Looking for life in unlikely places: reasons why planets may not be the best places to look for life*

Freeman J. Dyson

Institute for Advanced Study, *Princeton*, *NJ*, *USA*
e-mail: dyson@ias.edu

Abstract: A new method is proposed to search for extraterrestrial life adapted to cold environments far from the Sun. To keep warm, using the light from a distant sun, any life-form must grow a system of optical concentrators, lenses or mirrors, to focus sunlight on to its vital parts. Any light not absorbed, or any heat radiation emitted from the vital parts, will be focused by the optical concentrators into a narrow beam pointing back towards the sun. To search for such life-forms, we should scan the sky with optical and infrared telescopes pointing directly away from the Sun. Any living vegetation will be seen as a bright patch in strong contrast to its dark surroundings, like the eyes of a nocturnal animal caught in the headlights of a car. This method of search may be used either with space-based or with ground-based telescopes. Examples of places where the method would work well are the surfaces of Europa, Trojan asteroids or Kuiper Belt objects. Any life-form that adapted successfully to a vacuum environment would be likely to spread widely over objects with icy surfaces in the outer regions of the solar system.

Pit-lamping at Europa

I leave it to the audience to decide whether this paper is an elaborate hoax, a piece of bad science fiction or a serious contribution to the planning of future space missions.

My son, who lived for many years in Canada, informs me that in rural Canada, night-time hunting with a carefully shielded flashlight is called 'pit-lamping'. It is illegal, because it is too effective at turning up game. The reason why it is effective is that the eyes of animals staring into the light act as efficient reflectors. The eye reflects a fraction of the light that is focused on to the retina, and the reflected light is again focused into a narrow beam pointing back to the flashlight. If you are standing behind the flashlight, you can see the eyes as bright red points even when the rest of the animal is invisible. Pit-lamping is too easy and too efficient. It results in extermination of the game, spoiling the fun for other hunters. The same strategy is used legally by sheep-farmers in New Zealand to exterminate rabbits who compete with sheep for grazing land. The farmers drive over the land at night in heavily armed land-rovers with headlights on, shooting at anything that stares into the headlights and does not look like a sheep.

I am suggesting that pit-lamping would be a good strategy for us to use when we are searching for life in the solar system.

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In this paper I will not discuss the search for intelligent life. The search for intelligent life is a fascinating subject but it is not on the agenda for today. Today I am discussing the search for dumb life, the sort of life that existed on this planet before humans came along. Consider for example the problem of looking for life on Europa. If life exists on Europa, it is most likely that it exists in the ocean under the ice. The ice is many kilometres thick. To look for life in the ocean will be very difficult and expensive. It would be much easier and cheaper to look for life on the surface. Life on the surface is less likely to be there, but easier and cheaper to detect. When we are choosing a strategy to look for life, detectability is more important than probability. Estimates of the probability of life existing in various places are grossly unreliable, but estimates of detectability are generally quite reliable. Probability depends on theories of the origin of life about which we know nothing, while detectability depends on capabilities of our instruments about which we know a lot. So I state as a general principle to guide our efforts to search for life: go for what is detectable, whether or not we think it is probable. For all we know, all kinds of unlikely things might be out there, and we have a chance to find them if and only if they are detectable.

When we are looking for life on Europa, we must begin by considering the question: what kind of life could exist and survive on the surface of Europa, where the ambient temperature is about 120 K or −150 °C? We may imagine that life originated and evolved for a long time where it

is warm, in the dark waters below the ice. Then by chance some living creatures were carried upwards through cracks in the ice, or evolved long shoots pushing up like kelp through the cracks, and so reached the surface where energy from sunlight was available. In order to survive on the surface, the creatures would have to evolve little optical mirrors concentrating sunlight on to their vital parts. To give you an image of the things I am talking about, I like to call them sunflowers. Some arctic plants on planet Earth have already evolved something similar, with parabolic petals reflecting sunlight on to the ovaries and seeds that grow at the centre of the flower. On Europa the mirrors would have to be more powerful than on the arctic tundra of Earth, but not by a big factor. Sunlight on Europa is 25 times weaker than sunlight on Earth, so the mirrors on Europa would have to concentrate sunlight by a factor of 25. That would be sufficient to maintain the illuminated area at the focus of the mirrors at a temperature of 300 K, at which water is liquid and life as we know it can function. The mirrors would not need to be optically perfect. Concentration of sunlight by a factor of 25 could be done with a rough approximation to parabolic shape.

Now suppose that we have a Europa orbiter looking for life on Europa. If the life happens to be on the surface, it must have some kind of reflector to concentrate sunlight. Then all we have to do is arrange for the orbiter to scan the sunlit face of Europa, always pointing the camera in a direction directly away from the Sun. If there is an optical concentrator on the surface, any sunlight that is not absorbed at the focus will be re-emitted and reflected into a beam pointing back at the Sun. Like the eyes of a moose in Canada or the eyes of a rabbit in New Zealand, any sunflower alive on the surface will then be 25 times brighter than its surroundings, assuming that the illuminated surface at the focus of the concentrators has the same albedo as the surroundings. Even if the surface at the focus has lower albedo, so long as the albedo is not close to zero, any patch of life on the surface will stand out from its surroundings like the animals in a pit-lamping hunt. Since our purpose is not to kill and eat the creatures but only to discover them, there is no reason why pit-lamping on Europa should be illegal.

If any of you have sat in a window seat on the shady side of a commercial airliner and looked down at a layer of cloud not too far below you, you will probably have seen the beautiful bright halo that sometimes surrounds the shadow of the airplane as the shadow moves along the clouds. The halo is produced by backscattering of light in water droplets or ice crystals in the cloud. This is only one of many ways in which non-living materials can mimic the backscattering effect of a living creature. The fine dust on the surface of our Earth's moon also produces a sharp increase in albedo when the Moon is observed with the Sun directly behind the Earth. If we observe strong backscattering of sunlight from a patch on the surface of Europa, we should not immediately claim that we have discovered life. Other explanations of the backscattering must be carefully excluded before any claims are made. A good way to do this would be to carry

a sensitive infrared bolometer looking in the same direction as the optical camera. If the optical backscattering is caused by reflection from optical concentrators attached to living creatures, then the warm surface at the focus of the concentrators will radiate thermal infrared radiation, and the thermal radiation will also be reflected back in a narrow beam pointed toward the Sun. The infrared bolometer will detect a signal from a patch of living creatures viewed from the direction of the Sun, and this signal will stand out from the cold surroundings even more strongly than the optical signal. It is unlikely that any non-living backscatterer could mimic this infrared signal. Another way to distinguish living from non-living backscatterers would be to analyse the back-scattered light with a spectroscope and look for spectral features that might be identified with biologically interesting molecules. Laser illuminators of various wavelengths could also be used. But an infrared bolometer, if available and not too expensive, would give a more reliable diagnosis of reflectors as living or non-living than an optical spectroscope.

The same strategy of orbital pit-lamping could be used to search for evidence of life on any celestial body that has a cold surface with a transparent atmosphere or no atmosphere at all, and is situated far from the Sun but not too far for us to send an orbiter. After we are done with Europa, we could try the same technique on Ganymede and Callisto, on any of the moons of Saturn except Titan, on the moons of Uranus and Neptune, on the Trojan asteroids, or on asteroids in the main belt between Mars and Jupiter. But this would not be a very promising way to go, if the only purpose of the orbiters were the search for life. After the first two or three orbiters had failed to find evidence of life, it would be hard to get funding for more of the same. It should be a fundamental principle in the planning of space operations, that every mission searching for evidence of life should have other exciting scientific objectives, so that the mission is worth flying whether or not it finds evidence of life. We should never repeat the mistake that was made with the Viking missions, whose advertised purpose was to give a definitive answer to the question whether life exists on Mars. After the Viking missions failed to find evidence of life, the further exploration of Mars was set back for 20 years. We should be careful to see that every orbiter despatched to the outer solar system takes full advantage of the opportunity to explore a new world, whether or not the new world turns out to be inhabited. Fortunately, there is another promising and cost-effective way to search for life beyond Europa. The second way is to use pit-lamping, not from orbit close to the target but from back here on Earth. The second kind of pit-lamping, which I call home-based pit-lamping, can be done from telescopes such as Hubble close to the Earth, or even better from big telescopes on the ground.

Home-based pit-lamping

When we do home-based pit-lamping, we make a big jump in the distance and the number of objects that we might hope to search. Think of the Kuiper Belt, which begins about

ten times further from the Sun than Europa and is supposed to contain billions of objects of size ranging from a kilometre upwards. Suppose that life has somehow succeeded in establishing itself on the surface of one of these objects. This may seem unlikely, but nobody can prove it to be impossible. Let us imagine that the surface of one of the objects at the inner edge of the Kuiper Belt is covered with sunflowers. These creatures are living in sunlight that is a hundred times weaker than sunlight on Europa. So they must have evolved optical concentrators that are a hundred times stronger. They must concentrate sunlight by a factor of 2500 instead of 25. This still does not require high-precision optics. The angular resolution of the concentrators must be of the order of $1°$ instead of $10°$. This is still about 50 times less precise than the optics of the human eye. A roughly parabolic reflecting surface would be good enough to do the job. When sunlight falls upon the concentrator, the light that is not absorbed is reflected into a beam $1°$ wide that is pointed back toward the Sun. Now it happens that the Earth's orbit around the Sun is also about $1°$ wide when seen from the inner edge of the Kuiper Belt. The Earth is close enough to the Sun, so that the reflectors will increase the brightness of the object as seen from the Earth by a factor of the order of 2500. As the Earth moves around the Sun, when we look outward at an object in the Kuiper Belt covered by sunflowers, the brightness of the object may vary noticeably as the Earth moves nearer or further from the axis of the reflected beam. It will be brightest when the Earth is directly between the Sun and the object.

Home-based pit-lamping is not a substitute for orbital pit-lamping. The two kinds of pit-lamping complement each other without much overlapping. Both are needed if we are to extend our search for life as widely as possible. Orbital pit-lamping can search for small and sparse patches of life on a few objects such as Europa. Home-based pit-lamping can search for big and luxuriant patches of life covering the surface of a large number of more distant objects. Orbital pit-lamping on Europa is like searching for lichens in rocks in Antarctica with a hand-held magnifying glass. Home-based pit-lamping in the Kuiper Belt is like searching for rain-forests on Earth with a camera on the Moon.

To discuss the possibilities of home-based pit-lamping in a quantitative way, I need to introduce some units. Since we are talking about astronomical observations, it is convenient to use the astronomical unit of apparent brightness which is the magnitude. The magnitude is a logarithmic measure of brightness. A greater magnitude means a smaller intensity of light. For those of you who are not amateur astronomers, here are the magnitudes of the planets in the outer part of the solar system: Jupiter minus 2, Saturn plus 1, Uranus 6, Neptune 8, Pluto 15. Adding one to the magnitude means making the light fainter by a factor of 2.5. Now suppose that Pluto itself were covered with living creatures with optical concentrators. Then its light would be brightened by a factor of 2500, which means 8.5 magnitudes. Pluto would be magnitude 6.5, almost as bright as Uranus, and brighter than any of the asteroids except for Vesta. Pluto would

have been discovered 200 years ago when the first asteroids were found. So we can be sure that Pluto is not covered with exotic sunflowers gazing at the distant Sun.

Pluto is a unique object, the biggest so far discovered in the Kuiper Belt, with diameter 3000 km and magnitude 15. The faintest objects we can identify in the Kuiper Belt with ground-based telescopes are about a thousand times fainter, with magnitude 22.5 and a diameter of about 100 km. With the Hubble telescope we can detect objects about 5 magnitudes fainter, to magnitude 27.5 and diameter 10 km, but we do not usually get enough observing time on Hubble to determine the orbit of an individual object and identify it as belonging to the Kuiper Belt. The practical limit for identifying Kuiper Belt objects is magnitude 22.5, until we have a space telescope with large amounts of time dedicated to this purpose.

Suppose one of the smaller objects at the inner edge of the Kuiper Belt is covered with sunflowers. Suppose that it is barely detectable, with magnitude around 22.5. This means that without the sunflowers it would have had magnitude 31, 16 magnitudes fainter than Pluto, far too faint to be detected even by Hubble. With the sunflowers, if it has the same albedo as Pluto, it would be 1500 times smaller than Pluto. Its diameter would be about 2 km. The home-based pit-lamping strategy enables us to detect any object at the inner edge of the Kuiper Belt that has as much as 3 km^2 of area covered with sunflowers. And this is not all. The Kuiper Belt extends far beyond the distance of Pluto, and beyond the Kuiper Belt there is the Oort Cloud, containing billions of objects orbiting the Sun at distances extending out further than a tenth of a light-year. Pit-lamping becomes more and more effective, the further out you go.

For non-living objects shining by reflected sunlight, the brightness varies with the inverse fourth power of distance, two powers of distance for the sunlight going out and another two powers for the reflected light coming back. For living objects with optical concentrators, the concentration factor increases with the square of distance to compensate for the decrease in sunlight. Then the angle of the reflected beam varies inversely with distance, and the intensity of the reflected beam varies with the inverse square instead of the inverse fourth power of distance. Because the linear size of the reflected beam is independent of the distance of the object, the Earth will remain within the beam no matter how far away the object sits. If an object is at a tenth of a light-year distance, the concentration factor will be 100 million, and the angle of the reflected beam will be about 20 arcsec. This requires optical quality a little better than the human eye but much less precise than an ordinary off-the-shelf amateur telescope. At that distance, we could identify an Oort Cloud object covered with sunflowers if its diameter were as large as 400 km. This diameter is much smaller than Pluto and comparable with other Kuiper Belt objects that have been discovered over the last few years.

The prospects for pit-lamping look even more promising if we look at the situation not from our Earth-bound point of view but from the point of view of the life that we are

searching for. A community living on the surface of a small object far from the Sun has two tools available to increase its chances of survival. One tool is to grow optical concentrators to focus sunlight. The other tool is to spread out into the space around the object, to increase the area of sunlight that can be collected. So far, we have only considered the effect of optical concentrators. Next, we consider the effect of increasing the area by spreading out leaves and branches into space.

Imagine an ecological community containing a large variety of species ranging from bacteria to plants and animals, comparable with a rain-forest on Earth, and occupying 1 km² of area. It requires for its sustenance an input of 200 W m^{-2} of sunlight, or 200 MW for 1 km². Now imagine this community installed on a little comet of diameter 1 km and moved to the Kuiper Belt. It must grow optical concentrators, as we have seen, to concentrate sunlight by a factor of 2500 and keep its absorbing surfaces at a comfortable temperature. But it must also increase its absorbing area by a factor of 2500 to keep its total supply of energy constant. It must grow out into space to form a disc of diameter 50 km instead of 1 km. The gravity of an object of this size is so weak that it imposes no limit on the distance to which a life-form such as a tree can grow. The living community with diameter 50 km, with its optical concentrators spread over the enlarged area, will then be visible from Earth as a speck of light of magnitude 15, about as bright as Pluto.

Now suppose that the same living community is moved out to the Oort Cloud at a distance of a tenth of a light-year, a factor 200 further away than Pluto. To maintain the same life-style with the same population of creatures, it must concentrate sunlight by a factor of 10^8 and also increase its area to 10^8 km². It will grow into a thin disc of diameter 10 000 km, covered with big flimsy mirrors to concentrate the light. The original comet with diameter 1 km will have a mass around 10^9 ton. To make an optical concentrator, using thin-film reflectors 1 μm thick, requires about 1 g m^{-2} or 1 ton km^{-2}. With an area of 10^8 km², the community needs to use only one-tenth of the mass of the comet to make the reflectors, with the other nine-tenths left over to use for its other activities and for building structures. Now comes the remarkable conclusion of this calculation. The community in the outer region of the Oort Cloud is still visible to us as a magnitude 15 object. The inverse fourth power dependence of brightness on distance, which holds for non-living objects, can be completely cancelled for living objects. Living communities can cancel two powers of distance by their use of optical concentrators, and can cancel two more powers of distance by their increase in area. If the rate of consumption of energy by a community is fixed, the brightness of the community as seen from the Earth is independent of distance. We can easily detect any community that uses 100 MW of sunlight or more for its life-support, out to a distance of a light-year from the Sun. Beyond a light-year, the Sun is outshone by Sirius. Anything living beyond a light-year from the Sun would point its concentrators at Sirius rather than at the Sun. At that point, home-based pit-lamping no longer

works, unless we are thinking of alien pit-lamping astronomers in orbit around Sirius, with Sirius as their home base.

The practical upshot of these calculations is that it would make sense to search for life on the surface of objects in the outer solar system with ground-based telescopes. All we need to do is look for objects in the Kuiper Belt or the Oort Cloud with unreasonable brightness. Anything with parallax and proper motion appropriate to the Kuiper Belt or the Oort Cloud, and with brightness greater than expected for an object at that distance, would be a candidate for an inhabited world. If we find such objects and they do not turn out to be inhabited, they would still be important discoveries. They would be objects of outstanding size, a new family of giant comets or small planets, in a remote part of the solar system. If such objects exist, either inhabited or uninhabited, it may already be possible to find them by looking at the output of the Sloan Digital Sky Survey or other sky surveys. Any interesting candidates could be examined more carefully with larger telescopes.

Life in vacuum

I want now to talk in a more general way about the possible history and evolution of life if it happens to exist away from planets. We have seen on planet Earth that life has two outstanding qualities that distinguish living from non-living objects. These qualities are adaptability and invasiveness. During the 4 billion years that life has existed on Earth, it has adapted itself to an amazing variety of ecological niches with an amazing variety of ways to make a living. It has invaded the most inhospitable and inaccessible corners of the planet, from frozen rocks in Antarctica to thermal vents in the depths of the oceans. It is reasonable to expect that life, if it exists elsewhere, will still be characterized by extreme adaptability and invasiveness. In an unstable and unpredictable universe, these qualities are needed if life is to survive, either on a planet or anywhere else.

The most important invasion in the history of life on Earth was the move from the ocean on to the land. This invasion was not easy. Life was confined to the oceans for nearly 3 billion years before it learned how to survive on land. We do not know precisely how or when the invasion began. It probably began with microbes, followed later by plants and then by animals. The fact that the Earth has an atmosphere was helpful to the invaders in at least five ways. The atmosphere protected the invaders from lethal ultraviolet radiation from the Sun. It also provided shielding from cosmic rays. For the plants, it provided carbon dioxide and molecular nitrogen for their metabolism. For the animals it provided molecular oxygen for the more rapid metabolism demanded by brains and muscles. And finally, it carried clouds and rain that provided life-saving water to replace the ocean that the invaders had left behind. The invaders made full use of these resources provided by the atmosphere as they slowly adapted to the new environment.

Now I am speculating that if life had originated on an airless satellite such as Europa instead of on a planet with air,

the move from ocean to vacuum would not necessarily have been more difficult than the move from ocean to air. Let us consider in turn the five resources provided by an atmosphere. The shielding from ultraviolet radiation would hardly be needed on Europa since sunlight is very weak, and if shielding were needed it could be provided by a thin layer of opaque skin or bark. The shielding from cosmic rays would not be needed if the invaders evolved the same resistance to radiation damage that many species of microbes and insects have evolved on Earth. The carbon, nitrogen and other elements required for metabolism of plants are probably available in the dark stripes that we see on the surface of Europa, where brine from the ocean underneath seems to have emerged from cracks in the ice. Water is certainly available in unlimited quantities anywhere on the surface. Finally, the oxygen required by animals poses the most difficult problem, but there are many ways in which this problem may be side-stepped. One possible way was imagined by Konstantin Tsiolkovsky more than a hundred years ago in his book, *Dreams of Earth and Sky* (Tsiolkovsky 1895).

Tsiolkovsky's vacuum dwellers were not divided into plants and animals but combined the characteristics of both. He called them animal-plants. Here one of them is explaining how his metabolism works: 'You see these green appendages on our bodies, looking like beautiful emerald wings? They are full of chloroplasts like the ones that make your plants green. A few of your animals have them too. Our wings have a glassy skin that is airtight and watertight but still lets the sunlight through. The sunlight dissociates carbon dioxide that is dissolved in the blood that flows through our wings, and catalyses a thousand other chemical reactions that supply us with all the substances we need'. If you are an animal-plant, the oxygen released by photosynthesis in your wings is carried in your blood to your brain and muscles, so you do not need air to supply it. If you were living on the surface of Europa, you would not have needed to invent lungs. Tsiolkovsky imagined many other clever tricks by which life might have adapted to the perils and opportunities of the vacuum environment. Lacking air to transmit sound, his animal-plants found a better way to communicate with each other. 'One part of their body carries under the transparent skin an area like a camera obscura, on which moving pictures are continually playing, following the flow of their thoughts and representing them precisely. The pictures are formed by fluids of various colors which flow through a web of fine channels under the skin.'

Let us suppose that life has emerged on to the surface of some body without an atmosphere and has developed a robust ecology of creatures adapted to living in vacuum. This might have happened on Europa or on Callisto or anywhere else in the outer solar system. Now comes the most important advantage of vacuum life as compared with air-breathing life. It is far easier for vacuum life to spread from one world to another than it is for air-breathing life. The reason is simple. If a chunk of ice is knocked off Europa by a cometary impact, and if the chunk has vacuum-life on its surface, then the life has a good chance of surviving the impact and

continuing to flourish while the chunk wanders around the solar system. The environment after the impact is not much different from the environment prior to it. And if the chunk happens to land on another object with not too high a relative velocity, the life has a chance to survive the second impact and establish itself on another world. This transition from one world to another is far more difficult for air-breathing life. Joe Kirschvink (2000), has shown that it is possible that life could have spread from Mars to Earth in the interior of a chunk of rock knocked off Mars and landing on the Earth. He studied the patchy magnetization in thin slices of the famous Mars-rock ALH84001, which was picked up in Antarctica, and demonstrated that the magnetization would have disappeared if the interior of the rock had ever been heated above 40 °C during its exit from Mars or during its arrival on Earth. If a living bacterium or spore had been hiding inside that piece of rock, it could conceivably have survived the trip and emerged to populate the Earth with its descendants. But any living passengers in rocks travelling from Mars to Earth must have been microbes or spores in a state of suspended animation. Air-breathing creatures could not have come to Earth in this way. Only if life is adapted to vacuum, might a whole ecology of more advanced creatures make the trip together from one world to another.

Europa, as it happens, is one of the more difficult places for life to escape from, because of the large gravitational potential of Jupiter. The escape velocity from Europa itself is less than 2 km s^{-1}, but the escape velocity from Jupiter starting from the orbit of Europa is about 6 km s^{-1}. If a chunk of ice escapes Europa but does not escape Jupiter, it will continue to orbit Jupiter in a Europa-crossing orbit, and it is likely to crash into Europa again before it encounters any other possible destination. To escape from Jupiter with a velocity of 6 km s^{-1} departing from Europa, it must have the good luck to leave in the right direction so that its velocity is added to the orbital velocity of Europa. If surface life exists on Callisto, escape from Jupiter would be easier but still not probable. Callisto itself has an escape velocity of 2.3 km s^{-1}, a little larger than Europa, and the escape velocity from Jupiter starting from Callisto's orbit is 3 km s^{-1} instead of 6 km s^{-1}. It would still need an improbable combination of circumstances for life on Callisto to escape from Jupiter. But hopping from world to world becomes rapidly easier as we move out beyond Jupiter to the Kuiper Belt and the Oort Cloud.

If surface life exists on a typical object in the Kuiper Belt with a diameter of a few kilometres, the escape velocity will only be a few m s^{-1}. Orbital motions in the Belt are slow, and relative velocities of neighbouring objects are typically around 1 km s^{-1} or less. Gentle collisions between neighbouring objects will be common. Life has a good chance of surviving when a gentle collision knocks a piece of its home into space, and when the piece later makes a gentle collision to land on another object. In this way, life could spread from world to world like neutrons in a divergent nuclear chain reaction. A large fraction of the objects in the Kuiper Belt might become inhabited. If this should happen, the

process of Darwinian evolution would then select life-forms that are particularly well adapted to travelling. Life-forms might evolve that do not require a chance collision to leave their home but spontaneously hop into space when conditions at home become crowded, taking with them enough material resources to survive independently. Such life-forms would be winners in the race to colonize new worlds.

Life-forms that do not hop, but grow far out into space around their home territory, would also have an advantage in spreading to other worlds. In addition to acquiring more sunlight, they would acquire a bigger cross-section for collisions with other Kuiper Belt objects. When life has grown out into a thin disc with an area thousands of times larger than its original territory, the effect of a collision will usually be to punch a small hole in the disc, with minor damage to the life that stays behind, and with a substantial chance of transferring seeds of life to the object that punched the hole. In the Kuiper Belt there is probably a substantial quantity of matter in the form of dust and ice crystals, too small and too dispersed for our telescopes to detect. By growing out into space, life-forms could greatly increase the amount of this material that they encounter, and could collect and use it for their own metabolism. Life-forms that adopt this strategy would be like the filter-feeders that we find in tidepools on Earth. Other life-forms in the Kuiper Belt might adopt a more active strategy, using eyes to locate larger objects floating by with small relative velocity, then hopping into space to intercept them. When life has colonized a substantial fraction of Kuiper Belt objects and the competition for real estate becomes intense, we may expect to see life-forms diversifying into predators and prey, carnivores and herbivores. In the wide spaces of the Kuiper Belt, evolution will drive life to take maximum advantage of the occasional collisions and catastrophes that punctuate its otherwise quiet existence. Life will be driven by Darwinian competition towards maximum adaptability and invasiveness, the same qualities that competition nurtured on our own planet.

Beyond the Kuiper Belt lies the Oort Cloud, where the distances between habitable objects are larger and the relative velocities smaller. In the Oort Cloud, relative velocities will be of the order of 100 m s^{-1} rather than 1 km s^{-1}. Here it will be even easier for life to hop from one object to another. We know very little about the total number of these objects, but we know quite a lot about their chemical and physical constitution, since these are the objects that we see as long-period comets when they are occasionally deflected by gravitational perturbations into orbits that pass close to the Sun. Then we see them boil off tails of gas and dust that we can observe and analyse. We know that they typically have diameters of a few kilometres and are largely composed of the biologically essential elements, hydrogen, carbon, nitrogen, oxygen. Since the reservoir of these objects in the Oort Cloud delivers about one object per year into the inner Solar system where we can observe it as a comet, and since the system is 4 billion years old, the reservoir must contain at least several billion objects of kilometre size.

It is not likely that the Oort Cloud, a vast desert of space with habitable oases separated by huge distances, is actually inhabited. But it might conceivably be inhabited by sunflowers with sufficiently precise mirrors to concentrate sunlight by a factor of 10^8. The remarkable fact is that the strategy of home-based pit-lamping could enable us to detect such life-forms if they exist.

Beyond the solar system

Next, I will talk briefly about the possibilities of vacuum-life existing beyond the solar system. Jack Baggaley is a radio astronomer at the University of Canterbury in New Zealand. He uses a radar system called AMOR (Advanced Meteor Orbit Radar) to track incoming micro-meteors that leave trails of ionized plasma in the upper atmosphere (Baggaley 2000). The tracking is accurate enough so that he can determine the velocities of individual objects with a 3σ error of 10 km s^{-1}. The objects that he can detect have diameters of around 20 μm, much larger than normal interplanetary dust particles, much smaller than normal meteorites that fall to the ground. He finds that a substantial fraction of these objects have hyperbolic velocities relative to the Sun, so that they do not belong to the solar system but are coming in from outside. He finds a second fact which is not so firmly established but still appears to be true. Of the objects that come from outside the solar system, a substantial fraction are coming from a single direction, roughly from the direction of the star Beta Pictoris, known familiarly to astronomers as Beta Pic.

Beta Pic is famous because it is a bright young star, only 63 light-years distant from the Sun, with a very large disc of dust orbiting around it. The disc around Beta Pic is estimated to contain about a thousand times as much material as our Kuiper Belt. The dust grains that Baggaley observes coming from Beta Pic are our first direct evidence that objects are actually being exchanged between one solar system and another. The dust grains are presumably thrown out of the Beta Pic system by gravitational encounters with Beta Pic planets that we have not yet observed. And if this happens to dust grains, it presumably also happens to kilometre-size objects. We must expect that among the billions of objects in our Oort Cloud there will be a substantial population of kilometre-size interlopers passing through on their way from Beta Pic. No such interloper has been seen among the long-period comets that we observe passing close to the Sun. All the comets for which orbits have been accurately measured belong to the solar system. But the total number of observed comets is small, and the absence of observed interlopers is consistent with the presence of millions of unseen interlopers passing through the Oort Cloud. The transit time from Beta Pic to our solar system is about half a million years, which is short compared with the age of even a young star like Beta Pic.

Another radio astronomer, John Mathews at Pennsylvania State University, observing with the radar telescope at Arecibo in Puerto Rico, has also found dust grains arriving from outside the solar system, but he disagrees with Baggaley

about the direction from which they are coming (Meisel *et al.* 2002). Mathews finds a substantial fraction coming from the direction of a famous object called Geminga, a supernova remnant which is also a source of gamma-rays in the constellation Gemini. Geminga is an enigmatic object with no resemblance to Beta Pic. I will not try to resolve the dispute between Mathews and Baggaley. It seems likely that they are both observing the same stream of dust grains. Beta Pic and Geminga are at the same ecliptic longitude but differ in ecliptic latitude. Beta Pic is close to the latitude of New Zealand, Geminga is close to the latitude of Puerto Rico. It is easy to imagine that observational bias resulted in the different identifications of the source of the dust grains. To avoid further argument, I shall arbitrarily assume that at least some of the grains are coming from Beta Pic.

If life can exist in our Kuiper Belt, then much more life might be flourishing in the bigger and denser disc around Beta Pic. And if kilometre-size objects are leaving the Beta Pic system and arriving in our solar system, it is possible that Beta Pic life is passing through our Oort Cloud as we speak. It is then an interesting question, whether we could detect life on Beta Pic objects in the Oort Cloud using home-based pit-lamping. We assume that the Beta Pic creatures direct their optical concentrators toward the Sun as soon as they come within range. The problem is that the Beta Pic objects, unlike the Oort Cloud objects, are likely to be moving at high velocities transverse to our line of sight. Sunlight that impinges on a Beta Pic object will not be reflected straight back at the Sun. The reflected light will be deflected by the angle $(2V/c)$, where V is the transverse velocity of the object and c is the velocity of light. The conical reflected beam has half-angle (a/D), where a is the Earth–Sun distance and D is the distance to the object. According to Baggaley's measurements, a typical transverse velocity is $50\ \mathrm{km\ s^{-1}}$, which gives a deflection angle of (1/3000) radian or 1 arcmin. The reflected beam will miss the Sun if the distance D is greater than 3000 times a, or greater than a 1/20 of a light-year. This leaves a very substantial volume within which detection of life on Beta Pic objects is in principle possible.

If we are to take seriously the possibility of life travelling from one solar system to another, two more questions need to be addressed. First, is it possible for life to survive the transit using ambient starlight as it moves through the galaxy? To answer this question, we remark that here on Earth we have three stars brighter than 0 magnitude in the sky, not counting the Sun, namely Sirius, Canopus and Alpha Centauri, and a couple of others, Arcturus and Vega, that are within a tenth of a magnitude of 0. If our present situation in this part of the galaxy is not exceptional, we can safely assume that on the way from Beta Pic to here we always can see at least one star in the sky that is 0 magnitude or brighter. If the life in transit uses optical concentrators weighing $1\ \mathrm{g\ m^{-2}}$, then the light from a single 0 magnitude star provides 0.02 W of available energy per ton of concentrators. If the object in transit is an average comet weighing a billion tons and uses half its mass for concentrators, then the available energy is 10 MW. This is enough energy to sustain

a modest community of living creatures as they cruise across the galaxy. It would be enough to sustain a village of a few hundred human beings with a modern western standard of living. The second question that needs to be addressed is whether, after an inhabited object arrives from Beta Pic with high velocity, it is possible for it to become a slow-moving object belonging to our own solar system. The answer to this question is again affirmative. Although the great majority of fast-moving objects will pass through the Oort Cloud without any interaction, a few will be deflected by close encounters with planets. A fraction of these few will be captured into orbits around the Sun, and a smaller fraction will be deflected by further gravitational encounters into orbits indistinguishable from orbits belonging to our own Kuiper Belt or Oort Cloud. From that point onward, the alien life would be at home in the solar system and could spread to other Kuiper Belt or Oort Cloud objects as if it were native. Having answered both these questions in the affirmative, we can assert that life adapted to vacuum has the potential to spread from its place of origin, not only from world to world within our solar system, but far and wide through the galaxy. Life adapted to an atmosphere is stuck on the planet where it started.

If we look at the universe objectively as a home for life, without the usual bias arising from the fact that we happen to be planet-dwellers, we must conclude that planets compare unfavourably with other places as habitats. Planets have many disadvantages. For any form of life adapted to living in an atmosphere, they are very difficult to escape from. For any form of life adapted to living in vacuum they are death-traps, like open wells full of water for a human child. And they have a more fundamental defect: their mass is almost entirely inaccessible to creatures living on their surface. Only a tiny fraction of the mass of a planet can be useful to its inhabitants. I like to use a figure of demerit for habitats, namely the ratio R of total mass to the supply of available energy. The bigger R is, the poorer the habitat. If we calculate R for the Earth, using total incident sunlight as the available energy, the result is $12\,000\ \mathrm{ton\ W^{-1}}$. If we calculate R for a cometary object with optical concentrators, travelling anywhere in the galaxy where a 0 magnitude star is visible, the result is, as we have seen, $100\ \mathrm{ton\ W^{-1}}$. The cometary object, almost anywhere in the galaxy, is 120 times better than planet Earth as a home for life. The basic problem with planets is that they have too little area and too much mass. Life needs area, not only to collect incident energy but also to dispose of waste heat. In the long run, life will spread to the places where mass can be used most efficiently, far away from planets, to comet clouds or to dust clouds not too far from a friendly star. If the friendly star happens to be our Sun, we have a chance to detect any wandering life-form that may have settled here.

Political coda

This paper has been about science and technology. Let me end it with a few remarks about the politics of space

missions. I do not use the word politics in a derogatory sense. So long as space missions are paid for by taxpayers and funded by politicians who represent the taxpayers, politics are an essential and healthy part of the business of exploring space. Science and technology provide the means for exploring space. Politics decide which goals are worth the cost of exploring. As a general rule, a space programme flourishes when there is political agreement about goals, and fails to flourish when there is political disagreement. At the present time, there are signs of a dangerous division of opinion about the goals of exploring space beyond the Earth–Moon system. On the one side, there are the astronomers and planetary scientists whose goal is to understand the physical and chemical processes going on in the universe as widely as possible. On the other side, there are the professional astrobiologists and the amateur enthusiasts whose goal is to search for evidence of extraterrestrial life. To keep the programme healthy, it is essential to fly missions that satisfy both of these goals, so that they will generate political support from both sides. It will be much easier to find such dual-purpose missions, if the search for life is not narrowly construed to mean searching on Mars and Europa only. The wider our search for life, the easier it will be to combine it with other exploratory objectives. In addition to the scientific reasons for expecting life to be detectable away from planets, there is also a strong political reason to search for it in unlikely places.

What is the moral of this story for our space programme? The chief moral that I draw is that all-sky surveys are a good idea. We need to fly more all-sky missions like IRAS, COMPTON, MAP, not to mention ground-based surveys like 2MASS and the Sloan Digital Sky Survey. We may hope to find life with searches targeted on planets and their satellites, on Mars and Europa in particular, but we may have a better chance to find evidence for life in unexpected places if we search in all directions with an all-sky survey. I will not be surprised if the first extraterrestrial life to be discovered turns up in a part of the sky where there is nothing to be seen but a couple of dim Kuiper Belt objects with anomalously small parallaxes and anomalously slow proper motions. I will also not be surprised if the first sign of life is an anomalous infrared emission from something that looks like a small interstellar dust cloud. The main practical lesson that I want to leave with you is this: keep on looking for life in unexpected places, and especially in places where we may find clues to other scientific mysteries that have nothing to do with life.

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