Interstellar Travel

If aliens haven't visited us, could we go to them? In this lecture we will have some fun speculating about future interstellar travel by humans. Please keep in mind that, as we discussed earlier, this cannot be considered a solution for the problems that we have on Earth, for the simple reason that the expense per person is utterly prohibitive and will remain so in any conceivable future scenario. Nonetheless, given enough time it could be that we have the capacity to move out into the galaxy. Incidentally, we will leave discussions of really far-out concepts such as wormholes to a future class.

Interstellar distances

The major barrier to interstellar travel is the staggering distance between stars. The closest one to the Sun is Proxima Centauri, which is 4.3 light years away but not a likely host to planets. There are, however, a few possibilities within roughly 10 light years, so that is a good target.

How far is 10 light years? By definition it is how far light travels in 10 years, but let's put this into a more familiar context. A moderately brisk walking pace is 5 km/hr, and since one light year is about 10 trillion kilometers, you would need about 20 trillion hours, or about 2.3 billion years, to walk that distance. The fastest cars sold commercially go about 400 km/hr, so you would need about three billion hours or a bit less than thirty million years. The speed of the Earth in its orbit, which is comparable to the speed of the fastest spacecraft we have constructed (all unmanned, of course), is about 30 km/s and even at that rate it would take about a hundred thousand years to travel ten light years.

The point is that for humans to engage in interstellar travel will require either dramatically improved propulsion technology or the willingness to commit to extremely long voyages. We will consider both, but will first discuss some of the hazards of interstellar travel.

Hazards of travel

Even if we improve our propulsion to an astonishing degree, so that we can travel at a tenth the speed of light and thus reduce the duration to just a hundred years, it is clear that the trip will take a very long time. Some of the issues faced on the journey could include:

The necessity for being self-contained.—There will be no stops along the way, so absolutely everything that is needed for a hundred years or a hundred thousand will have to be brought along. This isn't easy. When we've thought about locations for life on planets, one of our criteria was that there had to be a source of energy. Where would this come from on an interstellar trip? If we picture a standard science-fiction scenario, in which we have hundreds of people and a thriving ecosystem, the energetic demands grow pretty large. Since the ship would be far from any star, starlight is not an option. Since there are no big planets along either, tidal forces and geothermal energy don't contribute. Perhaps a crew could tap into whatever energy source was propelling the ship. Another option, which we will discuss later, is that we put the crew in stasis or send eggs rather than sending living people.

Radiation damage.—We are pretty well-protected on Earth from high-energy charged particles from the Sun and other sources, simply because the Earth has a significant magnetic field. Unless the ship did as well, the inhabitants would not be protected from such particles. Even if a magnetic field were generated, it would have to be very strong indeed to prevent particles from hitting the ship. The problem is that Earth's field extends over a large region, meaning that particles can be deflected gently, but over the size of a ship the field would have to be huge to have the same effect. The radiation itself doesn't even have to be the main problem. Impacts of the particles with atomic nuclei in the ship can produce unstable nuclei that radiate later; this actually happens with some spacecraft away from the Earth. Over hundreds to hundreds of thousands of years, this could have a devastating cumulative effect.

Micrometeoroids.—Even for a stationary spacecraft in space, impacts with interstellar dust occur at speeds of several tens of kilometers per second, i.e., a hundred or more times the speed of a bullet. If our ship moves at a tenth of the speed of light, we get to tens of thousands of kilometers per second. The dust is somewhat charged but not enough to be deflected by any reasonable magnetic field. Therefore, as the ship travels it is continuously damaged by minute impacts. Unless there is careful and continuous repair, the ship would ultimately lose air and other supplies.

Weightlessness.—This is primarily a problem if we want to send active people along on the mission. Russian cosmonauts and (to a lesser extent) our astronauts have occasionally spent several consecutive months in near weightlessness. The results are terrible for their bodies. They lose weight and more importantly bone mass, often being so affected that they cannot stand up when they return to Earth. Over centuries or much more, the inhabitants of the ship would lose muscle tone from birth. One perspective on this is that reputedly sleeping on Earth gives you more net exercise than activity in zero gravity, because of the load borne by your heart.

One could imagine producing artificial gravity to counteract this. Constant linear acceleration towards the target, then deceleration, would do this, but maintaining one Earth gravity's worth of acceleration seems absurdly beyond what we could do in the forseeable future. A more realistic possibility, as shown in the movie "2001: A Space Odyssey", is to spin the ship so that the outer portions experience acceleration. The potential drawback is that this would exert stress on the ship, but you can't have something for nothing!

Isolation.—Also a problem only if we require live humans on our ship, but a potentially dicey issue. Unless we have gigantic starships with at least dozens of people (which would require monumental amounts of energy to accelerate and support), the small number of people and large amounts of time would be a recipe for psychological conflict and isolation. For comparison, consider the ill-fated Biosphere 2 experiment. This was an attempt to put eight people in a completely self-contained and self-sustaining environment with plants. This suffered many difficulties, one of which was cliques and sabotage after a number of months.

All in all, the problems are many and a great deal of development will be needed to deal with them. We now explore some ways that at least propulsion might be improved so that we can wait merely centuries instead of hundreds of thousands of years!

Rocket science

As there is no air in space, the kind of engine that runs your car simply won't work. Fortunately, the principle of conservation of momentum tells us that if we can eject something out of the back of a rocket, the rocket will go forward as a result. To understand this concept, suppose that you and a friend are floating together in the middle of space. If you give your friend a push, you move backwards as a result. Similarly, if you were to throw a baseball then you would go backwards, although not as fast as the baseball moves forwards because you have much greater mass than the baseball.

It is *not* necessary for the material that is ejected to have something like air to "push" against. This was not understood by the New York Times when on January 13, 1920 they derided the pioneering rocket experiments of Robert Goddard: "That Professor Goddard, with his 'chair' in Clark College and the countenancing of the Smithsonian Institution, does not know the relation of action to reaction, and of the need to have something better than a vacuum against which to react - to say that would be absurd. Of course he only seems to lack the knowledge ladled out daily in high schools."

Ahem. No, in fact a rocket works just fine in a vacuum; better, in fact, than it does in air because air resistance would slow down the rocket. Those who get their science exclusively from the mass media are doomed to frequent disappointment.

In any case, it is clear that the faster you can expel your fuel from the back of the rocket, the faster your rocket will go. You might also anticipate that the more fuel you have, the faster you will go eventually. That is true, but not nearly to the extent we might hope, because the fuel also has mass and has to be accelerated as well. This is encapsulated in the rocket equation, which was first derived in the early 1900s as part of weapons research. Suppose that we have a rocket whose total mass including fuel starts out as m_0. Let the fuel be ejected at a speed v_e, and let the final mass of the rocket after the fuel has been ejected be m_1. If we also assume that the fuel comes out one small bit at a time rather than all at once, then the final speed of the rocket is

$$v_{\rm final} = v_e \ln(m_0/m_1) \ . \tag{1}$$

Here "ln" means the "natural log" to base $e = 2.71828\ldots$. For example, suppose that the fuel makes up 90% of the total mass, so that when it is spent $m_1 = 0.1m_0$. Then the final speed is not ten times v_e but just $\ln(10) = 2.3$ times v_e. If the fuel makes up 99% of the total mass then the final speed is $v_{\text{final}} = 4.6v_e$, not $100v_e$. Again, the problem is that we have to accelerate all the fuel as well as the payload or passengers. If we could burn all the fuel at once we could do better. For example, if the fuel makes up 99% of the total mass and is all ejected at once with the speed v_e, then the final speed of the payload would be $99v_e$ instead of just $4.6v_e$. However, when the payload involves people, such enormous acceleration would turn them into piles of quivering sludge, which is why this is not an option!

The typical speed of rocket exhaust with current technology is about 4 km/s. To get this up to the 30 km/s that we mentioned earlier (with a journey time of 100,000 years to get 10 light years away) would require a fuel:payload mass ratio of $\exp(30/4) \approx 1800$. That's huge, and suggests reason for pessimism for very fast trips, but let's examine some specific suggestions.

Propulsion methods

Since current methods obviously won't work, what are some other suggestions? One that appears technically feasible is nuclear pulse propulsion, such as was proposed in Project Orion. Invented by the mathematician Stanisław Ulam, the idea is that explosives powered by nuclear fission or nuclear fusion would be dropped out of the back of the rocket. Some tens of meters away, these would be detonated and caught by a large metal plate on springs. The springs would catch the blast and spread the impulse out over several seconds, leading to a less jerky ride. Various other clever methods were designed to reduce risks, but the spacecraft would have had to be pretty massive (at least 300 tons) to survive the blasts. One model would have had thousands of such impulses, each adding about 50 km/hour to the speed. It has therefore been likened to an atomic pogo stick!

With this design it was estimated that a spacecraft could get up to 8–10% of the speed of light. Some of the ideas included a "super-Orion" which would have been 400 meters in diameter and weigh 8,000,000 tons. At this size there could have been a significant colony aboard, possibly mitigating concerns about isolation. This is therefore an intriguing design. However, serious work on this project stopped in 1963 with the Partial Test Ban Treaty, which said that any nuclear detonations had to be underground (to prevent fallout in the atmosphere). Such a ship could not realistically be launched from the Earth as a result, and construction in space would magnify the undoubtedly gargantuan costs by many times.

There are other more far-fetched suggestions along these lines as well. For example, the highest efficiency engine possible would involve matter-antimatter reactions, since these would convert all the reactants into energy and provide the highest achievable thrust. The issue here is creation of the antimatter and confinement away from matter. Right now antimatter can be created in particle accelerators, but only in incredibly tiny quantities. Moreover, although in principle one might imagine magnetic "bottles" that would confine the antimatter, in practice any reasonable density of the stuff would leak out in matters of seconds, leading to explosions we didn't intend! Maybe in the far future we will find ways around this.

Since the fuel mass is a major limiting factor, can we find clever ways to bypass this problem? One suggestion is called the Bussard ramjet after its originator Roger Bussard. The idea is that rather than carrying along, say, hydrogen to use in fusion reactions, we should take advantage of the huge amount of hydrogen already in space. Yes, it has very low density, but with a big enough scoop in front perhaps the hydrogen could be channeled to reaction chambers where it would be fused into helium and used for propulsion. That way, the rocket is almost all payload and passengers rather than almost all fuel. It's a great idea, but unfortunately more detailed calculations suggest that the drag on the scoop caused by motion through the hydrogen would be greater than the thrust produced, for pretty much any conceivable scoop design. Pity.

Another possibility has the thrust generated by laser light produced in the home system rather than on the spaceship. That is, we can imagine attaching a large reflective sail on the front of a ship that intercepts a beam of light that is sent out from Earth. Again we benefit from not carrying fuel along. This design could even be used to decelerate the ship when it neared its destination, by having the sail partially detach and bounce some of its light off the forward-facing part of the sail. Robert L. Forward, who wrote several science fiction books and also did many serious calculations, proposed some specific possibilities that would allow the spacecraft to achieve speeds up to half the speed of light. The difficulty is that for human missions, this would require lasers with powers on the order of 75,000,000 gigawatts! Given that the current world power output is 15,000 gigawatts, this may also be a bit in the future.

Long-duration voyages: interstellar arks

Given that any reasonable trip will take between several and several thousand human generations, how can this be managed? Several strategies have been proposed. Note, incidentally, that even if as a species we decided that this was to be our highest priority, improvements in propulsion technology mean that any ship launched now would be passed by future ships with better acceleration, so we should wait.

The most straightforward one conceptually is a "generation ship" or "interstellar ark". There would be a colony of people on the ship living normal lives, so the excessive duration of the trip means that those who arrived at the destination planet would be descendants of the original crew. Because of this, there would be an additional consideration beyond essentials such as how well the environment could be maintained or the psychological health of the people. As we discussed in the lectures on evolution, genetic diversity is critical to maintenance of good health. With too few people the diversity would not be enough, and many generations down the line the inbreeding would have led to catastrophic problems. In saying this, of course, I am limiting myself to current biological knowledge and technology; if it becomes possible in the future to correct genetic deficiencies in the womb this may not be so bad after all. Even if that is the case, trips lasting hundreds to thousands of years could lead to major cultural changes on the ship; how many societies do you know that have maintained their culture and purpose unchanged for millennia?

Another possibility is extension of human lifetimes, either normal lifetimes or via suspended animation or cryogenics. Many technical obstacles must be overcome for this to be practical. In addition, one would have to have either a rotating series of wakeups for the crew or outstanding computers to maintain and guide the ship while the crew was in stasis. If this is possible, it seems to me that an even better option would be to launch a completely automated ship that contains frozen human eggs and a means to gestate them. One could do similar things with other terrestrial animals and plants. This would have the advantage that no energy would be required for food. It would also mean that ship accelerations could be much higher than would be tolerable for adult humans. On the other hand, it would require confident identification of habitable planets and the development of robots that could take the role of human parents until the children had become adults.

Any way you slice it, the enterprise would be difficult and costly. It would, however, be an extension of humans beyond Earth and would render us much less vulnerable to total extinction. Do you think this is something we should pursue actively?