An Astrophysical Explanation for the Great Silence

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An astrophysical model is proposed to answer Fermi's question. Gamma-ray bursts have the correct rates of occurrence and plausibly the correct energetics to have consequences for the evolution of life on a galactic scale. If one assumes that they are in fact lethal to land based life throughout the galaxy, one has a mechanism that prevents the rise of intelligence until the mean time between bursts is comparable to the timescale for the evolution of intelligence. Astrophysically plausible models suggest the present mean time between bursts to be $\sim 10^8$ years, and evolutionarily plausible models suggest the rise of intelligence takes $\sim 10^8$. Hence, this model suggests that the Galaxy is currently undergoing a phase transition between an equilibrium state devoid of intelligent life to a different equilibrium state where it is full of intelligent life.

"Where are they?", Fermi asked [1]. In classic Fermi style, he had worked through an order of magnitude calculation capturing the essence of a problem, in this case the existence of extra-terrestrial civilizations. He had realized that the likely time scales of the expansion of a civilization through a galaxy are so much shorter than the age of the galaxy itself that, given the existence of one intelligent race, one has to wonder where everyone else is.

Fermi's question is so simple and so powerful it is worth going over it in detail. First, the Galaxy is roughly 10^{10} years old. Second, the Galaxy is roughly 100,000 light years across and on average has a star every light year. The average time it takes a civilization to move between stars sets it's expansion velocity. At Earth orbital velocities, 10^{-4}c, it takes 10,000 years. Technologies that allow 10^{-1}c seem feasible, lowering the interstellar time to 10 years. Take the mean time to be 1000 years, corresponding to 10^{-3}c, to allow for the inevitable delay between the colonization of one system and the embarkation upon a new colonization project. The time it takes a civilization to colonize from one end of the galaxy to another is $t_c \sim r/v \sim 10^8$ years. (More careful studies suggest times ranging from 50 million years [2] to 10^9 years [3], showing the power of Fermi's order of magnitude argument.) The capstone to Fermi's question is the mismatch between the galactic colonization timescale and the age of the galaxy: $t_g \sim 10^{10} \gg t_c \sim 10^8$. Once an interstellar spacefaring civilization develops, it should sweep across the galaxy like wildfire, as viewed on galactic timescales.

Have they come and gone? Clearly the vast majority of humans today are unaware of any contact with extra-terrestrials. Just as clearly, the nearest handful of sun-like stars show no civilization produced radio emissions. Furthermore, the solar system appears primordial in the sense that it does not show the effects of the mega-engineering projects seemingly within Mankind's grasp in the coming centuries. The Moon appears untouched since the great bombardment 4 billion years ago. Venus and Mars have not been terraformed. The asteroids show every evidence of being in the orbits they formed in. There is no evidence of past or present presence of extra-terrestrial civilizations in the solar system. Where are they?

Brin [4] named this the Great Silence, and cataloged explanations for this silence. Here I wish to add a new one: an astrophysical reason for the late development of intelligent life in the galaxy.

An Astrophysical Explanation

Gamma-ray bursts are 10 second flashes of $\frac{1}{2}$ Mev photons occurring 300 times a year at positions isotropically distributed on the sky. It has been shown that they are at cosmological distances [5]. The energy output during a burst is enormous, 10^{52} ergs over a few seconds. This is comparable to that released by supernovae, but differs in two important ways. First, the bulk of the energy released by a supernova escapes in the form of neutrinos. We know too little about gamma-ray bursts to know if they also release neutrinos. Second, the small amount of energy that escapes from supernovae as photons must work its way out of an opaque fireball, a process that takes place over days. In gamma-ray bursts the photons are released in seconds.

If a gamma-ray burst occurs anywhere inside the observable universe, we see it. The observed rate of 300 times a year gives over a 10^6 years 3×10^8 bursts. The observable universe contains about 10^9 galaxies, so the data are consistent with each galaxy having a gamma-ray burst every 3×10^6 years. This is intriguingly close to evolutionary time scales.

The rate of gamma-ray bursts almost certainly was higher in the past than in the present. There are many astrophysical reasons to expect the number to decline with time, both empirical and model dependent. For example, the leading contender for the cause of gamma-ray burst is colliding neutron stars. These would have been born in binary systems and fairly rapidly spiral inward. Their numbers reflect the star formation history of the universe, which peaked 10 billion years ago and has declined since.

We can model this with a per galaxy gamma-ray burst rate that falls exponentially with time:

$$r_\gamma(t) = r_\gamma(0)e^{-t/\tau} \ ,$$

where τ is the decay time constant. Take a plausible $\tau = 2.5$ billion years. Given the mean rate of $\bar{r}^{-1} = 3 \times 10^6$ years we know $r_\gamma(0)$, and can predict the rate at any time t. At present $t = 15$ billion years, so the current rate is $t_\gamma = r_\gamma^{-1}(\text{now}) \approx 220$ million years.

The crux of the explanation is this: assume that each gamma-ray bursts is a mass extinction event on a galactic scale. The energetics of gamma ray bursts are such that if one went off in the galactic center (and absorption by dust was not a factor) then we here two-thirds the way out the galactic disk would receive, over a few seconds, and all in 300 keV γ rays, the equivalent of 1/10 the solar flux. The assumption of lethality is an assumption that there exists some mechanism that would translate the energy in photons to lethal radiation at the planetary surface. The atmosphere prevents the γ-ray photons from being directly lethal, but bursts may damage the atmosphere. Thorsett [6] catalogs the effects of nearby gamma ray bursts on the atmosphere: the strongest possibility is the disruption of the ozone layer, where a 50% reduction in ozone results in a factor of 50 increase in the 295 nm solar UV flux most disruptive to protein structure. Uv absorption here is highly lethal to all known forms of cellular activity. There are other possible mechanisms. Here I will explicitly assume that gamma-ray bursts are lethal.

The gamma-ray burst model is therefore one where galactic scale mass-extinctions occur often. Ten billion years ago, the rate was quite high, perhaps every 3 million years. Over time this rate slows down and now the rate is perhaps once every 220 million years. Given the premise of this model, the last such burst in our Galaxy was before the solid surface of the Earth was covered with life, 270 million years ago. These bursts are not likely to be lethal to an advanced civilization, so their effectiveness at preventing the Galaxy from being colonized lies in their effectiveness are preventing intelligent life from evolving in the first place. We will need a timescale for the evolution of intelligence.

Evolutionary Timescales

There are many evolutionary timescales evident on Earth. It took less than 1 billion years for life to form, and 3 billion before it moved beyond simple multi-cellular creatures. The last $\frac{1}{2}$ billion years saw the rise of fish, land animals, and intelligence. Of this, 300 million years were dominated by fish, 200 million years were dominated by dinosaurs, and 70 million by mammals.

But the relevant timescale is the rise of intelligent life. The rise need not start from unicellular life. The gamma-ray burst model predicts lethal events occurring on 1-100 million year timescales. It is built into the assumptions of the model that most life on land cannot survive through a burst. What matters is the timescale for land animals to develop intelligence: while this is long compared to the mean time between bursts in a galaxy, intelligence cannot form.

One could take the full 400 million years that life has been on land as the timescale, but this is an overestimate and is misleading. Fish have had 500 million years to develop language, tool, and math using intelligence and never have; dinosaurs were an immensely successful form that had 200 million years filling every possible land-based niche, and they did not rise to intelligence. Mammals spent 100 million years competing with dinosaurs and did not rise to intelligence, but allowed to test the limits of their form, it took just 70 million years to do so.

The issue here is probably the complexity of the organisms. Bonner [7] argues that there has clearly been an increase in complexity of organisms over time. He uses raw size as a proxy for complexity. The argument is that the more complex a phyla or class is, the larger the organism can be built on that model. Not that the largest creatures are the most successful: far from it. These creatures are on the margin and do not survive well mass extinction events. But the smaller members of the more complex phyla or classes tend to survive and dominate the next era. It is demonstrably true that the largest creature in both the seas and on the land has been getting larger.

An interesting speculation is that evolution can not produce intelligence until it has a complex enough base class to start with. The data tend to support this, as we can show using brain mass. There is a scaling relation between body and brain: brain mass $\propto$ body mass$^{3/4}$ which one can see in figure 1. The significant point is that the earlier evolutionary classes of fish, reptiles, and dinosaurs lie on one scaling relation while the later classes of birds and mammals lie on a second. These relations have the same slope but differ in zeropoint, with the later classes having a factor of 10 larger brain mass for a given body mass. Not surprisingly, to my mind, birds and mammals are in general smarter and exhibit more complex behavior than

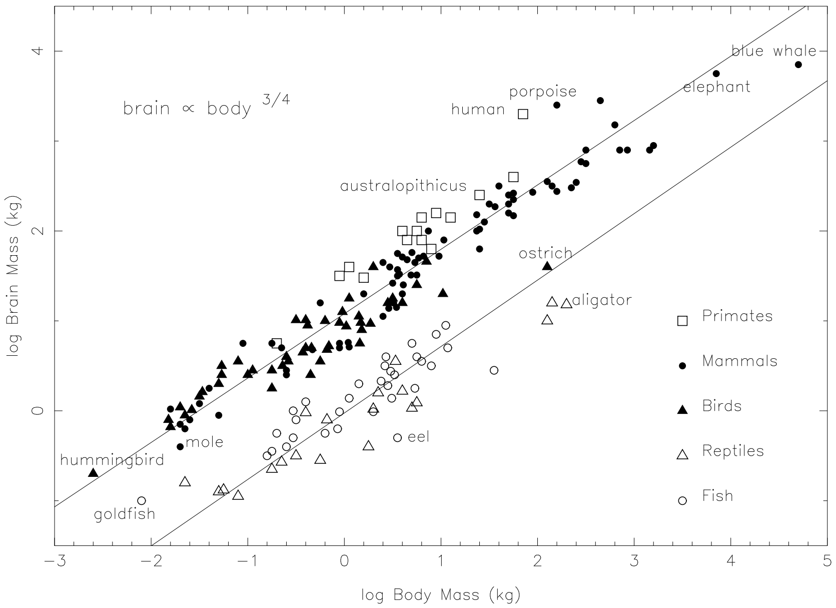

Figure 1. The brain mass – body mass diagram. The scaling relation between brain and body is $m_{brain} \propto m_{body}^{3/4}$. Different classes of vertebraes have different relation zeropoints, with the later classes of birds and mammals having a factor of 10 larger brain mass then the earlier classes of fish and reptiles at a given body mass. The solid lines are least square fits to the early and late classes; both lines have similar slopes. The roughly 200 million years separating the origins of the classes in the two relations is taken as the minimum time scale for the evolution of classes complex enough to support high intelligence. The data are from Bonner [6].

either fish or reptiles. Primates are on the high side of the higher scaling relation. Humans and porpoises scatter off the high side. Suggesting that land base is important, as it was the land based humans that developed civilization.

It took perhaps 200 million years of land-based evolution to produce creatures on the upper brain mass – body mass relation. Once a mass extinction event eliminated the dinosaurs, releasing the evolutionary niches they controlled, evolution could experiment with the more complex classes of phyla chordate. In roughly 100 million years, intelligence formed in the mammals. Evoluton had far more time to explore the limits of the classes on the lower complexity scale, but their limits were short of intelligence.

We have therefore argued that there are only two evolutionary timescales of relevance. The first is the $t \sim 10^8$ evolution takes to develop sufficiently complex base classes of land-dwelling creatures. The second is the $t \sim 10^8$ year time scale for intelligence to develop given sufficiently complex base classes.

A Phase Transition

Astronomers have long since learned the power of the Copernican principle: humans do not occupy a special place in the universe. Arguments such as "intelligent life is incredibly improbably, hence we are likely alone in the universe" therefore strike astronomers as themselves incredibly improbably. The fact that humans stand on the Earth and look out into the universe suggests that others are doing the same or have done the same. Yet they are not here, now.

Brin [4] is responsible for pointing out the power of the idea of equilibrium in this context. It is usually fruitful, when considering some new system, to assume that it is in equilibrium. Most often changes can be considered a perturbation on a quasi-equilibrium state. This is true for the work done by an expanding gas and it is true for when considering a galaxy on billion year timescales. Most responses to Fermi's question, though, propose states of profound non-equilibrium. Both "they haven't had time to reach here" and "we are first and alone" (with its implication of our standing on the brink of colonizing the galaxy) imply situations far from equilibrium without any explanation for this better than random chance (or, equivalently, an appeal to the anthropic principle's "just so" story). The gamma-ray burst model presented here does suggest an explanation: the Galaxy is presently undergoing a phase transition.

The concept of a phases transition provides a clear and powerful model for the transition from one equilibrium state to another. Examples include the transformation of water into ice as the temperature drops, and the transition from an optically thick to an optically thin universe as electrons first combine with protons to form hydrogen, again as the temperature dropped. For our purposes, the "phase transition" can be defined as the lowering of a suppressive force below some threshold, past which a previously forbidden process becomes allowed.

It is possible that the rise of intelligence in the universe is a phase transition, and that now, all over the galaxy, there are races standing up and looking out into space. Given the 10 billion year age of the galaxy and 0.1 billion year time scale for galactic colonization, this would look like a remarkable coincidence, a remarkable feat of synchronization. But that is the nature of a phase transition: once a process is allowed it happens everywhere and rapidly.

The important element in this argument is the nature of the suppressive force, which requires a process able to suppress the rise of civilizations throughout the Galaxy, and perhaps the universe. Gamma-ray bursts may play such a role.

The timescales are on the same order. The toy model for the evolution of gamma-ray bursts suggests $t_\gamma \approx 2 \times 10^8$. Our arguments about evolution suggest a timescale of 10^8 years for the rise of organisms complex enough to support intelligence, and another 10^8 years for the rise of intelligence given those organisms, suggesting an evolutionary timescale of $t_{evo} \approx 2 \times 10^8$ years. We have the situation of $t_\gamma \approx t_{evo}$, and we therefore can expect a phase transition to occur. (Interestingly enough, the galactic colnization timescale is also 10^8 years.)

The model essentially resets the available time for the rise of intelligent life to zero each time a gamma-ray burst occurs. It therefore answers Fermi's question with "They haven't had time to get here yet". More importantly, it defeats his analysis by changing one of his timescales: the time available for the rise of intelligence is changed from the age of the galaxy, 10^{10} years, down to the time since the last gamma-ray burst, 10^8 years. Since that timescale is comparable to that needed for a) the rise of intelligence, and b) the colonization of the galaxy, Fermi's question loses it's power.

Implications

Mass extinction events on Earth were for long thought to be totally due to internal events: atmospheric transformation, climate change, or increased competition from other organisms. In the 1980's it became clear that the Earth is not a closed box, and the other Solar System bodies, namely comets and asteroids, could cause mass extinction events. This paper points out that the Solar System itself is not a closed box, and in principle mass extinction events could be caused by galactic events, and could be on galactic scales. We were never promised that the Galaxy is a safe place to live.

If the lethal gamma-ray burst model is correct, the current mean time between galactic mass extinction events is 200 million years. If our speculations on evolution and complexity are on the right track, then once organisms are able to survive on land, the time scale for the rise of intelligence is 200 million years. The timescales match. Thus the non-equilibrium condition of at least one species looking out into the galaxy and thinking about interstellar travel, yet not living in a galaxy already packed full of intelligent life is explained as the onset of a phase transition. A previously forbidden configuration is now allowed. It is likely that intelligent life has recently sprouted up many at places in the Galaxy, and that at least a few are busily engaged in spreading. In another 10^8 years, a new equilibrium state will emerge, where the galaxy is completely filled with intelligent life.

References

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