## Relativity and Time Travel

Prepare to set your weird receptors to full, because in this lecture we are going to talk about some truly bizarre stuff. Our theme will be simple: suppose we had an alien species that was arbitrarily advanced but still obeyed the laws of physics. What could they accomplish?

The tenth supplement gives an overview of the fundamentals of special and general relativity, and some of the strange effects that really do happen. I suggest you read that before continuing with these lecture notes. We will use those concepts to consider some highly speculative stuff such as wormholes and time travel. Hang on!

### The twin paradox

But how does this relate to aliens? We discussed in the lecture on interstellar travel some of the many challenges that await us, but since we are dealing with arbitrarily advanced aliens we don't have to worry. With that in mind, special relativity allows aliens ways of traveling vast distances in their lifetimes, even if they live lives of the same duration as ours.

To see how, let's consider the twin paradox. Pat and Robin are identical twins. Robin, however, wants to explore the universe, whereas Pat is happy on Earth. Robin therefore gets in a ship, accelerates to nearly the speed of light, goes to a destination and comes back. Since moving clocks appear to run slowly, Pat will watch Robin's clock moving more slowly that Pat's does for the entire trip. Therefore, when Robin returns to Earth to compare clocks, Pat's has more elapsed time. But our own lives are clocks of a sort, so this also means that Robin has aged less than Pat, by a factor that is sort of an average of the Lorentz factor $\gamma$ through the trip. Note, though, that $\gamma$ can be made as large as we want by making our speed as close as possible to the speed of light. For example, if $v = 0.9c$ then $\gamma = 1/\sqrt{1 - v^2/c^2} = 2.29$. Therefore, Pat would age 2.29 times as much as Robin. If Robin aged 10 years, Pat would age 22.9 years. If instead $v = 0.99c$ then $\gamma = 7.09$, so when Robin had aged 10 years Pat would have aged 70.9 years and be close to death. If $v = 0.9999999c$ then $\gamma = 2236$ and a mere 10 year trip by Robin would equate to 22,360 years on Earth, more than double the time since the invention of agriculture!

You may wonder how this turns into the twin "paradox". The problem is that it might seem that Robin would also see Pat's clock running slowly, and would thus conclude that Pat should be the younger one when they meet. In reality, though, Robin is the only one experiencing acceleration (due to the rockets firing during the trip), so the viewpoint in the previous paragraph turns out to be the right one.

In any case, this opens up some pretty cool possibilities. Suppose a really advanced alien wanted to see its star evolve to a red giant. Maybe that would take five billion years.

No problem: the alien just gets in their ship, goes close enough to the speed of light, and comes back. Again, the alien would not *feel* as if it had lived any longer than normal, but the rest of the universe would age by billions of years if the alien went fast enough. You could imagine very advanced civilizations in which individuals did this rather than wait out the boredom of everyday life. This also makes interstellar travel easier from the point of view of the passengers. Yes, it might still take 1000 years to go to another system from the standpoint of the galaxy as a whole, but to you it might take only one year. Not bad!

In the tenth supplement we note that in principle if you could withstand the gravity near (but outside!) a black hole, you could hang out there and watch the universe speed into the future. But is there a way to use special or general relativity to travel *backwards* in time? Let's explore this concept.

**Time travel and the grandfather paradox**

Many science fiction stories have explored the concept of time travel. An early classic is "The Time Machine" by H. G. Wells, but more recent ones include the "Back to the Future" trilogy, "12 Monkeys", and a great sequence in "Harry Potter and the Prisoner of Azkaban". Is this possible in principle for a sufficiently advanced species?

If you think about it for a while, there is an objection that might seem fatal. This goes by the name of the "grandfather paradox", although I'm not sure why it couldn't just be the father paradox. The idea is as follows. Suppose that I am an evil, but brilliant, scientist and I construct a time machine. I go to St. Louis in 1930, where I meet my then 12-year-old grandfather. Being evil, I kill him. Naturally now he won't be able to meet my grandmother and therefore my father won't be born. But then I can't be born, which means that I can't cackle evilly and construct a machine that I use to go back to 1930 and kill my grandfather. This means that my grandfather *would* be able to meet my grandmother, and I could be born, so I could go back and kill him, so I couldn't, so I could, so...

This kind of paradox loop might seem to kill all time travel. In science fiction the resolution often comes down to personal choice. For example, in the first "Back to the Future", Marty McFly does change things, but for the better; his father ends up being a confident winner instead of a wimp. There are other creative solutions that have been used, too. In "The Men Who Murdered Mohammed" by Alfred Bester, a rather whacked scientist goes back and forth in time, killing historical characters, but finds that as a result he cannot access his original plane of reality!

People have confronted this a bit more seriously, though. The basic point researchers such as Kip Thorne have made is that it is *inconsistency*, not time travel itself, that must be avoided. That is, it is inconsistent to imagine a time sequence in which I am born and then kill my ancestors, because to be consistent we would have had to take into account that my ancestors would already have encountered my future self.

To give one example that doesn't involve human decisions, imagine that we shoot a pool ball into a pocket that allows the ball to travel backwards in time. Can we arrange things so that the future ball hits the past ball and prevents it from going in the pocket? That's the inanimate version of the grandfather paradox. The answer is no, we can't. What *can* happen self-consistently is that the future ball grazes the past ball and makes it go through the pocket in such a way as to produce a future grazing collision. Going back to science fiction, this principle of consistency was a key element of a sequence near the end of "Harry Potter and the Prisoner of Azkaban". Without ruining the film with details, I'll say that Hermione and Harry travel backward in time, but the sequence is carefully self-consistent.

The net result is that, with some restrictions, time travel might be possible in principle. It actually also might *not* be possible in principle, but with what we know at this time it can't be ruled out absolutely. What methods might we use?

**Faster than the speed of light?**

If you look at Einstein's equations for special relativity you might convince yourself that one way to travel backwards in time is to move faster than the speed of light. This has interested people enough that they have coined a term for particles that do this: "tachyons". The problem is that nothing can be *accelerated* from a slow speed to beyond the speed of light. You can see this by noting that as you get closer to light speed the effective mass increases. That means, from Newton's second law $F = ma$, that more and more force is required to accelerate the mass. Ultimately an infinite force would be needed to move the mass at the speed of light, so this can never happen. In fact, even tachyons, which probably don't even exist, aren't accelerated to beyond light speed. Instead, they *always* travel faster than light. Even if they do exist, this won't work for normal particles such as make up humans and aliens.

**Wormholes**

In the wonderful book "A Wrinkle in Time", a tesseract is explained as a folding in spacetime. Imagine, for example, a piece of paper. Going from the top to the bottom is a long way. However, if the paper is bent over, then although the normal distance (along the paper) from top to bottom is still the same distance, the distance through the air is much less. Therefore, even if you are restricted to less than the speed of light you can get to your destination faster.

Wormholes, therefore, are essentially shortcuts through spacetime. At any given point on a journey through a wormhole the local speed is less than the speed of light. Constructing them might take some serious effort, but let's assume our aliens could do that. Might they have set up wormholes in various places in our galaxy or beyond so that they could zip in and have a quick chat with that nice multitentacled cephalopod from Rigel?

In detail, there turn out to be some difficulties. The simplest wormholes that obey the equations of Einstein's general theory of relativity are unstable. That means that if anything went through them (alien, matter, photon) the wormhole would collapse at the speed of light, destroying the traveler. That's not nice.

In the 1980s, however, Kip Thorne and colleagues started taking a serious look at wormholes in response to Carl Sagan's request to come up with a plausible interstellar transport system for his novel "Contact". What Thorne realized is that a traversable wormhole could in principle exist if it were constructed from "exotic matter". Specifically, the matter would have to have a net negative mass-energy density. Huh? Negative mass-energy? Sounds impossible. And yet, this has been demonstrated theoretically on very small scales (look up "Casimir effect"), and is related to whatever dark energy is. So we're not dead yet.

The problem comes back to time travel. It turns out that if you can move faster than light would through normal space (which is the point of wormholes!), it is also possible to travel backwards in time. So, consider an advanced civilization that has just completed a traversable wormhole. As soon as it opens up, various things go through it, such as light and even weirder things like quantum fluctuations of the vacuum. They travel backwards in time and go through again. The problem is that all of those things have *positive* energy density, meaning that when they go through they add up and eventually cancel the negative energy density that keeps the wormhole open. This destroys the wormhole, pretty much immediately as it turns out. The net result is that probably wormholes and related things like warp drive can't exist. The conclusion is that, most likely, although aliens could buzz around close to the speed of light with the resulting effects, faster than light travel is not promising. Poor aliens!

I told you this would be weird...

**Terraforming and the Future of Humans in Space**

Human colonization of other planets, even in our Solar System, is a long way away. When that time comes it is likely that the first colonies will be in self-contained domes that carry a bit of the Earth with them. Eventually, however, many people envision transforming whole planets into ecosystems that can support Earth life without the need for isolated containment facilities. This transformation is called terraforming, and it will be our last subject in the class.

There are different ways to approach terraforming, so let us follow Martyn J. Fogg (an expert in the subject) and begin by discussing three different types of planets and the level of effort needed to terraform them:

- Habitable planet. This is what Star Trek liked to call a "class M planet", in which you basically step off your starship, take a deep breath, and pronounce the planet ready to go. This is a planet so like Earth that it can be inhabited just as it is, with minimal effort.
- Biocompatible planet. A planet that has the necessary physical parameters (i.e., the chemical building blocks, energy, liquid water, and stability) so that it could eventually host a complex ecosystem if seeded with life. We will discuss various methods of such seeding below.
- Easily terraformable planet. A planet that could be rendered biocompatible with relatively limited resources, such as might be present on a starship or in a precursor robot mission rather than requiring a sustained armada of ships.

For a habitable planet, the job is already done for us. Maybe the atmosphere contains more argon than ours, or a bit more or less oxygen, but the planet by definition already has life and thus establishing a human colony there is no more difficult than it has been to put colonies on Australia.

Let us therefore consider the next level, of biocompatible planets. It is an interesting question of whether such planets exist, because by definition they have no life but could sustain it if the life were seeded there. Basically, we are asking whether the origin of life is difficult enough that it might not happen even given the right conditions. Could the early Earth have been like this? Might Europa be an example now? In any case, supposing that we have such a planet before us, what should we do?

It seems reasonable that the establishment of a pioneering biosphere, which has been dubbed *ecopoiesis* (meaning "the making of an abode for life"), would have to be started with the most primitive organisms, i.e., bacteria and archea. Indeed, if the candidate planet is hotter or colder, more acidic or more basic than we would like, extremophiles will have to be pressed into service. Depending on how rapidly we need to proceed we could even recapitulate the progression of life on Earth, by using cyanobacteria to generate oxygen and then moving in with plants and eventually animals. If we were in a hurry then more dramatic technological solutions might be necessary.

To get a better idea about how this might work, let us specifically consider how we might terraform Mars.

**Terraforming Mars: warming and thickening the atmosphere**

As background, we note that many of the substances needed for terraforming Mars are available in more or less accessible locations. Dry ice, which is frozen carbon dioxide, makes up the polar caps during the Martian winter. We know water is present as ice, and some liquid water might exist below the surface. Oxygen is present in the water, as is hydrogen, so these gases could be released by electrolysis. Large amounts of oxygen are also present in the form of iron oxide (rust!) and other metal oxides. Analysis by the Mars Phoenix lander shows that other essential minerals are also present in the Martian soil. Mars' lower surface gravity compared to the Earth means that gases released into the atmosphere (either for greenhouse purposes or for us to breathe) will gradually drift off into space, but the timescale for this is millions of years and therefore not relevant to reasonable timescales for colonies.

Clearly the two main challenges to terraforming Mars are to warm it up and thicken its atmosphere. Given enough time and effort we could do this, but how much would really be required with forseeable technology? A decade? A century? A million years? We also need to estimate the energy and resources needed. Fortunately, Robert Zubrin and Christopher McKay wrote a 1993 article that goes into some depth on these issues, so we will follow them closely.

A key point that will make terraforming Mars much easier is the principle of a runaway greenhouse effect. Suppose that we were to warm Mars up by a few degrees Celsius. This would release some of the carbon dioxide in the permafrost, but since $CO_2$ is a greenhouse gas this would increase the temperature further, releasing more gas, and so on. Therefore, even though the current average surface temperature on Mars is $-60°$C, we would not have to heat it by $60°$C to give life a fighting chance. The true temperature increase needed is much less. Probably all we need to do is provide the first $5°$C warming and then let the runaway take care of the rest.

One method of heating would be to insert greenhouse gases into the Martian atmosphere. It turns out that halocarbons such as chlorofluorocarbons (CFCs, which are the main culprits in the destruction of our ozone layer) are thousands of times more effective as greenhouse gases, molecule for molecule, than $CO_2$ is. If we want to produce a $5°$C heating over 20 years then Zubrin and McKay estimate that the power required given current technology will be about 1300 megawatts. For comparison, a typical nuclear power plant on Earth outputs about 1000 megawatts, which is enough to power a medium-sized city such as Denver. This power level is therefore possible, although it would require a pre-existing station on Mars in a self-contained facility. As another option, this power level is the amount of solar radiation at Earth's orbit per square kilometer. Taking inefficiencies into account, and the greater distance of Mars from the Sun, a few tens of square kilometers of solar cells would do the job.

It is estimated that if all of Mars' $CO_2$ were liberated from the surface the atmospheric density would be about 40% that of Earth. Not all can be liberated, since as the soil concentration of carbon dioxide drops the soil acquires a greater affinity for $CO_2$, but 30%

of an Earth atmosphere could be maintained. This would be enough for people to walk around in ordinary clothes, although they would have to have breathing apparatuses. This density would be plenty for large inflatable tents to be set up, and would also be enough for a thriving plant ecosystem.

Sounds pretty good, doesn't it? There is, however, a serious problem with this scenario. If CFCs lasted 100 years in the Martian atmosphere as they do in ours, then once the system was set up over 20 years then it would take only 20/100=1/5th of the original energy expenditure, per year, to maintain their level. Unfortunately, the thin atmosphere and absent magnetic field of Mars mean that CFCs are not as protected as they are on Earth. Instead, ultraviolet radiation comes through quite nicely, and estimates of the survival time of CFCs range from hours to days! This is absurdly short, and would require a constant power supply a thousand times what we discussed above. If the atmosphere had already been thickened then the molecules might survive longer, but the prospects are poor for this mechanism by itself.

We therefore explore the second suggestion, which is that if ammonia-rich asteroids or comets exist in the outer solar system, then altering their orbits to hit Mars would release ammonia, which is a better greenhouse gas than $CO_2$. We say *outer* solar system because, counterintuitively, it would take less energy to divert such an object to Mars than it would take for one in a closer orbit. The basic reason is that objects farther away orbit more slowly. Therefore, only a slight change in the speed is needed to make it go from an orbit to a radial plunge. For objects closer in a much larger change in speed is necessary. In addition, we can be clever by using "gravity assists" from the outer planets, in which we divert an asteroid so that it goes close by, e.g., Uranus, whose gravity then moves it onto a collision course with Mars. This principle is used all the time to save energy on orbits of satellites that are sent to planets in our Solar System. For the orbits we have in mind, the flight trajectory would take some decades to hit Mars.

In the 1960s, nuclear thermal rocket engines were tested that produced 5000 megawatts at 2500 K, which would suffice to heat some of the asteroid's ammonia and use it to help in the thrust. If we consider a 10 billion ton asteroid (with a diameter of about 2.5 km), ten years of thrusting would be required. This would hit Mars with enough energy to melt a trillion tons of water, if the spot were selected properly. Forty missions of this type would double the nitrogen content of Mars' atmosphere (or more, if the impacts were targeted to beds of nitrates). At one mission per year this would lead to a temperate climate over much of Mars and enough water to cover a quarter of the planet to a depth of 1 meter.

This is a decent scenario, but it suffers from its own drawbacks. Ammonia probably would last less than a century in the atmosphere, meaning that the impacts would have to continue to be effective. Given that each impact would have a thousand times the energy release of the largest bomb ever exploded (although it wouldn't have the radioactive fallout!), this could be problematic. One possible way around this is to use bacteria that produce ammonia out of nitrogen and water. If the ammonia atmosphere were set up once and the bacteria put in place, a self-sustaining ecosystem might be possible.

Nonetheless, we should consider Zubrin and McKay's third scenario. They suggest that an orbiting mirror could be put in place that would warm selected regions of Mars by a few degrees. The kicker is that we are talking about a **big** mirror here! If you wanted to warm up the area south of 70 degrees south latitude by 5°C, you would need a mirror with a radius of 125 km, which at a typical surface density of 4 tons per square kilometer (e.g., for mylar) amounts to 200,000 tons!! Yow. Clearly this wouldn't be launched from Earth, but maybe it could be constructed in space. The energetic cost for construction would be about 120 megawatt-years, which is actually not too terrible if there are some 5 megawatt nuclear reactors in space. Note also that if you have these giant mirrors in space anyway, having solar cells on a few paltry tens of square kilometers of it would also supply power to the Martian inhabitants.

These three methods (greenhouse gases, asteroid impacts, orbiting mirror) might be used together for greater efficiency. In any case, although the project would be large indeed, it is not out of the question given today's technology and a century to work. However, this is only the first step. For the atmosphere to be breathable by us and for a complex ecosystem to exist on Mars, we would need to generate large amounts of liquid water and oxygenate the atmosphere. Let's consider those now.

**Terraforming Mars: hydrosphere and oxygen atmosphere**

Getting liquid water won't be too bad given the means needed to produce a thick, warm atmosphere. As we indicated above, collisions with asteroids or comets will provide liquid water via their impacts. If we had a large orbiting mirror, it would provide a lot more power than the impacts, so with sufficient targeting the water could be heated just fine. This is another major benefit to having such a huge mirror in space.

An oxygenated atmosphere is another story. Indeed, Zubrin and McKay consider the establishment of such an atmosphere to be the most challenging and long-term of all the barriers to terraforming Mars. The problem is that although bacteria, archea, and primitive plants can survive without oxygen, more advanced plants need at least 1 mb to be in oxygen (1 bar is the pressure of our atmosphere at sea level, and 1 mb is 1/1000 of a bar; 1 mb of oxygen is 1/200 of our oxygen level, given that our atmosphere is 20% oxygen). Humans need 120 mb, or 0.6 times our level, to survive over long periods. How do we get the oxygen? In addition, we need to have a buffer gas such as nitrogen to avoid oxygen toxicity and runaway fires.

In principle, plenty of oxygen exists in metallic oxides on the surface. Unfortunately the energetic requirements are gigantic. Zubrin and McKay estimate that it would take about 2200 terawatt-years for every mb produced. Since the current world annual power output is 12 terawatt-years, that would take either a long time or huge power improvements or both! Similar amounts of energy are needed for plants to process carbon dioxide, but at least those are self-propagating. The process would therefore involve two steps. In the first, brute force and an enormous amount of energy would be employed to push the oxygen content up to 1 mb. With three 125 km radius mirrors (yet another use for them!), this would take about 25 years. Then plants would be introduced, genetically engineered to survive the different Martian soils and other conditions and to be at least 1% efficient in producing oxygen (high, but not unprecedented). With still substantial input of power (100 terawatts), human-breathable levels of oxygen could be produced in about 1000 years. A possible spinoff is that since power installed on the surface would be important in this scenario and it would require nuclear fusion (not fission, used in today's nuclear power plants), this technology could be used in future interstellar flight.

All in all, therefore, the easiest planet in our Solar System to terraform would take about a millennium to be ready for human habitation without breathing apparatuses. That is a *long* time. In fact, it is long enough that given our staggering improvement in technology over the last century it makes sense to postpone any serious efforts in this direction for at least another century. With that in mind, however, it is fun to speculate about what we might be able to do in the more distant future, so let's do that now.

**Terraforming: the farther future**

There are other planets we might imagine colonizing, such as Venus. The challenges here are much greater than they are for Mars, including having to get rid of a thick atmosphere rather than generating one from a thin starting point. Collisions would be ineffective, so people have discussed high-energy fountains that strip away the atmosphere gradually. There is also an almost complete absence of water from the atmosphere or (probably) the surface layers, so it isn't a simple matter of heating up the surface and letting the water bubble to the top. In addition, since Venus is closer to the Sun than Earth is, the natural temperature is a lot higher and is indeed out of the habitable zone. Giant solar shades might be one way to go, but they would make the already-huge 125 km radius mirrors we discussed for Mars seem paltry by comparison.

One possibility is that rather than terraforming Venus we could put floating colonies about 50 km up in the atmosphere. The pressure there is about 1 bar (same as Earth at sea level), and the temperature is also Earth-like: $0-50$°C. The solar energy there is abundant, providing plenty of power, and winds would drive such a colony around the planet once every few days. In addition, our standard 20:79 oxygen:nitrogen mixture would float in the Venusian atmosphere, so essentially the colony would live in a giant balloon! Therefore colonization of Venus might be surprisingly straightforward, but it is not terraforming in the sense we have explored thus far.

What else might we do with an additional century or more of technological development? One obvious line to pursue involves specialized microorganisms genetically engineered for particular environments to allow us to transition to Earthlike conditions. Some research along these lines is proceeding, by taking current bacteria and archea and putting them in more and more Mars-like environments. Note, though, that there are limits to what evolution can do. All life on Earth needs liquid water for its full life cycle, so if you just sprinkled bacteria on Mars they would dry up and turn to dust fairly rapidly. You can't just gaze at Martian soil and intone "Evolve!" at it with hope of success. For extrasolar planets that have liquid water already this might be more promising.

Another approach might involve nanotechnology. Suppose we construct very small but intelligent robots with orders to reproduce themselves and to move towards release of greenhouse gases or other chemicals that would be needed to turn a biocompatible world into a habitable world. For such robots there would be much greater flexibility about energy sources and other requirements; for example, liquids would not be essential, and the robots could process minerals directly rather than needing them for sustenance. If the target world had been studied enough in advance, these robots could be specialized to the proper conditions. Since they can reproduce, with a short enough generation time they could easily spread over the entire planet within a year or so, allowing rapid large-scale changes and possibly quick adaptation to the conditions we prefer. This technology is at least decades in the future, but might be useful as unmanned ships are sent to distant planets to pave the way for later colonization.

Finally, we have to at least start thinking about ethical issues. If a planet has absolutely no life at all then presumably people will be okay with terraforming. What if there is life, but it is only microbial? This could be the case on Mars. Obviously we would want to study the life closely, but would it eventually be okay for us to completely redo the biolandscape? What if there are animals, but nothing more complicated than insects? What if there is intelligent life? Would it be okay for us to occupy and terraform part of the planet? I don't think there are obvious answers to these questions.

What do you think?