Astrobiology—a melting pot of open scientific questions

1 Venus Orbital Station

Vladimir and Jack are monitoring microbial densities in the lower cloud layer of Venus. The possible presence of microbes in the lower atmosphere of Venus has previously been postulated by various authors [1–5]. The underlying idea is that Venus was a planet positioned in the habitable zone of our Sun—many billions of years ago—meaning that liquid water was stable on its surface. The earliest traces of life we know from Earth are at least 3.8 billion years old [6], possibly older [7]. Some researchers [2] propose that oceans could have existed on Venus for well in excess of one billion years. The argument then is: given that early conditions on Venus were very similar to Earth, and we know Earth had life at least 3.8 billion years ago, then life could have originated on Venus. Alternatively, it is well known that microbes can survive space travel being ejected by an asteroid impact from one terrestrial planet of the inner Solar System and deposited onto the other [8]. Thus, even if life did not originate independently on Venus, it could have been transferred from Earth at a time when liquid water was still stable on its surface. Once microbial life got established on the surface of Venus, it would be tenacious and trying to survive any ensuing environmental changes. Indeed, Venus' environmental changes during its planetary history were quite challenging as it became the greenhouse planet it is today with surface temperatures well above 450 °C with little water around. However, microbial life could have survived these shifts in environmental conditions if they occurred gradually enough and if they would have had an environment on Venus to retreat to. The surface is too hot (and dry) as is the subsurface, but the lower atmosphere is what many researchers would consider a borderline habitat for microbial life. This is based on the following observations [5] (1) The clouds of Venus are much larger, more continuous, and stable than the clouds on Earth; thus providing a more amenable habitat to life than Earth's atmosphere; (2) the atmosphere is in chemical disequilibrium, with hydrogen gas and oxygen gas, and hydrogen sulfide and sulfur dioxide coexisting (disequilibrium conditions in the atmo-

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sphere are usually considered a possible biomarker for life, like the disequilibrium of oxygen and methane is in Earth's atmosphere); (3) the lower cloud layer contains nonspherical particles comparable in size to microbes on Earth; (4) temperatures of 30–80 °C, approx. pH 0, and a pressure of about 1 bar are environmental conditions in the lower cloud layer of Venus that are tolerated by some microbes on Earth; (5) the super-rotation of the atmosphere enhances the potential for photosynthetic reactions by reducing the time duration without light (a day–night cycle of 4–6 Earth days compared with 117 Earth days on the surface); (6) an unknown absorber of ultraviolet (UV) energy has been detected in the Venusian atmosphere, which could be related to microorganisms that use a fluorescent material (e.g., cycloocta sulfur, the stable yellow sulfur you can buy in your drugstore) to convert UV-radiation into visible light suitable for photosynthesis; and (7) while water is scarce on Venus, water vapor concentrations can reach near 1 % in the lower cloud layer. Traditionally planetary atmospheres have not been considered as a likely habitat for permanent habitation. However, some more recent work calls this into question. For example, some scientific investigators [9] showed that bacteria in cloud droplets at high altitudes on Earth are actively growing and reproducing, and concluded that the limiting step for the persistence of microbial life in cloud droplets is residence time in the atmosphere. It turns out that particles in the Venusian atmosphere have much longer residence times than in Earth's atmosphere, on the order of months compared with days on Earth [10, 11]. Microbial reproduction can occur within hours, more commonly within days in the natural environments, but this still lies within the particle residence time of these droplets. Even if these cloud droplets sink and evaporate on average after a time period of one month, several cycles of reproduction could have already occurred. A space mission should be designed to analyze the cloud droplets for their composition to investigate whether these particles are microbes that are covered by an inorganic fluorescent layer. The Pioneer mission in the 1980s had as one objective to investigate the composition of these so-called mode 3 particles, but unfortunately, the instrument designed to measure it, a pyrolyzer, failed to function. Thus, until the day of this writing it is still an open question whether microbial life might exist in the lower cloud layer of Venus as a remnant of an earlier biosphere that started in the Venusian oceans.

2 Earth

Rigorous physical and psychological training is a well-known component which NASA uses to get astronauts ready for space missions. Especially the psychological stability under stress is a critical parameter [12]. The witch cage and some of the other methods used as described in the novel are known by the author from various martial arts training programs and could thus plausibly be employed for such a longer and extremely challenging space mission.

The quantum entanglement (QE) chip developed by human scientists on Earth during the time span of the plot is a fictional device that allows instantaneous communication over long distances based on the fundamental quantum mechanical phenomenon of entanglement. As an example, consider two photons (quanta of light) created jointly by the same quantum-mechanical process, having thus their physical parameters correlated. Prior to any actual measurement their state (e.g., polarization) is undetermined. However, once a polarization measurement is made on any of the two photons, the states of polarization of both photons are known simultaneously, however large the distance between them, since they have been created together in the first place. The current understanding of the phenomenon is that no information can be transferred from one particle to the other, though some recent research seems to undermine that notion [13]. Information transfer which is faster than light involves extraordinary problems with causality [14] in a relativistic universe.

3 Mars

A human station on Mars has been in the planning stage for many years based on NASA long-range objectives, but nowadays also by goals advocated by private space companies such as SpaceX. The idea that Mars is inhabited by microbial life is under intense discussion. On one hand, the current surface conditions make it for life (as we know it from Earth) quite challenging to survive in this nutrient-deprived, cold, dry, and radiation-intense environment. Organisms would not only need to survive for a limited amount of time, but also would need to metabolize and undergo reproduction. The only-ever-conducted life detection experiment (the Viking landers in the 1970s)—as of this writing—came back inconclusive. All three experiments conducted by the Viking landers observed chemical changes that indicated the possible presence of life, although the expected signals were not as large as expected for a biological response and tapered off with time, casting doubt on a biological explanation. This led at the time to the consensus view that Viking had detected reactive, oxidizing surface chemistry, but not biochemical metabolic processes [15]. However, Gil Levin, the Labeled Release Experiment's principle investigator maintains until today that his experiment proved metabolic activity by Mars microorganisms [16]. Joop Houtkooper and Dirk Schulze-Makuch proposed that Martian microbes might utilize a hydrogen peroxide–water mixture as their internal solvent (compared to salty water that is used by Earth organisms) as special adaptation mechanism to thrive at the near-surface of Mars [17]. This postulated adaptation would have several advantages as the solvent would stay liquid down to temperatures of -56 °C, it is hygroscopic (meaning it is like honey or many salts that can attract water directly from the atmosphere, which would be a great evolutionary advantage when living in a very dry environment), and it could be used in metabolic pathways as a source of oxygen. If Martian microbes had indeed a hydrogen peroxide water solution in their cells, it would also explain why little to no organics were detected with the Viking's gas chromatograph mass spectrometer (GC-MS) instrument, because hydrogen peroxide becomes unstable when heated and would oxidize all organics to carbon dioxide – and indeed a flux of carbon dioxide was measured in the GC-MS. The GC-MS, however, measured a trace of chlorinated organic compounds that was at that time interpreted as contamination from Earth. Rafael Navarro-Gonzalez and coauthors interpreted that signal as organic material from Mars, related to the perchlorates that were discovered by NASA's Phoenix Mission and also by the Curiosity Rover [18]. Perchlorates in the Viking samples when heated to 500 °C could have decomposed into reactive oxygen and chlorine oxidizing any organics present and producing the trace chlorinated organic compounds detected [19].

In the novel the discovery of the exploration teams on Mars is based on two analog environments that are studied on Earth. Mars has large salt deposits, especially sulfur salts. The place where this can be observed on Earth is Lake Lucero, which is part of White Sands National Monument. Here one can find large crystals of gypsum up to some tens of centimeters and enormous amounts of other salts, in an environment that is referred in geologic terms as a playa (a lake that is usually dry) [20]. The microbialites (mounds of calcareous material built by microbes) can be found in Pavilion Lake, Canada. These structures are up to a meter tall or taller and occur in a nutrient-poor mid-latitude lake, and must have formed in the lake sometime after the last ice age about 10,000 years ago. Yet, that distinctive assemblage of freshwater calcite (which has some similarities with coral reefs in seawater, but is not as diverse and only microbial in nature) at Pavilion Lake has been associated with organisms just before the Cambrian explosion about 550 million years ago [21]. The Cambrian explosion is referred to the time as Earth's biota emerged from the melting of the near-global ice coverage when organisms diversified in an unprecedented matter of new forms and building plans. Research at Pavilion Lake has confirmed that the organisms that build up consist entirely of microbes and communicate with quorum sensing molecules [22]. These organisms might also indicate a precursor community just before the ascent of multicellular life. The microbial community also includes cyanobacteria (with the metabolic strategy of photosynthesis). The fraction of cyanobacteria declines sharply in the deeper microbialite structures, thus representing still a possible analog to the Martian cave environment, where the fraction of the photosynthesizing microorganisms would be expected to be zero or close to zero.

4 Titan

Saturn's moon Titan is truly exotic. It has a substantial atmosphere (1.5 bar near the surface), with nitrogen and methane being the major compounds (98.5 % and 1.5 %, respectively), with methane concentrations approaching 5 % near Titan's surface [23]. Other organic compounds are present as minor components. Measurements indicated the presence of methane rain on Titan [24, 25] and liquid methane-ethane lakes on Titan's surface [26]. The landscape may resemble an oil spill area in northern Alaska or Antarctica, only that it is much much colder. Yet, despite the frigid temperature at Titan's surface, 95 K (less than -150 °C), it has been speculated that possible life on Titan would use metabolic pathways that involve reactions with photochemical acetylene [27], hydrogen, and heavier hydrocarbons [28], all compounds that are present in Titan's atmosphere. Even a National Academy of Sciences report [29] concluded that the environment of Titan meets the absolute requirements for life. Titan's current atmosphere is likely to be quite similar to Earth's early atmosphere, about four billion years ago, before cyanobacteria developed that increased the atmosphere's oxygen content of Earth significantly.

There is not much liquid water to be found at Titan, probably only as an ammonia-water mixture deep in the subsurface, and possibly in a form of a deep subsurface ocean [30]. However, a hydrocarbon solvent may actually increase the chances for the origin of life. For example, extensive experience with organic synthesis reactions has shown that the presence of water greatly diminishes the chance of constructing nucleic acids [31]. And organic reactivity in hydrocarbon solvents is at least as versatile as in water, and many enzymes derived from organisms on Earth are thought to catalyze reactions by having an active site that is hydrophobic (nonpolar) [32]. Therefore, the construction of organic macromolecules in a hydrocarbon solvent may actually be more straightforward than in a polar solvent such as water or ammonia. Life though, if it were to exist in such an environment, would have to be quite different. In a hydrophobic solvent, cellular membranes would have to be constructed differently. In Earth organisms the membranes are hydrophilic (polar) to the outside to optimally interact with the polar compound water, and hydrophobic to the inside. Since the outside solvent would be a hydrophobic hydrocarbon compound on Titan, the structure would likely to have been reversed. Also, life with a water solvent has to be quite small, or at least the basic unit (the cell), because of surface-to-volume constraints. In a hydrocarbon solvent those constraints are more lose, and the basic unit could be much larger to overcome the low solubility of organics in liquid methane and enzymes to catalyze reactions at the low temperature [19]. Life expectancy is another factor which is very variable in principle. Our life expectancy on Earth is quite short, because we live in a relatively high-temperature environment (processes move faster with higher temperature) with high oxidative stresses (our macromolecules such as DNA have to be constantly repaired). In a cold environment such as Titan, processes would move much slower and there is little solar radiation, thus in principle the life span of an organism could be thousands, if not millions of years. Thus, the hypothetical Titan slugs are feasible as organisms in such an environment.

5 Deep Encounter

Many science fiction movies have been made about a first encounter with an alien intelligence. Usually these encounters are portrayed to end up in a disaster. There is a reason why. Any intelligent extraterrestrial species we would encounter in space would likely have a predatory instinct. Why is that? It is related to the reason that sheep are not very intelligent. The primary function of sheep is to graze and to escape when a predator is coming. The task of the predator is much more challenging, because it has to outsmart the sheep, catch it, and consume it. This requires anticipatory thinking of how the sheep will react once it recognizes the predator. Also, the predator has to align the movement of the sheep (presumably running away) with its own movement when pursuing the prey in a high-risk effort. The predator has to jump onto the prey, subdue it, and finally kill it. The predator has also to weigh in whether the possibility of injury, which in the wild means often death, is worthwhile the risk. Thus, it looks for a weak or very old or young individual. If the predator can hunt in a group such as in a pack of wolves, the predator is likely more successful. However, this will even require more coordination and intelligence, and also social interactions. Our ancestors, who brought down mammoths which are much bigger and heavier than an individual human, excelled at this endeavor. Thus, any extraterrestrial intelligence encountered would be expected to be a social organism with at least some predatory genes or instincts.

Even if the intelligent alien species were not to be hostile per se, a conflict could very quickly arise, because of a misunderstanding, or a rightfully or not perceived threat by the alien from us in order to protect themselves. Communication will be a major challenge. A good example of this kind of challenge is that we still don't know how to communicate with dolphins, which are no doubt an intelligent species and are even quite closely related to us. Encounters with dolphins are usually a positive experience for humans and there seems to be some mutual understanding, much based on the altruistic behavior of dolphins. But how would such an encounter play out in space, behind the walls of a spacecraft? And what kind of communication would we be able to establish with meta-intelligences (intelligence of the group or state), such as an ant, bee, or termite colony. They do not have the individuality as we do (or the dolphin). How could we even relate to them? The same is true on the other side of the individuality spectrum for an octopus. Although all of these organisms are related to us, we usually cannot communicate with them, especially not from a distance. The chance of successful communication is greater if they are related to us or at least match us in their behavioral pattern. However, even if we were to encounter a species with similar behavioral patterns, there would be plenty of opportunity for misunderstandings that could easily result in conflict. If and when we encounter an alien intelligence, chances are that they are not at all related to us. One last point to be made is that colonization attempts by humans of new lands, where indigenous peoples lived, usually didn't go very well for the indigenous people, who were at a lower level of technology. And these unfortunate encounters occurred between groups of the same species!

6 Tethys II

The aliens are based on some of the same physical characteristics and social structure as termites. Since termites (like other social insects such as bees and ants) have a highly sophisticated nest and breeding structure, even with air-conditioning in the case of termites, a more intelligent queen in that structure would logically be mostly concerned with the offspring, because that is the main purpose it serves. Social insects as we know them from Earth are not considered intelligent in a conventional sense, and as individuals they certainly do not meet the criteria usually used for intelligence. However, as an aggregate or group, they display some of the features that would suggest intelligence were they a single organism [31]. For example, they build elaborate housing, divide labor, communicate symbolically (at least in the case of the bees), radically modify their environment, grow and cultivate food (in the case of fungus-growing ants), domesticate other species, wage war, and cooperate for the good of the entire group [33–35]. As such, they represent a case of meta-intelligence [36]. The success of the social insect is testimony of the adaptive utility of this form of intelligence and that it should not be underestimated.

The alien termites in the novel live underground in a cold environment, thus they use an ammonia-water mixture as an internal solvent. Ammonia is a solvent very similar to water and in mixtures with water conveys amazing antifreeze properties. Also, since the alien termites or termkins live in this kind of environment where chemical processes proceed slowly, they also move rather slowly. Otherwise, however, they are more technologically advanced and the faster movement and thinking is the only advantage the human species has in the conflict, and the advantage is much less pronounced when you can't run away (e.g., when Earth itself is attacked). As a technologically advanced species it makes sense that they would take their home, i.e., their home planetoid, with them. As they are adapted to live in a cold environment, the heat of the planetoid is provided mostly from the radioactive decay of the interior rather than sunlight.

7 The Voids

The existence of the voids is fiction. However, there is in Buddhist spirituality the goal to reach the void, which refers to the absence of inherent existence in all phenomena, and it is complementary to the Buddhist concept of nonself. There is also the concept of vitalism, the notion that living organisms are fundamentally different from nonliving entities because they contain some nonphysical element or are governed by different principles than are inanimate things [37]. In modern science, especially with the discovery of DNA, vitalism has been replaced by more empirically mechanistic models. Vitalism explicitly invokes a vital principle, for example, why is one body alive while another is not, and that element is often referred to as the "vital spark", "energy", or in a more spiritual connotation is also equated in humans with the soul. There is also some thought that the reality we perceive is only a small part of what really exists, particularly when it relates to quantum processes. Thus, the voids are fictional entities woven together from these various concepts. In particular, the novel pictures all voids connected at the quantum level, perhaps being created and entangled when life (the definition and reason for it not further explained here) came into existence, which was intrinsically connected to the universe and related to a time when quantum fluctuations were dominating the universe's expansion (quantum cosmology). Exciting one of the voids—as done unintentionally by Tanya or intentionally by Suleiman—can thus be seen as quantum mechanical measurement of their state, providing simultaneous information about the other voids in the universe.

The discovery of the voids also touches on the Fermi paradox, which asks the question why we haven't been in contact with extraterrestrial intelligence given that there are so many stars and planets [38]. Surely, on some planets where life originated it should have developed to technologically advanced life forms? Usually the Drake equation is cited in this context [39], which—in its conventional form—states:

$$N = R^{*} \cdot f_p \cdot n_e \cdot f_l \cdot f_i \cdot f_c \cdot L$$

where:

N = the number of civilizations in the galaxy with which communication might be possible
R^{*} = the average number of star formation per year in the galaxy
f_p = the fraction of those stars that have planets
n_e = the average number of planets that can potentially support life per star that has planets
f_l = the fraction of planets that could support life that actually develop life at some point
f_i = the fraction of planets with life that go on to develop intelligent life (civilizations)
f_c = the fraction of civilizations that develop a technology that releases detectable signs of their existence into space
L = the length of time for which such civilizations release detectable signals into space

The Fermi paradox becomes even more puzzling, because there should exist many civilizations before us (and after us), which should be able to contact us using reasonable estimates. Also, many scientists conceived so-called von Neumann machines, a self-replicating machine that is capable of autonomously manufacturing a copy of itself using raw materials taken from its environment (after an earlier concept from von Neumann [40]). If there were only one such civilization in the whole galaxy and travelling by 10 % of light velocity, which is even for us realistic to achieve on long space flights (e.g., see, for example, the 100 year Starship Symposium held in 2011, web link http://100yss.org/symposium/2011), then the whole galaxy could be occupied by these autonomic machines in about four million years. Thus, the question remains what the solution of the Fermi paradox is. Many different hypotheses have been offered from the Zoo hypothesis (humans are kind of a wildlife preserve or, if you prefer, aliens may apply Star Trek's prime directive) to the idea that we live in a computer simulation [41]. Of course, the solution could be as mundane as that the origin of life is so difficult to achieve that there are not many life forms elsewhere in the universe (just making one factor of the Drake equation very small would make the number of civilization in our galaxy very small) and that any civilizations would be so far apart in both time and space, that a contact between them would statistically be extremely unlikely. In this novel, the solution of the Fermi paradox is provided by appealing again to the symbiosis between the physical universe and the phenomenon of life: once a void reaches a critical size (e.g., reflects a civilization that has become sufficiently large and intelligent) it vanishes by creating a new baby universe with its own development and destiny.

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