The Fermi Paradox

In the last lecture we discussed some of the many reasons why interstellar travel will be very challenging. In this one we will indicate that it should be easy... given enough time. More specifically, we will address the Fermi Paradox. In 1950, the Italian physicist Enrico Fermi was at a lunch where a number of his fellows were expressing optimism that our galaxy is teeming with intelligent civilizations. He asked the simple question "then where is everybody?" That is, if technologically sophisticated aliens are common, why don't we have obvious evidence of them?

To discuss this we will first do some simple calculations to demonstrate that although our galaxy is large, the time available is so enormous that there has in principle been plenty of opportunity to colonize the entire Milky Way. We will then explore a number of possible answers to Fermi's question.

Colonization of the Milky Way

As we showed last time, the distances between the stars are huge. However, our galaxy has existed for more than ten billion years, so does the time or the distance win? An easy way to see that the time is triumphant is to note that a speed of 30 km/s, comparable to the fastest spacecraft our still-young civilization has launched, is about 1/10,000 times the speed of light. Our galaxy is about 100,000 light years across, so even at a slow rate the time to cross the galaxy is about $100,000 \times 10,000 = 10^9$ years, or one billion years. This is short compared to the age of the galaxy, so the amount of time is more than enough.

You may object that I have surely left out important considerations. Two obvious ones are:

- We've emphasized that if rocky planets are needed for life to develop, heavy elements are essential. Perhaps it is only now that these elements are in sufficient abundance, so much more ancient civilizations do not exist.
- Our time calculation assumes a straight-line journey, but this is a ridiculous oversimplification. There are a few hundred billion stars in our galaxy, which at an average separation of a few light years means that the total distance traveled is around a trillion light years, which could not be traveled by light let alone slow spacecraft in the ~ 14 billion year history of the universe. This is like the Santa Claus problem: going around the world on Christmas Eve is possible, but not visiting billions of houses.

These difficulties are only apparent. For the first, note that a billion years is short compared to the age of the galaxy, and even relatively short compared to the 4.6 billion year age of our Sun. Yes, it is true that a billion years before the Sun formed the average fraction of heavy elements in the universe was less than when our Sun emerged. However, local variations are much more prominent than a mere billion year difference. For example, the larger number of stars per volume closer to our galactic center means that the environment is richer in heavy elements there. In addition, the time it took on Earth to produce an intelligent civilization might have been longer by a billion years than elsewhere. This is a minor issue.

The second is a bit less obvious and requires a necessarily uncertain assumption about the desire of aliens to explore or conquer. Yes, no single ship or contingent of aliens could visit all of our stars in a reasonable time. But think of the following strategy, which again points out the power of exponentials.

Suppose that our aliens send out a ship to the nearest star to them, and this takes 100,000 years to get there. When they arrive, they take 1,000 years to acclimate, breed, and fully settle in. That's a long time; it is for example greater than the time from the Norman Conquest of England (1066 AD) to now. However, it barely adds to the 100,000 years of travel. After that time, both the original world and the new world send out ships to different stars, taking 100,000 years, and these two new colonies also take 1,000 years to get their local affairs in order. At the end of that period, the four worlds send exploratory ships out, and so on.

This is exponential growth again. After 100,000 years the aliens have two worlds. After 200,000 years, they have four; after 300,000 years eight, and so on. The number of worlds they have can be described by the equation

$$N = 2^{t/100{,}000\ \mathrm{years}} . \tag{1}$$

This would say that after just 10 million years, the total number of stars they would have would be $2^{100} \approx 10^{30}$, which is actually a hundred million times the total number of stars in the visible universe. Clearly this can't be; the resolution is that after a short time the various colonies would run into each other. The net result is that the bottleneck really is how long it takes to get from one star to another. If a species had a strong planet grab instinct it could easily occupy every single planetary system in our entire galaxy within a billion years.

They wouldn't even have to do it themselves. Another possibility would be to send self-replicating machines that made copies of themselves from the local resources of any system they found.

Incidentally, this argument does *not* work when we consider the distances between galaxies. For example, the nearest big galaxy to ours is the Andromeda galaxy, some 2.2 million light years away. At 30 km/s, the trip would take 22 billion years, i.e., longer than the universe has existed. Civilizations that span a single galaxy are in principle possible with nearly-current technology, given enough time, but ones that range over many galaxies would require significant advances in propulsion.

These are the calculations that underlie the Fermi Paradox. If aliens are so common, why don't we have definitive evidence that they exist? Shouldn't they have visited us by now? We now explore a sequence of suggested answers.

Solution #1: we are unique in our galaxy

Maybe it took one or several spectacularly lucky accidents for life on Earth to reach the point of intelligence. Various things we've discussed in the course could be key. For example, life itself emerged so rapidly that it seems tough to argue that it wouldn't happen elsewhere. But the three billion years it took to produce multicellular life is a sign that this step is a tough one. Suppose it took a tremendously unlikely event for this to stick. Then maybe there are a billion planets in our Milky Way with single-celled life but only ours developed further. Maybe intelligence is not nearly as important an adaptation as we'd like to think.

Alternatively, it could be that although intelligence develops on a fair fraction of planets, technology is extremely rare. Our opposable thumbs allow us to create things and manipulate our environments to an amazing level, from the construction of cars and computers to writing, which has done more than anything else to allow one generation to build on the successes of its predecessors rather than reinventing everything. A world in which dolphin-like creatures acquire human-level intelligence and communication skills would not be able to progress far because they would be limited to their innate capabilities.

Note also that with intergalactic distances being so large, it is also possible that there are millions of galaxies (out of tens of billions in the visible universe) that have life much more advanced than ours, but they haven't had time to get here yet. Or, perhaps we are truly unique in our universe.

Solution #2: advanced civilizations are short-lived

There are various reasons why this might be so. Self-destruction is one obvious possibility: perhaps on any sufficiently advanced world the toys get too big, and competition automatically leads to global wars that set the society back. Another prospect is something we see today, that use of nonrenewable resources exacts a toll. If viable alternatives are not found, it could be that we will have to take a step backwards in our technological level. One could imagine other catastrophes, including famine or disease cutting out a high enough fraction of the population that interstellar travel is put on hold eventually. I hope this isn't the reason, because I'd like to think that we have what it takes to choose wise future courses.

It has also been pointed out that if the last few hundred years of human history had unfolded differently, the situation could be dramatically different with respect to nonrenewable resources. For example, suppose that oil deposits had been deeper down and thus discovered significantly later than they were. We could imagine that wind, water, and solar power would have taken the lead. If they got sufficiently entrenched, perhaps our dependence on oil would have been minimal and our society would have been that much more sustainable. Could this have happened on other planets?

Solution #3: interstellar travel is too hard

We have no idea whether this is true, given our small number of space travel attempts. Note, though, that we argued that apart from situations similar to Jupiter's moons it appears highly valuable to have a host planet with enough mass to hold onto an atmosphere and probably to have plate tectonics. That is, we want a planet with a mass similar to that of the Earth.

An inevitable consequence is that getting off our planet is tough due to its strong gravity. Recall that putting a few people on the Moon cost about $150 billion in today's money. Other than national pride it is not clear what purpose going back to the Moon would serve. Interstellar trips with creatures you wanted to keep alive would be vastly more expensive. The costs could be cut dramatically by sending unmanned vehicles (like the self-replicating robots discussed above), but even those would be multibillion dollar missions. If no shortcuts are found, it could be prohibitively difficult to adopt the colonization procedure we discussed.

A completely automated expansion would also have to face some technical issues that might be solvable in the future but that are certainly not trivial now. Millions of years may be a blink of an eye to the galaxy as a whole, but individual stars can move a lot in that time. For example, our Sun orbits our galaxy in about 200 million years, at an average rate of about 700 light years per million years. Complete automation therefore requires careful tracking of a couple hundred billion stars to avoid repeat visits or misses. It might also be that self-replication itself is not easy after many generations, with cumulative errors coming in with a vengeance.

With all that said, however, my feeling is that with the astonishing technological progress we have made in the last century, I would expect that another thousand years of similar progress would allow us to solve these problems if we decided that galactic colonization was a worthy goal. Presumably aliens would have the same capabilities.

Solution #4: advanced civilizations wouldn't have the motivation

Really, who can tell about alien sociology. There are, however, several reasons why such expansive missions might not be attractive:

- Interstellar colonization can't solve the problems of a planet. As we have mentioned a few times, only a negligible fraction of individuals could be launched from a planet with gravity sufficient to host life.

- There would be no net economic return. This is also true of many unmanned missions to planets in our Solar System, but the scale of interstellar colonization would be tens of thousands of times greater. Why do it?
- Even the benefit to society is questionable. The distances are so great that communication would be difficult. Perhaps, though, this is something that would acquire different significance if conditions on Earth were so dire that extinction was a possibility.

By the way, even if aliens did have the motivation the question is how long it would take to colonize *every* habitable planet in our galaxy. For example, it could be that some civilization has occupied 90% of habitable planets, but because we are away from the center of the galaxy we have a pretty good chance of being one of the 10% that are left out.

So far we have examined solutions in which galaxy-spanning civilizations do not exist. Now let's explore some possibilities in which they do exist, but for various reasons we have not detected them yet.

Solution #5: aliens are holding off on contact

Perhaps aliens abide by a form of Star Trek's Prime Directive, which basically says it is forbidden to interfere in the internal workings of another society, particularly if that society is sufficiently primitive. Naturally the real prime directive is that Captain Kirk does anything he wants, but suppose aliens abide by the letter of the law. In this view, our planet has been off-limits since its origin, and will remain so until we reach some designated threshold of technology or social structure. The aliens might be observing, but will not visit or communicate with us.

This is an interesting solution that has been explored many times in science fiction. I have to admit that it would be rather cool for us to accomplish something major and then be told that we now qualify for membership in the galactic federation. Perhaps it will happen the next time the Cubs win the World Series. More seriously, how likely is this solution? If there is only one civilization that spans the galaxy, it might be by accident that they really do have principles like this and stick by them. But having only one versus none is really not that big a difference, so if we think that technology and an urge to expand are common we have to consider interactions between many such civilizations. The more there are, the greater the likelihood that at least some of them would have no qualms about interference, so the odds of this being the right answer go down. Of course, if it is inevitable that galaxy-spanners will compete with each other and only one will emerge the victor, perhaps there really is only one around. In that case, though, it might seem less likely that the winner would leave us alone!

Solution #6: we are too primitive to communicate

Maybe aliens haven't been everywhere but there are thriving groups of thousands to millions of planets and they communicate all the time. However, we have not yet developed the proper technology to understand the communication. For example, perhaps they use X-rays instead of radio waves (because of the much greater bandwidth of X-rays), beaming them rather than broadcasting over a wide range of angles. Or, maybe they use normal speech rather than recognizably artificial signals such as a series of prime numbers. It could also be that their signals are everywhere around us but they think and communicate in such utterly alien ways that we have no chance to detect them yet. In this scenario, once we develop further we will be able to detect their signals.

Solution #7: they are here but we cannot recognize them

I'm not talking about aliens kidnapping people on deserted country roads at 3 AM. I'm supposing instead that they are observing us with such superior technology that we cannot tell at all. For example, suppose the aliens have nano-technology with robots the size of sand grains or dust, measuring many things and reporting back. We might not ever be able to tell. We could even imagine that such aliens are favorably disposed towards us, and that they even give us pushes in the right direction on occasion. That would also be nice to believe, but as there is no evidence in favor of this (even if we can't rule it out) it seems wise to proceed as if we are on our own!

Summary

From my standpoint it appears that some combination of Solutions 1, 2, or 3 are most likely. The late origin of complex life on Earth might be typical and might speak to some extremely rare accident being needed. If so, by the way, it doesn't mean that we were particularly favored; only places that develop intelligent life would be able to speculate about this, so there is a rather strong bias towards such places having developed complex life! The unfortunate possibility of a short technological lifetime exists, and interstellar travel will always be resource-intensive, so these seem possible to me as well. The other solutions seem to me to rely too much on uncertainties of alien sociology, but that very uncertainty means that they are at least possible.

What do you think?