifetime of these stars. This contributes 10^{28} kg-years of potential integrated biomass per star, and the 10^{11} such stars in the galaxy would contribute 10^{39} kg-years of integrated biomass.

In the long term, collisions between brown dwarfs will give rise to the last red dwarf stars, possibly forming also habitable planets [31]. The total power output of these last stars in the galaxy will be similar to that of a single star like the Sun, on the order of 10^{26} Watts, supporting 10^{24} kg biomass. With lifetimes of 10^{14} years they can contribute 10^{38} kg-years to the integrated biomass in the galaxy. However, their number in the galaxy is not available and therefore their total contribution to the integrated biomass cannot be ascertained. This contribution may be smaller than of other ecosystems, but this mode of star formation can produce liveable environments for a long time.

The longest lasting stars in the galaxy will be the white dwarfs. Most of the stars that have ever formed in the galaxy will end up at this stage, yielding on the order of a trillion, 10^{12} such stars [31]. As discussed above for our Sun, each can yield a $\mathrm{BIOTA_{int}}$ of 10^{33} kg-years giving a $\mathrm{BIOTA_{int}}$ of 10^{45} kg-years in the galaxy.

The estimates of biomass for each ecosystem in the galaxy can be extended to the universe by multiplying by the estimated 10^{11} galaxies. Unless there is local life in these galaxies, they must be reached by colonizing life forms while they remain within the accessible event horizon. With the accelerating expansion caused by the dark force, physical casual contact with all but the local group of galaxies will be lost after 10^{11} years. However, if life colonizes the galaxies, biology and human life may continue there about long-lived stars much past the time of separation. Organic gene/protein life, even branches of humankind, may then exist in billions of galaxies separated permanently beyond mutual communication.

These calculations concern upper limits of biomass and populations, i.e., the carrying capacities of the ecosystems as determined by resources of mass or energy. The actual populations may be limited by the mechanism and expansion rate of life. A natural “random walk” mechanism to populate the galaxy would take trillions of years [31], while purposeful colonization may succeed in a billion years.

Until the difficulties of human interstellar travel are overcome [40], life may be spread through directed panspermia using current-level technology [19-22]. The cometary materials in our Solar System are sufficient to seed with micro-organisms all the new planetary systems that will form in the galaxy during the next five billion years [22]. The maximum rate of growth of biota in the galaxy, i.e., the biotic potential in ecological terms, is likely to depend on technology and purpose rather than on natural limitations.

3. 4 The Ultimate Amounts of Life

Finally, it is of interest to estimate the theoretical limits of biological life in the universe. Although the details of future life are unpredictable, the upper limits follow from cosmology.

In terms of materials, biological matter would be maximised if all ordinary baryonic matter was converted to elements in their biological proportions, and these elements incorporated into biomass. The amount of baryonic matter may be estimated from the mass of the Sun, 10^{30} kg, multiplied by the 10^{11} stars and 10^{11} galaxies, yielding 10^{52} kg. A more sophisticated calculation based on the volume of the universe in an event horizon of 15 billion light-years and the estimated density of baryonic matter of 4.1×10^{-28} kg m^{-3} yielded a similar result of 5.9×10^{51} kg [42].

If all baryonic matter is converted to biomass, only dark matter, gravitational energy, dark energy and background radiation remain as energy sources, and they may be impractical to utilise. A portion of the biomass must be then converted to energy at a rate that provides the required power for the remaining biomass. The maximum energy may be produced according to $e = mc^2$ by the relativistic conversion of mass. Equations for calculating the rate of conversion are given by equations A8 – A11 in the Appendix 2. To support a power of 100 Watts per kg biomass, a fraction of 3.5×10^{-8} of the mass must be used per year. The remaining biomass after time t with this rate of dissipation can be calculated from equation A5 in Appendix 2 (substituting k_{waste} by $k_{use} = 3.5\times10^{-8}$ year^{-1}). At this rate, the 10^{41} kg of baryonic matter in the galaxy would be reduced to the last 50 kg human after 2.6 billion years and to the last micro-organism after 3.7 billion years. The integrated $\mathrm{BIOTA_{int}}$ will be 3×10^{48} kg-years, possibly as 10^{47} human-years. As an ultimate limit, if all the 10^{52} kg matter of the universe was used concertedly, it would be reduced to the last 50 kg human after 3.3 billion years, and to the last 10^{-15} kg micro-organism after 4.4 billion years. The total integrated BIOTA_{int} will be 3×10^{59} kg-years, possibly in the form of about 10^{58} human-years.

In ecology, the maximum rate of growth of biota in an ecosystem is defined as the biotic potential. In astroecology, converting all baryonic matter to biomass at the fastest technological rate would constitute the cosmic biotic potential. Further, gradually converting a fraction of this biomass to sustaining energy would achieve the maximum time-integrated biomass. However, at this rate, life would become extinct after a few billion years. However, this approach may be useful for maximizing life if an accelerating expansion should make the universe uninhabitable after a few billion years.

However, if proton decay rather than the expansion and cooling of the universe is the limiting factor, then life may exist much longer, to 10^{37} years [31]. The total time-integrated biomass, limited by baryonic matter, remains the same, but we may wish that life should exist as long as time allows. This can be achieved by converting the 10^{41} kg baryonic matter in the galaxy to biomass and then to energy at a slower rate, sustaining a steady-state biomass of 3×10^{11} kg, possibly as 10^{10} humans, comparable to the current world population. In this manner life would last for 10^{37} years, yielding the same maximum BIOTA_{int} of 3×10^{48} kg-years. The 10^{52} kg of baryonic matter in the universe would allow a steady-state biomass of 3×10^{22} kg, possibly as 10^{21} humans, a hundred billion times the current world population, to last for 10^{37} (ten trillion trillion trillion) years, to yield a time-integrated biomass of 3×10^{59} kg-years.

These numbers illustrate the potential scope of future life. Depending on the projections of cosmology, the rate of constructing biomass, and its steady-state amounts may be designed to allow life throughout the habitable lifetime of the universe.

4. Conclusions

The upper limits of life, in terms of time-integrated biomass, can be assessed by astroecology that compares biological needs with resources in future periods of cosmology. The maximum amounts of life allowed by material and energy resources were assessed for the Solar System and for various star-centred ecosystems, and for the galaxy, and the habitable universe.

The limiting nutrients N and P, and other materials especially carbon and water, contained in asteroids and comets are sufficient to maintain large populations during the next five billion years. Further, biological life and humans can survive the red giant Sun and continue much longer about the white dwarf Sun and other such stars. Considering energy requirements and resources, we estimated the amounts of life allowed about these and other types of stars in the future galaxy.

The present paper aimed to introduce some concepts, especially time-integrated biomass. This concept allows quantitative assessment of the amount of life, including the amounts of life in future habitas. The results give a sense for the potential magnitude of future life. As to the actual numbers, note however that the observable past 14 billion years are only one part in 10^{27} of the future allowed by baryonic matter, too short to form definitive predictions.

As cosmology evolves, the outlook for life will need to be continually re-evaluated. This open-ended future allows a positive outlook, which is needed when technology can make our predictions self-fulfilling. In such a self-designed future, the amounts of life will depend as much on ethics as on physical resources. The great scope of future life can motivate panbiotic ethics that seeks to expand life in the universe (see Appendix 4).

Combining astroecology and cosmology yields a framework that can quantify future life. The projections of cosmo-ecology suggests that we can expand life with a view to an immense future.

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Appendix 1: Calculations of Steady State and Time-Integrated Biomass

Organisms take up nutrient elements from resource materials and incorporate them in biomass. Various types of resource materials contain various concentrations $c_{x,resource}$ of each nutrient element x, reported in Table 2 in units of g/kg. Similarly, $c_{x,biomass}$ (g/kg) is the concentration of element x in a given type of biomass as summarized in Table 3. Equation (A1) gives the amount of biomass, $m_{x,biomass}$ (kg) that could be constructed from an amount $m_{resource}$ (kg) of resource material if element x was the limiting factor and the other components of elements were available without limitation.

$$m_{x,biomass} = m_{resource}\, c_{x,resource}/c_{x,biomass} \qquad \textbf{(A1)}$$

Table 3 lists the amounts of biomass (kg) that can be constructed from each nutrient in 1 kg of the resource materials. Note that more than 1 kg of biomass could be constructed from 1 kg of resource materials as based on element x, for example, if a rare nutrient x is over-abundant in the resource materials.

Appendix 2: Calculations of the Rates of Formation, Steady-State Amounts, and Total Time-Integrated Biomass

We consider ecosystems where biomass $M_{biomass}$ (kg) is formed at a constant rate $dM_{biomass}/dt = k_{formation}$ (kg y^{-1}) and is used or wasted at a rate $dM_{biomass}/dt = -k_{waste}\, M_{biomass}$ (kg y^{-1}). In astroecology, the formation may represent conversion of space resources to biomass while usage or waste may occur through leakage to space, or by the conversion of a fraction of the biomass to energy to provide power for the remaining biomass.

Note that the formation rate is zero order and the rate of waste is first order in $M_{biomass}$. Equation (A2) gives the rate of change of the biomass.

$$dM_{biomass}/dt = k_{formation} - k_{waste}M_{biomass} \qquad \textbf{(A2)}$$

Note that k_{waste} in units of y^{-1} represents the fraction of $M_{biomass}$ that is wasted per year. At steady state the rate of change of the biomass is zero i.e., $dM_{biomass}/dt = 0$, and equation (A3) gives the steady-state biomass $M_{biomass,\ equilibrium}$ (kg).

$$M_{biomass,\ steady\text{-}state}\ (kg) = k_{formation}\ (kg\ y^{-1}) \,/\, k_{waste}\ (y^{-1}) \qquad \textbf{(A3)}$$

Next we calculate the time-integrated BIOTA_{int} (Biomass Integrated Over Times Available) that can exist in the ecosystem during a finite time period. In equation (A4) we integrate $M_{biomass,\ t}$ i.e., the biomass at any time, from the starting time t_o of the ecosystem to the end time t_f of life in the ecosystem.

$$\text{BIOTA}_{int} = \int_{t_o}^{t_f} M_{biomass,t}\,dt \qquad \textbf{(A4)}$$

After the formation of a given amount of biomass $M_{biomass,\ o}$ has been completed, it may be used or wasted at the rate of $-k_{waste}$, i.e., the remaining amount of this unit of biomass decreases according to equation (A2) with $k_{formation} = 0$. The solution in equation (A5) gives the instantaneous amount that remains of this unit of biomass after time t.

$$M_{biomass,\ t} = M_{biomass,\ o}\exp(-k_{waste}\, t) \qquad \textbf{(A5)}$$

By integrating equation (A5), we obtain the total integrated amount of this amount of biomass that will have existed from its formation to infinity.

$$\text{BIOTA}_{int} = M_{biomass,\ o}/k_{waste} \qquad \textbf{(A6)}$$

Note that equation (A6) applies to each unit of biomass that decays at the rate of $-k_{waste}M_{biomass}$ regardless of when it was formed. Therefore, the total integrated biomass of the ecosystem depends only on the total amount of biomass created and on the decay rate, but not on the rate of formation. Equation (A7) gives the total time-integrated biomass $\text{BIOTA}_{int,ecosystem}$ of the entire ecosystem. If the total amount of biomass created during the lifetime of the ecosystem is $M_{ecosystem}$ then

$$\text{BIOTA}_{int,\ ecosystem}\ (kg\text{-}y) = M_{ecosystem}\ (kg) \,/\, k_{waste}\ (y^{-1}) \qquad \textbf{(A7)}$$

Note that if waste is reduced to zero and no mass is lost from the biosystem then $k_{waste} = 0$ and the integrated BIOTA_{int} is infinite for any finite amount of biomass. At the extreme, a single bacterium living forever would give an infinite amount of integrated biomass.

If all the mass $M_{resource}$ of the resource materials is converted to the maximum biomass that is allowed by the limiting nutrient according to equation (A1), then equation (A8) gives the total time-integrated integrated $\text{BIOTA}_{int,\ ecosystem}$ of the ecosystem.

$$\text{BIOTA}_{int,\ ecosystem} = (M_{x,resource}\, c_{x,resource}/c_{x,biomass})/k_{waste} \qquad \textbf{(A8)}$$

An interesting case occurs if a fraction of the biomass is used to provide energy for the remaining biomass. Assume that the power requirement is $P_{biomass}$ ($J\ s^{-1}\ kg^{-1}$) and the energy yield is $E_{yield,\ biomass}$ ($J\ kg^{-1}$) per unit (kg) biomass converted to energy. If the biomass is converted to energy at the rate required to provide the needed power for the remaining biomass, then

$$\begin{aligned}(-dM_{biomass}/dt)\ (kg\ s^{-1})\ E_{yield,\ biomass}\ (J\ kg^{-1}) \\ = P_{biomass}\ (J\ s^{-1}\ kg^{-1})\ M_{biomass}\ (kg)\end{aligned} \qquad \textbf{(A9)}$$

This is similar to equation (A2) with a formation rate of zero and with $k_{waste} = P_{biomass}/E_{yield,\ biomass}$.

The remaining biomass after time t is given according to equation (A5) as

$$M_{biomass,\ t} = M_{biomass,\ o} \exp\left(-(P_{biomass}/E_{yield,\ biomass})\ t\right) \qquad \textbf{(A10)}$$

The maximum energy can be obtained from a unit of mass by conversion to energy according to the relativistic relation $E = mc^2$. In this case $E_{yield,\ biomass} = c^2$, and assuming a power need of $P_{biomass}$ = 100 Watt/kg, the decay rate of the biomass is

$$\begin{aligned}k_{use} = 100\ (J\ s^{-1}\ kg^{-1})\ /\ (3 \times 10^8)^2\ (m^2\ s^{-2}) \\ = 1.11 \times 10^{-15}\ s^{-1} = 3.5 \times 10^{-8}\ y^{-1}\end{aligned} \qquad \textbf{(A11)}$$

For a simple estimate of the amount of baryonic matter in the universe, the 10^{30} kg mass of the Sun may be multiplied by the 10^{11} stars and 10^{11} galaxies, yielding 10^{52} kg of baryonic matter. A more sophisticated calculation that was based on the volume of the universe (event horizon with a radius of 1.5×10^{26} m and volume of 1.4×10^{79} m^3) and the density of baryonic matter, 4.1×10^{-28} kg m^{-3} lead to a similar result of 5.9×10^{51} kg as calculated by Wiltshire [42].

If all the baryonic matter in the universe were converted to elements according to their proportions in biomass, this process would yield 10^{52} kg of biomass. If a fraction of this biomass were converted to energy at the rate shown in equation (A11), there would be enough biomass left for one 50 kg human after 3.3×10^9 years, and for a single bacterium of 10^{-15} kg after 4.4×10^9 years. The total time-integrated life will have been 2.8×10^{59} kg-y.

It is unlikely of course even in principle that all the matter in the universe can be brought together in one biosphere, since the galaxies are receding beyond their mutual event horizons. By analogous considerations, the duration of life using the 10^{41} kg baryonic matter in each galaxy is 2.6×10^9 years until the last 50 kg human and 3.7×10^9 years until the last 10^{-15} kg microbe. The total integrated life is 2.8×10^{48} kg-y per galaxy, which yields 2.8×10^{59} kg-y in all the galaxies as above. This can amount to 5.6×10^{57} human-years, or 5.6×10^{55} humans who will have each lived 100 years. Although these numbers are not realistic and have large uncertainties, they illustrate the upper limits of biological and human life in the universe.

Appendix 3:
Energy Flux, Temperatures and Habitable Zones about Stars

The luminosity of a star is equal to its power output, i.e., its energy output per unit time. The power output is related to the surface temperature according to

$$L\ (J\ s^{-1}) = 4\pi r_S^2 \sigma T^4 \qquad \textbf{(A12)}$$

Here L is the luminosity, $4\pi r_S^2$ is the surface area and $T\ (^oK)$ is the surface temperature of the star, σ is the Stefan-Boltzmann constant, 5.67×10^{-8} J m^2 s^{-1} K^{-4}. The radius of the Sun is 6.96×10^8 m and its luminosity is 3.9×10^{26} J s^{-1}.

A spherical object with a radius r, at a distance R from the Sun, absorbs the solar flux intercepted by its projected area, at the rate

$$w_{abs} = (L/4\pi R^2)\ (\pi r^2)\ (1-a) \qquad \textbf{(A13)}$$

Here the terms in the first parentheses give the solar energy flux at the distance R, the second parentheses the projected area, and the third parentheses account for the albedo, that is, reflection of part of the radiation. This albedo is zero for a blackbody object.

The object also emits radiation depending on its radius and temperature according to equation (A12). At steady state the absorbed and emitted radiation are equal and equations (A12) and (A13) can be combined to give the steady-state temperature as equation (A14).

$$T^4 = L(1-a)/16\pi R^2 \sigma \qquad \textbf{(A14)}$$

The relation between heliocentric distance and temperature follow from this equation.

Appendix 4:
Implications for Astroecology and Astroethics

Expansion and evolution in space will be controlled by technology and its ethical guidance [43]. The cosmological future of life will therefore depend as much on biology and ethics as on physical resources.

In this respect, a "panbiotic" life-centered ethics [44-46] that seeks to maximize life, was discussed in this Journal [20-23]. Because of the relevance to the cosmological prospects, it will be summarized here briefly.

The unity of life: The interrelation of all life is supported by molecular biology. All cells are surrounded by selective membranes and process energy through biochemical cycles that use ATP. All cells have complex genomes coded by DNA and share a common mechanism to translate the genetic code into proteins. The proteins eventually help to reproduce the DNA code. These basic structures and the gene/protein cycle are central to all biology.

Phylogenetic trees indicate that all terrestrial life can be traced back to a common ancestor [47-48]. Amongst eukaryotes, organisms as different as yeasts and humans share half of our genome, while mice share over 90%, chimpanzees share over 95%, and different human individuals share over 99% of our genome [49].

Life and physics: Biological matter is uniquely complex. Also, biology requires a precise coincidence of the laws and constants of physics, such as electromagnetic forces that control biology, nuclear forces that form elements, gravity and thermodynamics that control planetary environments, and cosmology that allows the habitable universe [50-53]. A biocentric view [44-46] is strengthened by this special place of life in nature.

Observational equivalence, and purpose: Another unique feature of life is self-propagation. Although not performed with foresight, self-reproduction is observationally equivalent to action with purpose. This would assign self-propagation as the effective purpose of life.

The cosmological future: As part of life, humans share a purpose to propagate and maximize the total integrated amount of life (BIOTA_{int}) in the habitable universe. Panbiotic ethics that aims to propagate life can motivate these objectives, and natural selection will favour societies that pursue them.

These ethics can motivate advancing life by human expansion and by directed panspermia [19-22, 54]. Expansion in space will lead to new life forms with varying resource needs. For example, biological tissues may combine with inorganic substrates in cyborgs, which may alter the biological resource needs. Nevertheless, even this self-designed evolution will remain tested by survival. Biological survival will require control by biological brains that will have a vested interest to perpetuate the organic gene/protein life form. Therefore, organic biology and its resource needs can remain applicable on cosmological time-scales.

Combining biology, ecology and cosmology yields a framework of cosmoecology that projects an immense scope of future life. This potential future can further motivate panbiotic ethics that aim to maximize life in the universe.

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