The Cometary Biosphere

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ABSTRACT

Recent observations of cyanobacterial fossils on carbonaceous chondrites have conclusively established the presence of fossil organisms on extraterrestrial bodies widely presumed to be comets. Likewise, the data from four cometary flyby (and one impact) missions and the exploration of a peculiar S-type asteroid, show evidence of liquid water in the past or present. In addition, sand grains returned from the tail of comet P/Wild-2 demonstrate that comets accrete inner Solar System material. So it is a short step to propose the separate and independent existence of a cometary biosphere, the ecosystem of organisms that exploit the niche of an extraterrestrial environment. This paper attempts to lay the framework for such a hypothetical ecosystem, and establish criteria for its continued existence and spread.

Keywords: Comet, biosphere, cyanobacteria, astrobiology, panspermia

1. INTRODUCTION

There has been a long history of theories postulating the existence of extraterrestrial life,[1] going back at least to Newton's hypothesis[2] that cometary emanations led to the spontaneous generation of plants. The subsequent results of Pasteur convinced the scientific world that "spontaneous generation" was impossible, leading physiologist von Helmholtz to write "who could say whether the comets and meteors which swarm everywhere through space, may not scatter germs wherever a new world has reached the stage at which it is a suitable place for organic beings."[3] Helmholtz' view, called panspermia, was supported by other famous scientists of his time, including Lord Kelvin and Arrhenius, but by the early 20th century, such views were severely criticized[4–6] so that only the transport of pre-biotic organics[7,8] was championed. Even this view was suppressed, with the notable exception of Hoyle and Wickramasinge, who developed a modern version of panspermia, (see *Astronomical Origins of Life*[9](1999) as well as in many papers[10–15]). Hoyle and Wickramasinghe's many contributions cannot be overstated, but their theory failed to achieve widespread acceptance, perhaps because its principle support came from observations of astronomical spectra, which many took to be suggestive but not conclusive. However, recent comet flyby data[1] have changed this consensus, returning theorists to the 1908 thesis through observation of complex cometary organics, which if not taken to be due to the presence of life, may allow for the spontaneous generation of life. There is even a belated recognition that contrary to the accepted theory of the time, Hoyle and Wickramasinghe had correctly predicted that comet nuclei would be very black.

In this work, we turn the dial back 136 years to 1871, and like Hoyle, argue for the existence of extraterrestrial "germs", which are in fact, Newton's "plants", but highly evolved for life in space. In subsection 1.1 we review the evidence for cyanobacteria and their ecological niche. In subsection 1.2 we review the evidence that comets present a liquid water environment, which would support the safe transport of life. In subsection 1.3 we combine the previous two observations, and conclude that comets can infect each other independent of the existence of the Earth, thereby populating their own unique biosphere. This then becomes the launching pad for section 2, a hypothetical discussion of the properties of such a self-infecting, cometary biosphere: its probable size, infection rate, and biological adaptations resulting from evolutionary pressure. These conclusions are then compared to observed properties of cyanobacterial mats. Finally, we conclude that should our hypothesis prove true, that the cometary biosphere exists, then both evolution and creation paradigms will have to change.

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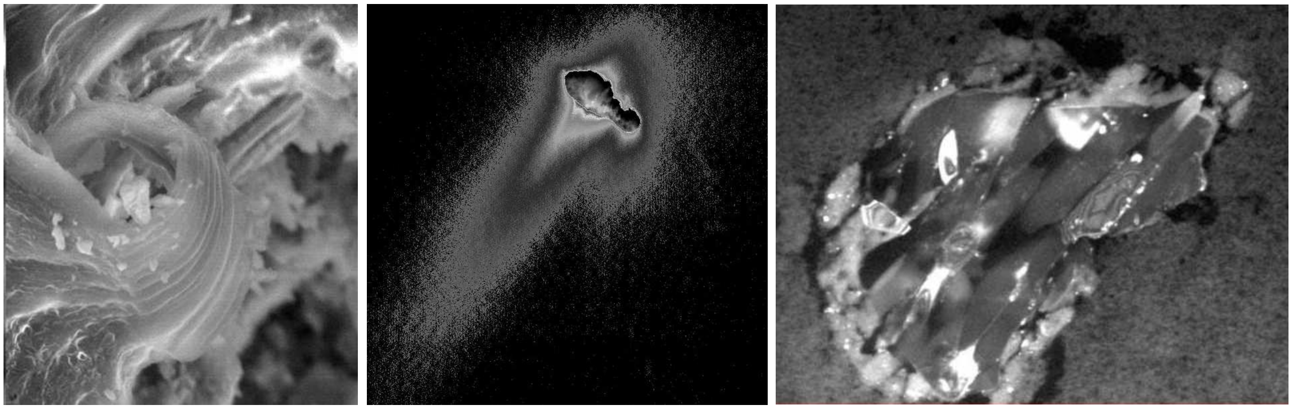

Figure 1. a) Electron micrograph of a cyanobacterial mat fossilized in the Murchison meteorite;[16] b) Highly prolate nucleus of comet P/Borrelly superimposed on its back-illuminated geyser plume courtesy of NASA's Deep Space 1 mission; c) 2 micron sand grain (forsterite) courtesy of NASA's Stardust mission.

1.1 Microfossils of Carbonaceous Chondrites

Microfossils have a checkered history, with the early announcement of keragenous, acid-resistant, plant-like "organized elements"[17–20] in carbonaceous chondrites disputed and eventually abandoned. However, the recent discovery of water-soluble mineral "casts" of cyanobacteria[16, 21–24] made with a scanning electron microscope and supplemented with EDS X-ray derived atomic composition, have made the existence of microfossils virtually unassailable.

In addition to spectacular microphotographs of fossil cyanobacteria, Hoover et al.[24] have catalogued the presence of all five categories of the cyanobacteria phylum. This diversity is best understood as characteristic of a symbiotic bacterial mat, such as those responsible for the oldest known fossil stromatolites. In such a bacterial mat, species are found at a particular horizontal layer, top layers specializing in photosynthesis and oxygen production with aerobic metabolism, while those at deeper layers specializing in organotrophic, anaerobic metabolism, such that the efficiency of the entire ensemble is a maximum. That is, these diverse cyanobacteria do not represent a random cross-section of Earth organisms accidentally lifted into space, but a highly efficient, mutually dependent ecosystem designed for pioneering the colonization of a sterile and potentially hostile ecological niche.

1.2 Evidence for Water on Comets

The comet flyby missions to comets P/Halley, P/Wild-2, P/Borrelly, and P/Tempel-1,,[25–28] have taken pictures of rigid, cratered, black, hot ($T>273K$) surfaces which bear no resemblance to the white, fluffy, cold snowballs expected. Many had assumed[29] that the surface would be a cosmic-ray transformed crust of organic goo of a few centimeters depth covering a snowy core, but when Deep Impact launched a $373kg$, $10km/s$ copper bolide into comet P/Tempel-1 in 2005, it raised a great deal of dust but no ice.[30–33]

All these observations are consistent with the transformation of a long-period comet into a short-period "wet" comet, as it makes its first pass inside the orbit of Mars. In Hoover et al.[21] a slowly spinning comet is described as a heat pump in A/C mode,[34] with the sunward side stable to the Rayleigh-Taylor (R-T) convective instability, and the nightside unstable, such that heat was pumped out of the comet. But a rapidly rotating comet has an equatorial band in which the heat pump operates in heating mode, with the sunlit side going R-T unstable and pumping heat into the interior of the comet, whereas the nightside is stable. Such a heat pump meant that the average temperature of a comet has a discontinuous jump as it begins to spin, which is inevitable on its first close approach to the Sun and subsequent evolution of gas jets.

In Sheldon and Hoover[35] the consequences of this R-T instability are explored, demonstrating that a spinning comet not only causes heat to move toward the center, but as the heat melts the dusty ice, the denser dust is removed from the core out to the equator, thereby raising the moment of inertia and slowing the spin back into A/C mode. The melting process is then regulated by a negative feedback mechanism, such that the spin of the comet is maintained very close to the rate required for critical R-T instability at the interior ice-water interface. By considering the evolution of the comet, we proposed that a comet would naturally become an egg-shell, with dense, hydrated minerals at the outer equatorial surface, then a water layer, then a vapor pocket, and finally the original icy interior at the core. Should the "concrete" equatorial band disintegrate, the comet would evolve into a prolate tumbler, such as seen at P/Halley and especially P/Borrelly, with a high likelihood of a near-polar geyser.

Thus short-period "wet" comets would possess a black, rigid, cratered, hot crust many meters thick, consistent with all the flybys and impacts. The very low albedo similar to carbon-black ∼0.03, arises from keratogenization of long-chain carbon compounds, which are themselves the probable product of living organisms growing on the carbon dioxide and carbon monoxide nutrients of the pristine comet. We went on to argue that all the dynamic properties of comets summarized in the pre-Halley overview "Comets",[36] including the lack of precession, stability of jets, apogee distributions, and dust/gas ratios, are all a consequence of this radical transformation from pristine long-period to "wet" short-period comets.

In Sheldon and Hoover[37] the predictions of wet comet theory were compared with the then recent results of three 2005 missions: Deep Impact, Stardust, and Hayabusa. The last was not a comet mission at all, but a soft landing on S-type asteroid Itokawa, which was found to be a highly prolate rubble pile. The boulders on the surface had a power-law distribution of sizes, with an anomalous excess of 2 meter sized boulders. We argue that this is expected as the end-state of a dried-out prolate comet, having collapsed from an egg-shell having $2m$-thick strata laid down during single passes by the Sun. The lack of carbon in the spectra indicates an "uninfected" comet, one that never polymerized its original stock of volatile carbon compounds, and thereby lost its carbon with its water. We also derived a relation between spinrate and age of a comet, suggesting that the lack of ice and water at P/Tempel-1 was a consequence of impacting an old and "spent" comet, nearly hollow from dehydration. The theory also predicts that the Rosetta mission to comet P/Churyumov-Gerasimenko,[38, 39] unlike P/Tempel-1, will find a young and wet comet, whose lander and drill may yet provide confirmation of the theory.

1.3 Cometary Accretion and Infection

Combining the observations of cyanobacteria in subsection 1.1 with the wet comet theory of subsection 1.2, lead us to the conclusion that life does not need Earth-type environments to flourish, but comet can infect comet directly. This occurs when an infected comet disintegrates, leaving a ring of spores and lyophilized bacteria in orbit around a star. We know that such rubble streams exist, for when the Earth passes through one, we experience meteor showers, such as the Perseids or Leonids, which are associated with named comets. These rubble streams have a large enough cross section to accrete onto a second comet, and hence are capable of infecting more comets. Given the century-long persistence of such rubble streams from historically named meteor showers, and the expected 10,000-100,000y lifetime of the 100+ short-period comets known today, the probability that infected material is continually found inside the orbit of Mars is very close to one.

Can lyophilized (freeze-dried) bacteria survive the rigors of space for the century or so necessary to seed another comet? The cold temperature and vacuum are helpful while the cosmic ray and UV radiation are detrimental. A recent study of cryophiles from an Antarctic glacier[40–42] suggests that the half-life for these organisms kept below $0C$ is $>1.1My$, albeit without damaging radiation exposure. However, since rubble streams have rubble, bacteria may escape the most damaging radiations of space if they are embedded in a $1cm$ or greater diameter dirtball.

We also know that accretion occurs, because some of the dust collected in aerogels by the Stardust mission and returned to Earth from the tail of P/Wild-2 were crystalline silicates that can only form at temperatures over $1100C$,[43] a temperature unlikely to have been encountered during a comet life-cycle. Now solar radiation pressure will expel grains less than 1 micron, while grains greater than a micron experience the Poynting-Robertson effect that drags them into the Sun. Since the sand grain observed at P/Wild-2 was much larger than a micron, it was most likely recently accreted in the inner Solar System.

Therefore just as sand grains can be accreted, so it seems likely that fragments of an infected comet can be accreted. Nor are such impacts likely to fuse or sterilize the entire fragment, both because of the low relative motion between comets in similar orbits, and because small grains are gently decelerated both by an (active) cometary atmosphere and by the fluffy regolith observed on most comets.

So it seems not just possible, but probable that an infected comet will fragment, form a rubble stream, and seed another comet traveling through. Thus the cometary biosphere need not involve a special collision with Earth, but may continue from comet to comet indefinitely, infecting pristine comets as they pass within the orbit of Mars.

2. PROPERTIES OF A COMETARY BIOSPHERE

To a large extent, the nature of an ecosystem depends upon the resources available, marking the principal difference between the Sahara and the Nile River that threads it. The same is true of a cometary biosphere that may be potentially rich or sparse depending on water resources available. Having argued for liquid water and DNA on comets, a second tier of limiting factors are: the size or density of resources, the frequency of colonizing transport, and the necessary evolutionary adaptations.

2.1 The Size

The standard theory explaining the origin of comets usually regards them as remnants left over from the nebular formation of the planets far outside the orbit of Pluto. These Oort Cloud comets are thought to be "pristine", reflecting the composition of the proto-solar nebula some $5Gy$ ago. There are also comets thought to be debris from the "construction" of the planets, forming the Kuiper Belt, somewhat closer than Pluto, but gravitationally outside of Jupiter's influence. Since Jupiter has cleared out all the planetesimal debris responsible for the $4.8Gy$ bombardment of the Earth and Moon, any short-period comets seen today are recent dynamically trapped comets originally in the Kuiper Belt or Oort Cloud.

Estimates of the total mass of comets in the Solar System usually fluctuate around 2-4 Earth masses, but divided into a trillion or so smaller objects. It is thought that the Earth lost its water and atmosphere during the Hadean bombardment (and formation of the Moon), but subsequent cometary bombardment has replenished the Earth's oceans. Oró and Lazcano[1] tabulate nine estimates that vary between 1e21-1e25g of cometary matter accreted by the Earth over the last $1Gy$, or 1e12-1e16g/y. Since an average comet is about $5km$ radius with a density somewhere around $0.5g/cc$ (the lower estimates at P/Tempel-1 we believe to be the result of an aged and hollow comet), this suggests that between 5-50,000 new comets/y have historically hit the Earth or been collected after fragmenting. This does not include those falling into the Sun (as observed by the SOHO coronograph at a rate of about $60/y$,[44] or collected on Mars, Venus or Mercury. Astronomical observations of β-Pictoris[45, 46] suggest something like 100 comets/y are impacting on the star, which is similar to the SOHO coronograph rates. So the Earth accretion rate should be seen as a lower limit of the inner Solar System cometary flux, perhaps <1% of the total, but we take the more conservative estimate of 10%. Since the published estimates of the past $1Gy$ vary by 4 orders of magnitude, this additional uncertainty raises it to 5 orders, and we accordingly use only order-of-magnitude estimation in what follows.

If we now take the average time for a comet to pass within the orbit of Mars to be 3 months, and the average solar constant to be $1kW/m^2$, and the average radius to be $5km$, and the average albedo 0.03, then the total solar energy collected during this time is 6e17J. If the comet is half snow and half rock it will have a specific heat of about $1.4J/gK$ from $4K$ up to the melting point of ice at $273K$, and then another $167J/g$ to melt the ice, so 6e17J will melt approximately 1e12kg of comet, producing $1km^3$ of water and about $0.3km^3$ of sediment. If the melted water covered the illuminated area of the comet, $80km^2$, then this would be a lake about $13m$ deep on $3m$ of mud (consistent with Itokawa). This is an upper limit, and of course, some heat is reradiated while some ice is sublimed, but 1-10m of water is consistent with other estimates of the depth of meltwater on comets.[34]

Now if a hundred comets are arriving in the inner Solar System per year, than at any given moment there are some $25km^3$ of liquid water in orbit around the Sun. Even if the ponds are only a few meters deep, the dissolved salts and the R-T heat pump keep the water liquid far past the orbit of Mars, as observed by cometary "outbursts" of water vapor even at the orbit of Jupiter.[34, 36] This would suggest that not only is the density of the cometary biosphere high, but the organisms can be transported between comets easily. The biosphere is dense.

More significant than the volume of water growing bacteria, is the total infected volume of water in the biosphere, mostly frozen as the comets leave the inner Solar System. The ultimate demise of a long-period comet is the gravitational capture and impact on an inner-solar system object, but the lifetime of a long-period comet after its first pass into the inner Solar System is expected to be not more than 10 orbits. If we assume that the initial apogee is in the middle of the Oort cloud at $1000AU$, then Kepler's 3rd law gives us a period of 30,000y. So if there are 100 new comets a year for 300,000 years, then some 3e7km^3 of previously melted ice in orbit around the Sun, potentially holding cyanobacteria. However, if we now suppose that this is a lower limit on the cometary influx, and the real flux is 10 times higher, then the net Solar System infected water might be 3e8km^3 or about the volume of the Indian Ocean. And if the cometary infall to Earth is a mere 1% of the total Solar System flux, then we find the infected cometary water to be twice the ocean volume of the Earth–a cometary biosphere indeed.

2.2 The Infection Rate

Now if all G-type or smaller stars form a nebula with a similar Oort Cloud of comets around them, then our Galaxy possesses over ten billion more Solar Systems with comets, potentially a billion times more infected water than found on Earth itself, that is, if infections can spread from star to star. The question becomes, can life survive an interstellar journey?

The cube root of the Milky Way stellar density is $\sim 4ly$ so it is not unreasonable to use the distance to α-Centauri as a typical separation between Oort Clouds. If a comet were to make a close encounter with the Sun, and should it be actively jetting, typically at $1km/s$, it is conceivable that a breakup might give a Δv of several km/s to some fragment. Or a gravitationally unbound comet could make a fast pass through the solar system and gain the local speed of the Sun ($16.5km/s$), or even the orbital speed of the Sun with respect to the galactic center ($200km/s$).

So at $2km/s$, the time to reach α-Centauri is $600ky$, or $60ky$ at $20km/s$, but since we have earlier reported that the half-life for viability of organisms found frozen in an Antarctic glacier was estimated to be $1.1My$, we have no trouble transporting these cyanobacteria through space at even colder temperature in less time while frozen in $10m$ or so of protecting ice.

The simple transport equation above does not give the time to spread across the galaxy, only the time to reach the nearest star. The problem is not accurately portrayed by diffusive transport, since the step size of each cometary escape and capture is likely to be a "soft" power law distribution, leading to an undefined 2nd moment, an infinite diffusion coefficient, and Lévy-flight behavior. In addition, the infected star-system is a huge amplifier for life as it infects a new reservoir of comets, so that life spreads more like an epidemic than a diffusive wave, with outbreaks widely separated and filling in the intervening spaces. In such a case, the speed of the infection is some fraction of the maximum likely comet velocity. We have suggested that non-gravitationally bound comets would gain the most velocity from a head-on (gravitational assist) near-Sun encounter, so it raises the question, are any comets likely to be gravitationally unbound?

If a comet were to be gravitationally unbound, then it would not be on an elliptical orbit around our Sun, but on a parabolic or hyperbolic orbit. Of the several hundred comets whose orbital elements have been tabulated by Marsden,[47] 307 are long period "Oort cloud" comets, and 33 of these are listed as hyperbolic trajectories. Krolikowska[48] argues that after accounting for non-gravitational forces such as cometary jets, only 10 candidates (in 200 years) appear to be unbound, though the other 23 may have transitioned from bound to unbound (he wasn't clear). In other words, 3% of the comets may arrive interstellar, and 6% leave interstellar.

From these considerations, there is a 10% ejection rate of comets leaving our Solar System, or $P = 0.1/y$, and the 3% interstellar rate suggests an interstellar density of a few percent of the Oort Cloud. Since the Oort Cloud is approximately $1ly$ from the Earth, and using an average distance between stars of $4ly$, with an interstellar density of 3%, then there are approximately twice as many interstellar comets in the galaxy than stellar.

All of these are of the "slow" km/s variety, which may be an observational bias, since a "fast" $20km/s$ interstellar comet might not generate much of a tail in a 4 week passage through the inner Solar System, if only because it hasn't warmed very much. The fact that "sun-grazing" comets are not detected with telescopes, but with a coronograph, suggests that many comets may produce little or no tail at $1AU$. But to achieve the largest ejection velocity, one should apply the Δv at perihelion, so sun-grazers are those most likely to experience the largest non-gravitational forces and become hyperbolic. Therefore Marsden's catalog of hyperbolic orbits may be missing the most important class of interstellar travellers, the sun-grazers. If $60/y$ of sun-grazers are not detected telescopically, then we may have a much larger number of hyperbolic orbits than listed, and we should take these numbers as lower limits. Using the 10% rule again, we then estimate 20 times as many interstellar than stellar comets.

Can we estimate the time for life to seed the entire galaxy? The interaction time, I, is usually defined $I = 1/(n\sigma v)$, where n is the density of targets, σ is the cross-section of the target, and v is the speed of the projectile. This is only the time needed to infect the first solar system, since each seeded solar system produces more infected comets, and the spread of the infection is exponential. We will calculate that numerically by summing the series, but first we begin by calculating I, and estimate the average cross section for a comet to be captured by another star as it passes through the galaxy. That is, the comet must shed its excess velocity and become trapped in the star's gravitational well. Impacts might accomplish this, but would also heat and sterilize the comet fragments. Therefore a gentler deceleration is sought.

An estimate of the needed deceleration begins with the observation that the maximum temperature life can withstand is about $120C$. This corresponds to a thermal motion of water molecules of $0.7km/s$. So if a comet is travelling even $1km/s$ relative to impact with another comet, the resulting thermalization of the kinetic energy will convert the ice to steam at temperatures high enough to sterilize all life. Of course, thermalization is not homogeneous, and recent experimental work demonstrate survival of bacteria at $4.5km/s$ impact speeds, where the destruction of bacteria is better correlated to peak pressure observed.[49] Paradoxically, a gentler impact into aerogel was found to be more lethal, perhaps because the thermalization was more homogeneous.

But if the leading edge of the comet becomes much hotter and ablates or sublimes, it can provide a decelerating force, the same non-gravitational force observed on comets around our Sun. By the conservation of momentum, the Mass * Velocity of the ablating material must equal the mass * velocity of the remnant comet. If we need the remnant comet to slow by some $20km/s$, so $MV/m = v$, where V is given by the temperature of ablation boiling off water, which at $400K$ is $V = 0.7km/s$. So to achieve a $20km/s$ deceleration, we need $M/m = 28$, or 96.6% of the comet would have to ablate, including the dust. Comets have geysers,[50] and geysers can get better momentum transfer by trapping dust in the plume, but this calculation is optimistic since it requires all the ablation to be directed as accurately as a retro-rocket. If we assume about 50% of the comet mass can be sublimed, then we get maximum deceleration of about $1.4km/s$, suggesting that faster comets will need multiple encounters or gravitational assistance from Jupiter-sized bodies to be trapped.

In the spirit of this article, we estimate that the sublimation velocity is a function of proximity to the star, such that higher surface temperatures result in higher decelerating effect. Since the temperature is proportional to radiative flux $T \propto 1/R^2$, the sublimation velocity goes as R_0/R, or the maximum capture radius of a star is R_0/v_c, where v_c is the comet relative velocity. For a $1km/s$ comet, we estimate $R_0 = 4AU$, so the capture cross-section is a disk, $\sigma = \pi(4/v_c)^2 AU^2$.

Another deceleration possibility is aero-braking, where in addition to the ablating material, there is the momentum transfer of gas reflecting off the front of the comet. This is quite effective when there is an atmosphere, and is not only used on the Space Shuttle, but implemented for Mars missions. For a comet, however, this means star-grazing; too high and the comet continues out of the system, too low and the comet falls into the star. The cross section is quite minute, perhaps a solar radii ($0.01AU$), though for red giants, it might be a $0.1AU$ annulus. Compared to σ, aerobraking is about 0.001% smaller, or roughly the cross section for a Jupiter-assisted capture. Then our cross-section is modified $\sigma = 50(1/1e5 + 1/v_c^2)AU^2$, where v_c is given in km/s.

While aerobraking may be a difficult way to stop a comet in a solar system, it is a very effective way for a comet to accrete small fragments using its outgassing atmosphere as a "cushion" to decelerate the fragments. Therefore as long as a rubble stream is gravitationally trapped by a star, other comets, even hyperbolic comets, may still successfully accrete viable biological material.

Since the dominant part of the cross section goes as $1/v_c^2$ (up until the comet is travelling faster than $300km/s$), then the interaction time, $I \propto v_c$, so a $20km/s$ comet will take ten times longer to infect than a $2km/s$ comet and the interaction time is weighted toward slower comets. This doesn't take into account multiple encounters, gravity assists and other higher-order mechanisms for trapping a comet that may change the first-order formula we derived, but for this paper we assume that $2km/s$ comets are the important ones for viable transport.

Taking the Milky Way to be a disk of 100,000ly diameter, 2500ly thick, and 200 billion stars, we get a density of 0.01 stars/ly^3, with a stellar capture cross section in ly of $\sigma =$1e-9ly^2. Then $I \rightarrow$1e16y, or longer than the age of the universe. During this time, however, we have ejected many comets, which can be calculated as $N = P * t$ each multiplied by the probability of an interaction during a short interval, dt/I. So the time required for the first infection is:

$$1 = \int_0^{T1} (P/I)t\ dt \quad = \int_0^{T2} (P/I)(2t + T_1)\ dt \quad = \int_0^{T3} (P/I)(3t + 2T_2 + T_1)dt \tag{1}$$

which when solved for T_1 gives 4e8 y. We can then add the rate of infected comets from the second solar system, and solve for the time T_2, and so forth. Then by summing the series numerically, we can calculate the number of infected systems as a function of time:

$$N = 0.6031 * \exp(0.83806\ T\sqrt{P/I}) \tag{2}$$

From this formula and the assumed P/I, we find that the Milky Way will be completely infected in 10Gy.

However, if the comet ejection rate is not constant, as some argue,[51, 52] but peaked early on immediately after the planet formation of the solar system, say, as $P = [0.1 + 1000\exp(-t/A)$, where $A \sim 100My$, then our formula integrates to $T_1 \rightarrow A/2$, or 50My. So if the exponential enhancement of early comet production has a pulse width significantly shorter than the steady state interaction time, the pulse dominates the integral.

Different stellar density assumptions can also change T_1 dramatically, so for example, if the infected system were in a 50,000 star globular cluster with an average density of about 1 star/ly^3, then T_1 reduces to 40My, and complete infection in 400My. In addition, many stars in a globular cluster are in the red giant branch of the stellar evolution curve with capture cross sections as much as 30AU in diameter reducing T_1 perhaps another order of magnitude to 4My, and complete infection in 100My. The prodigious output of a cluster (emitting some 10,000 ejected comets/y) could then infect a galaxy in approximately the propagation time from a cluster to the far edge of the disk. Since a cluster has a lot of internal stellar velocity, small clusters might have an average ejection speed of 70km/s, large ones 400km/s, so that the ejected comets would reach the far reaches of the Milky Way in about 100My for slowest, to 20My for the fastest, where the capture calculation is dominated by the bulk velocity because the velocity distribution has relatively few comets at slow speeds. Therefore the inhomogeneity of the stellar density throughout the galaxy is not a hindrance but a help in spreading the first infection of life across the galaxy, with the entire galaxy getting infected in ∼1Gy.

Finally we ask, could comets seed another galaxy? The Andromeda galaxy is some 2.5Mly away, which at 20km/s would take 40Gy to traverse, longer than the age of the Universe. But at 200km/s, the journey is an achievable 4Gy. If we assume the bulk of the interstellar comet velocities to be at 2 km/s, and use a Kolmogorov spectral index 5/3 to describe the velocity spectrum of interstellar comets, then the density of 400km/s comets (which due to the galactic gravitational well, will result in 200km/s escape velocity) is 0.02% of the parent population. But if the parent population has been observed at 0.1/y, then in about 100ky, we will observe such a fast comet at Earth, and of the estimated billion or so stellar Oort clouds in our galaxy, the Milky Way may be launching some 100,000 fast comets every year.

With the Andromeda galaxy subtending some 190'x60' of arc, or fractionally about 8e-5 of the entire sky, then every year the Milky Way would have sent at least one comet in the right direction. However, decelerating such a fast comet without incinerating and sterilizing it would be a challenge, so that aerobraking or Jovian-type deceleration might require flying within 0.1 solar radii = 0.001AU = 1e-8ly. Then the cross section is about 1e-16ly^2, and traversing Andromeda lengthwise is 100,000ly, so we have a volume of 1e-11ly^3. With an average galactic density of 0.01 star/ly^3, it would take 1e13 comets to get an effective collision, so even at one fast comet per year for 10Gy, the probability is still 1:100 that the Milky Way would not seed Andromeda. That is, any comet fast enough to make the trip may be going too fast to deliver viable life, whereas a slow and safer speed will take too long, making trans-galactic infection unlikely.

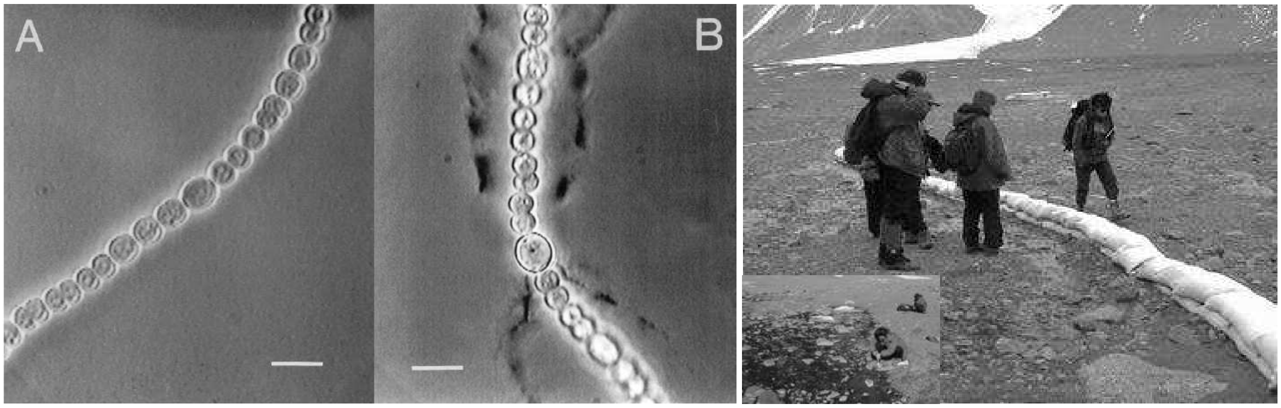

Figure 2. *Nostoc commune* cyanobacteria grown a) without and b) with UV/B light, showing protective pigmentation in polysaccharide sheath;[53] c) Black, dried, 20-yr old cyanobacterial mat in the dry valleys of Antarctica resuscitated by water directed along sand-bag dike. Courtesy Diane McKnight at UC Boulder[54]

2.3 The Evolution of Cometary Life

Having established that a cometary biosphere of a billion Earth oceans is likely to exist in the galaxy, then the significance of life on Earth for cyanobacterial evolution is relatively minute. That is, Earth should be constantly bombarded with cometary DNA, while contributing little to the extraterrestrial stock, so that cyanobacteria should be optimized by evolution for life on comets, rather than life on rocky bodies. With no attempt at rigor, we look at biological properties of cyanobacteria and speculate as to its adaptation in a cometary environment.

Lyophilization: All bacteria survive freeze-drying with remarkable resilience, (unlike, say, mammals), and this would be an important property for propagation between comets in space.

Bacterial mats: The depth of a typical pond on a comet is 1-10m deep, which would discourage any body shape that requires more than 10cm or so in depth. The tendency for cyanobacteria to form horizontal mats of a few centimeter thicknesses would be consistent with these limitations.

Polysaccharide sheaths: Dehydration is a major problem on a comet, since any rupture of the pressure vessel, would lead to spontaneous boiling and freeze-drying. The polysaccharides generated by cyanobacteria not only plug the pores of the hydrated minerals that form the shell of a comet[35] preventing water loss, but they also provide “glue” that increases the tensile strength and allows higher pressures inside the trapped volume. Exposure to UV blackens the polysaccharides (compare to cyanobacterial mats in the dry valleys of Antarctica), which decreases the albedo, filters out the dangerous short wavelengths, increases the thermal flux, and melts more ice. Since all four comets observed have had very low albedo <0.05, it would seem to be a very significant transformation for cometary colonization.

DNA conservation: From microfossils, we know the morphology of cyanobacteria has not changed over several billion years. This is usually taken to be evidence of DNA conservation over the same time period. In space, UV and cosmic radiation flux are much higher than on Earth, with corresponding increase in mutation (and death) rates, so one would expect that to survive 10,000 years or more in the frozen state, cyanobacteria must display a remarkable conservation of their DNA. The genome of the smallest photosynthetic cyanobacteria transcribed,[55] despite representing a minimal set of enzymes, still had redundancy in nucleotide synthesis, evidence that DNA conservation was critical for survival.

Nitrogen fixation: After carbon, hydrogen and oxygen, the most important nutrient for life is nitrogen. Yet nitrogen has few non-volatile minerals, so that nearly the entire nitrogen reservoir at Earth resides in the atmosphere.[56] On a comet continually outgassing to space, this loss of nitrogen would be the critical limitation on growth, and accordingly, cyanobacteria must have a mechanism for nitrogen fixation to successfully colonize comets.[57] On Earth, there are three kinds of bacteria that can fix nitrogen: rhizobacteria that are symbiotic with plants; azotobacter and similar organotrophs that eat organics for the energy required to split N_2; and heterocystous cyanobacterial autophototrophs. Neither of the other two bacterial groups can start from a sterile environment and begin fixing nitrogen, yet without fixed nitrogen the environment will remain sterile. Only cyanobacteria can grow in a sterile, organic-free environment and fix nitrogen at the same time, a trait essential for the cometary biosphere.

3. CONCLUSIONS

Having begun with the discovery of life on comets, we have explored the potential for life to exist in a galactic cometary biosphere, and found no physical limitation for life to spread throughout the galaxy via comets. Our calculations did not support intergalactic transport, however, at least, in the timeframe of a Big Bang cosmology. As supporting evidence for a cometary biosphere, we examine biological traits of cyanobacteria, and show why they are not just useful, but essential for the colonization of comets. All of this is circumstantial evidence, of course, and only show that such a biosphere is possible, not that it is actual.

Does this biosphere support the modern theory of panspermia? Like Hoyle and Wickramasinghe, it makes it possible to consider the entire galaxy as a single biological ecosystem, but they would prefer to have the entire Universe involved, whereas our first order calculations would exclude transport to nearby galaxies. Furthermore, we do not address the thorny question of the origin of life, merely it's potential transport, and even then, only the transport of single-celled cyanobacteria. Whether other prokaryotes or eukaryotic diatoms could survive interstellar transport, much less nematodes or invertebrates is not established by this work. And even should this work be completely correct, it still does not explain either the origin of cyanobacteria, or the resultant evolution on Earth into higher life forms. Thus it would be improper to call this paper a complete panspermia model, even if it does outline transport.

Does this biosphere support an abiotic, chance origin of life on comets? Once again, the model proposes only how life spread, and even then, only cyanobacterial life. Whether comets are the origin of life and higher life forms are derived from these, or some other designed process is not addressed by the model. In fact, evolutionary theorists may appreciate that this model enlarges both the time and the space for that all-important first cell, and creationists may appreciate that this model enlarges the scope of creation texts to include the entire galaxy.

For the Quran, Sura 21:30 reads, *The heavens and the earth were a closed-up mass, then We [God] opened them out. And We made from water every living thing.* Likewise, the first two verses of the Bible, Genesis 1:1-2 read: *In the beginning, God created the heavens and the earth. The earth was without form and void, and darkness was over the face of the deep. And the Spirit of God was hovering over the face of the waters.*

If the first use of the word "earth" is taken to be "solid matter" it could refer to the stellar nebula, before star burning had begun, in which case, "waters" would be the frozen Oort Cloud of comets around it. Since "Spirit" is the same word used to describe the awakening of Adam, "Spirit hovering" is equivalent to "life evoking". Even for creationists, life began with comets.

So this model has much to offer all interested parties. Just as Copernicus removed Earth from the center of the physical universe, so this model removes Earth from the center of the biological universe.

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