The Physics of Interstellar Travel

by Dr. Michio Kaku

When discussing the possibility of interstellar travel, there is something called “the giggle factor.” Some scientists tend to scoff at the idea of interstellar travel because of the enormous distances that separate the stars. According to Special Relativity (1905), no usable information can travel faster than light locally, and hence it would take centuries to millennia for an extra-terrestrial civilization to travel between the stars. Even the familiar stars we see at night are about 50 to 100 light years from us, and our galaxy is 100,000 light years across. The nearest galaxy is 2 million light years from us. The critics say that the universe is simply too big for interstellar travel to be practical.

Similarly, investigations into UFO’s that may originate from another planet are sometimes the “third rail” of someone’s scientific career. There is no funding for anyone seriously looking at unidentified objects in space, and one’s reputation may suffer if one pursues an interest in these unorthodox matters. In addition, perhaps 99% of all sightings of UFO’s can be dismissed as being caused by familiar phenomena, such as the planet Venus, swamp gas (which can glow in the dark under certain conditions), meteors, satellites, weather balloons, even radar echoes that bounce off mountains. (What is disturbing, to a physicist however, is the remaining 1% of these sightings, which are multiple sightings made by multiple methods of observations. Some of the most intriguing sightings have been made by seasoned pilots and passengers aboard air line flights which have also been tracked by radar and have been videotaped. Sightings like this are harder to dismiss.)

But to an astronomer, the existence of intelligent life in the universe is a compelling idea by itself, in which extra-terrestrial beings may exist on other stars who are centuries to millennia more advanced than ours. Within the Milky Way galaxy alone, there are over 100 billion stars, and there are an uncountable number of galaxies in the universe. About half of the stars we see in the heavens are double stars, probably making them unsuitable for intelligent life, but the remaining half probably have solar systems somewhat similar to ours. Although none of the over 100 extra-solar planets so far discovered in deep space resemble ours, it is inevitable, many scientists believe, that one day we will discover small, earth-like planets which have liquid water (the “universal solvent” which made possible the first DNA perhaps 3.5 billion years ago in the oceans). The discovery of earth-like planets may take place within 20 years, when NASA intends to launch the space interferometry satellite into orbit which may be sensitive enough to detect small planets orbiting other stars.

So far, we see no hard evidence of signals from extra-terrestrial civilizations from any earth-like planet. The SETI project (the search for extra-terrestrial intelligence) has yet to produce any reproducible evidence of intelligent life in the universe from such earth-like planets, but the matter still deserves serious scientific analysis. The key is to reanalyze the objection to faster-than-light travel.

A critical look at this issue must necessary embrace two new observations. First, Special Relativity itself was superceded by Einstein’s own more powerful General Relativity (1915), in which faster than light travel is possible under certain rare conditions. The principal difficulty is amassing enough energy of a certain type to break the light barrier. Second, one must therefore analyze extra-terrestrial civilizations on the basis of their total energy output and the laws of thermodynamics. In this respect, one must analyze civilizations which are perhaps thousands to millions of years ahead of ours.

The first realistic attempt to analyze extra-terrestrial civilizations from the point of view of the laws of physics and the laws of thermodynamics was by Russian astrophysicist Nicolai Kardashev. He based his ranking of possible civilizations on the basis of total energy output which could be quantified and used as a guide to explore the dynamics of advanced civilizations:

Type I – this civilization harnesses the energy output of an entire planet.

Type II – this civilization harnesses the energy output of a star, and generates about 10 billion times the energy output of a Type I civilization.

Type III – this civilization harnesses the energy output of a galaxy, or about 10 billion time the energy output of a Type II civilization.

A Type I civilization would be able to manipulate truly planetary energies. They might, for example, control or modify their weather. They would have the power to manipulate planetary phenomena, such as hurricanes, which can release the energy of hundreds of hydrogen bombs. Perhaps volcanoes or even earthquakes may be altered by such a civilization.

A Type II civilization may resemble the Federation of Planets seen on the TV program Star Trek (which is capable of igniting stars and has colonized a tiny fraction of the near-by stars in the galaxy). A Type II civilization might be able to manipulate the power of solar flares.

A Type III civilization may resemble the Borg, or perhaps the Empire found in the Star Wars saga. They have colonized the galaxy itself, extracting energy from hundreds of billions of stars.

By contrast, we are a Type 0 civilization, which extracts its energy from dead plants (oil and coal). Growing at the average rate of about 3% per year, however, one may calculate that our own civilization may attain Type I status in about 100-200 years, Type II status in a few thousand years, and Type III status in about 100,000 to a million years. These time scales are insignificant when compared with the universe itself.

On this scale, one may now rank the different propulsion systems available to different types of civilizations:

Type 0
Chemical rockets
Ionic engines
Fission power
EM propulsion (rail guns)

Type I
Ram-jet fusion engines
Photonic drive

Type II
Antimatter drive
Von Neumann nano probes

Type III
Planck energy propulsion

Propulsion systems may be ranked by two quantities: their specific impulse, and final velocity of travel. Specific impulse equals thrust multiplied by the time over which the thrust acts. At present, almost all our rockets are based on chemical reactions. We see that chemical rockets have the smallest specific impulse, since they only operate for a few minutes. Their thrust may be measured in millions of pounds, but they operate for such a small duration that their specific impulse is quite small.

NASA is experimenting today with ion engines, which have a much larger specific impulse, since they can operate for months, but have an extremely low thrust. For example, an ion engine which ejects cesium ions may have the thrust of a few ounces, but in deep space they may reach great velocities over a period of time since they can operate continuously. They make up in time what they lose in thrust. Eventually, long-haul missions between planets may be conducted by ion engines.

For a Type I civilization, one can envision newer types of technologies emerging. Ram-jet fusion engines have an even larger specific impulse, operating for years by consuming the free hydrogen found in deep space. However, it may take decades before fusion power is harnessed commercially on earth, and the proton-proton fusion process of a ram-jet fusion engine may take even more time to develop, perhaps a century or more. Laser or photonic engines, because they might be propelled by laser beams inflating a gigantic sail, may have even larger specific impulses. One can envision huge laser batteries placed on the moon which generate large laser beams which then push a laser sail in outer space. This technology, which depends on operating large bases on the moon, is probably many centuries away.

For a Type II civilization, a new form of propulsion is possible: anti-matter drive. Matter-anti-matter collisions provide a 100% efficient way in which to extract energy from mater. However, anti-matter is an exotic form of matter which is extremely expensive to produce. The atom smasher at CERN, outside Geneva, is barely able to make tiny samples of anti-hydrogen gas (anti-electrons circling around anti-protons). It may take many centuries to millennia to bring down the cost so that it can be used for space flight.

Given the astronomical number of possible planets in the galaxy, a Type II civilization may try a more realistic approach than conventional rockets and use nano technology to build tiny, self-replicating robot probes which can proliferate through the galaxy in much the same way that a microscopic virus can self-replicate and colonize a human body within a week. Such a civilization might send tiny robot von Neumann probes to distant moons, where they will create large factories to reproduce millions of copies of themselves. Such a von Neumann probe need only be the size of bread-box, using sophisticated nano technology to make atomic-sized circuitry and computers. Then these copies take off to land on other distant moons and start the process all over again. Such probes may then wait on distant moons, waiting for a primitive Type 0 civilization to mature into a Type I civilization, which would then be interesting to them. (There is the small but distinct possibility that one such probe landed on our own moon billions of years ago by a passing space-faring civilization. This, in fact, is the basis of the movie 2001, perhaps the most realistic portrayal of contact with extra-terrrestrial intelligence.)

The problem, as one can see, is that none of these engines can exceed the speed of light. Hence, Type 0,I, and II civilizations probably can send probes or colonies only to within a few hundred light years of their home planet. Even with von Neumann probes, the best that a Type II civilization can achieve is to create a large sphere of billions of self-replicating probes expanding just below the speed of light. To break the light barrier, one must utilize General Relativity and the quantum theory. This requires energies which are available for very advanced Type II civilization or, more likely, a Type III civilization.

Special Relativity states that no usable information can travel locally faster than light. One may go faster than light, therefore, if one uses the possibility of globally warping space and time, i.e. General Relativity. In other words, in such a rocket, a passenger who is watching the motion of passing stars would say he is going slower than light. But once the rocket arrives at its destination and clocks are compared, it appears as if the rocket went faster than light because it warped space and time globally, either by taking a shortcut, or by stretching and contracting space.

There are at least two ways in which General Relativity may yield faster than light travel. The first is via wormholes, or multiply connected Riemann surfaces, which may give us a shortcut across space and time. One possible geometry for such a wormhole is to assemble stellar amounts of energy in a spinning ring (creating a Kerr black hole). Centrifugal force prevents the spinning ring from collapsing. Anyone passing through the ring would not be ripped apart, but would wind up on an entirely different part of the universe. This resembles the Looking Glass of Alice, with the rim of the Looking Glass being the black hole, and the mirror being the wormhole. Another method might be to tease apart a wormhole from the “quantum foam” which physicists believe makes up the fabric of space and time at the Planck length (10 to the minus 33 centimeters).

The problems with wormholes are many:

a) one version requires enormous amounts of positive energy, e.g. a black hole. Positive energy wormholes have an event horizon(s) and hence only give us a one way trip. One would need two black holes (one for the original trip, and one for the return trip) to make interstellar travel practical. Most likely only a Type III civilization would be able harness this power.

b) wormholes may be unstable, both classically or quantum mechanically. They may close up as soon as you try to enter them. Or radiation effects may soar as you entered them, killing you.

c) one version requires vast amounts of negative energy. Negative energy does exist (in the form of the Casimir effect) but huge quantities of negative energy will be beyond our technology, perhaps for millennia. The advantage of negative energy wormholes is that they do not have event horizons and hence are more easily transversable.

d) another version requires large amounts of negative matter. Unfortunately, negative matter has never been seen in nature (it would fall up, rather than down). Any negative matter on the earth would have fallen up billions of years ago, making the earth devoid of any negative matter.

The second possibility is to use large amounts of energy to continuously stretch space and time (i.e. contracting the space in front of you, and expanding the space behind you). Since only empty space is contracting or expanding, one may exceed the speed of light in this fashion. (Empty space can warp space faster than light. For example, the Big Bang expanded much faster than the speed of light.) The problem with this approach, again, is that vast amounts of energy are required, making it feasible for only a Type III civilization. Energy scales for all these proposals are on the order of the Planck energy (10 to the 19 billion electron volts, which is a quadrillion times larger than our most powerful atom smasher).

Lastly, there is the fundamental physics problem of whether “topology change” is possible within General Relativity (which would also make possible time machines, or closed time-like curves). General Relativity allows for closed time-like curves and wormholes (often called Einstein-Rosen bridges), but it unfortunately breaks down at the large energies found at the center of black holes or the instant of Creation. For these extreme energy domains, quantum effects will dominate over classical gravitational effects, and one must go to a “unified field theory” of quantum gravity.

At present, the most promising (and only) candidate for a “theory of everything”, including quantum gravity, is superstring theory or M-theory. It is the only theory in which quantum forces may be combined with gravity to yield finite results. No other theory can make this claim. With only mild assumptions, one may show that the theory allows for quarks arranged in much like the configuration found in the current Standard Model of sub-atomic physics. Because the theory is defined in 10 or 11 dimensional hyperspace, it introduces a new cosmological picture: that our universe is a bubble or membrane floating in a much larger multiverse or megaverse of bubble-universes.

Unfortunately, although black hole solutions have been found in string theory, the theory is not yet developed to answer basic questions about wormholes and their stability. Within the next few years or perhaps within a decade, many physicists believe that string theory will mature to the point where it can answer these fundamental questions about space and time. The problem is well-defined. Unfortunately, even though the leading scientists on the planet are working on the theory, no one on earth is smart enough to solve the superstring equations.

Conclusion

Most scientists doubt interstellar travel because the light barrier is so difficult to break. However, to go faster than light, one must go beyond Special Relativity to General Relativity and the quantum theory. Therefore, one cannot rule out interstellar travel if an advanced civilization can attain enough energy to destabilize space and time. Perhaps only a Type III civilization can harness the Planck energy, the energy at which space and time become unstable. Various proposals have been given to exceed the light barrier (including wormholes and stretched or warped space) but all of them require energies found only in Type III galactic civilizations. On a mathematical level, ultimately, we must wait for a fully quantum mechanical theory of gravity (such as superstring theory) to answer these fundamental questions, such as whether wormholes can be created and whether they are stable enough to allow for interstellar travel.