3 December
2019

# *L*, CONTACT WITH EXTRASOLAR CIVILIZATIONS, & SPACE TRAVEL

Homework #8 due Monday by 7pm
Exam #3 on Tuesday – Review session Sunday at 7pm



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# Exam #3

1 hr 15 min in-class exam, open book and open notes

- Things you should DEFINITELY bring with you:
  - Writing utensil (pencil or pen – blue or black ink)
  - Calculator
- Things you should PROBABLY bring with you:
  - Lecture notes
  - Laptop or tablet (so that you can access the WeBWorK homework problems)

REVIEW SESSION – Sunday, 12/8 at 7pm in B&L 203H



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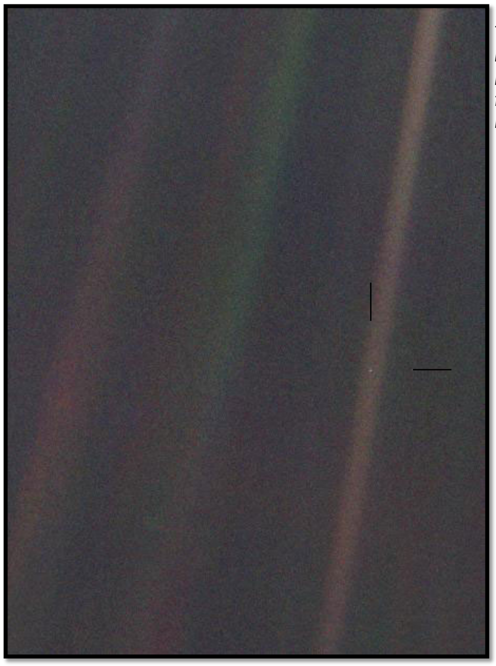

*The Pale Blue Dot: Earth as seen by NASA's Voyager 1 from a distance of 4 billion miles (0.0007 lyr)*

# $L$, Contact with extrasolar civilizations, & Space travel

Drake's $L$ and $N$

The distances to the nearest extrasolar civilization

Issues of communication, visits, and exploration

The search for extraterrestrial intelligence (SETI)

The prospects for exploration in person:

- Conventional space flight: rockets and ion drives
- Nuclear propulsion and Project Orion
- Wormhole space travel using gravity
- The health problems faced by space-travelling human beings





# $L$

How long until we run a huge risk of the various catastrophes?

- Nuclear destruction: 0 years
- Overpopulation: 200 years
- $CO_2$ ocean acidification and/or lethal greenhouse effect: 300 years
- Resource exhaustion: 300 years

A generous estimate of $L = 1000$ yr

- Supervolcanism: 50 Myr
- > 10 km asteroid impact: 50 Myr (Preventable by sufficiently clever, nuclear-capable civilization)
- Gamma-ray burst: 100 Myr, only if aimed at us
- Uninhabitable due to increased solar luminosity: 1.5 Gyr

Median around 100 Myr

# The two ranges of $L$ and $N$

We estimate that technological civilizations like ours have a substantial probability of destroying themselves within several hundred years of communicability.

But if they live through that – and especially if they learn to protect themselves from asteroid impact, which seems likely – then nothing would destroy them within about 100 Myr.

- And by then they seem likely to have found something to do about supervolcanism, and therefore last until their star dies: $L = 1.5$ Gyr.

If either **all** civilizations die of the Catastrophes or **all** live through them, we get these two values:

$$L = 1000\ yr \implies N = R_* f_p n_e f_l f_i f_c L = 2 \quad \textbf{Pessimistic}$$
$$L = 1.5\ Gyr \implies N = R_* f_p n_e f_l f_i f_c L = 3\times10^6 \quad \textbf{Optimistic}$$





# The two ranges of $L$ and $N$

So if **none of the Milky Way's civilizations were to make it past the self-inflicted catastrophes, there would only be a few communicable civilizations at present**.

But if **a substantial fraction of these civilizations were to run the gauntlet and live, then there would be somewhere around one million communicable civilizations at present**.

This means that, if there are lots of civilizations in the Galaxy, most of them are more advanced than ours since they have already lived through the catastrophes.

- **Example**: Suppose that half make it through the self-inflicted catastrophes and half do not; then the real $N$ is half of the sum of these previous results:

$$N = \frac{1}{2}(2 + 3\times10^6) = 1 + 1.5\times10^6 \approx 1.5\times10^6$$

**Us, and one million and a half more advanced civilizations**

Stephen Hawking thought that it would be dangerous to communicate with extraterrestrial civilizations because they are likely to be more advanced than us. Do you agree?

Question!

A. Yes. They will come take our resources and assimilate us if they know we are here.
B. No. They know our planet is here anyway without our call, and there are many resource-filled planets closer to them.
C. Yes. They will add us to the Galactic equivalent of a zoo.
D. No. Advanced civilizations might be able to help us avoid Catastrophe.



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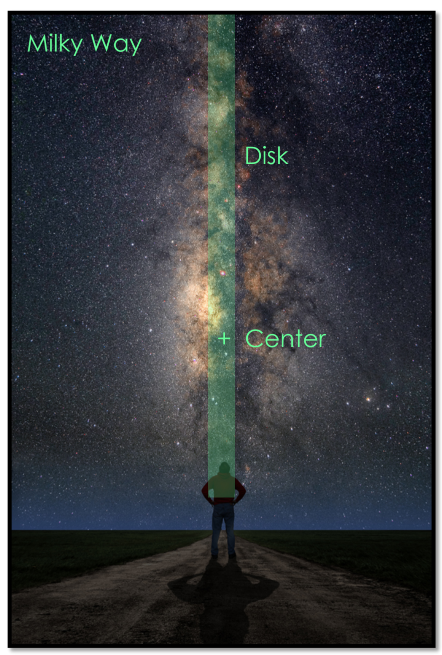
# How far to the next civilization?

Population I stars would seem to host most of our galaxy's planets, since they contain a higher abundance of the heavy elements.

Pop I is confined to the **disk** of the Milky Way galaxy: typically, these stars lie within $H = 330$ light years (ly) of the plane that bisects the Galaxy.



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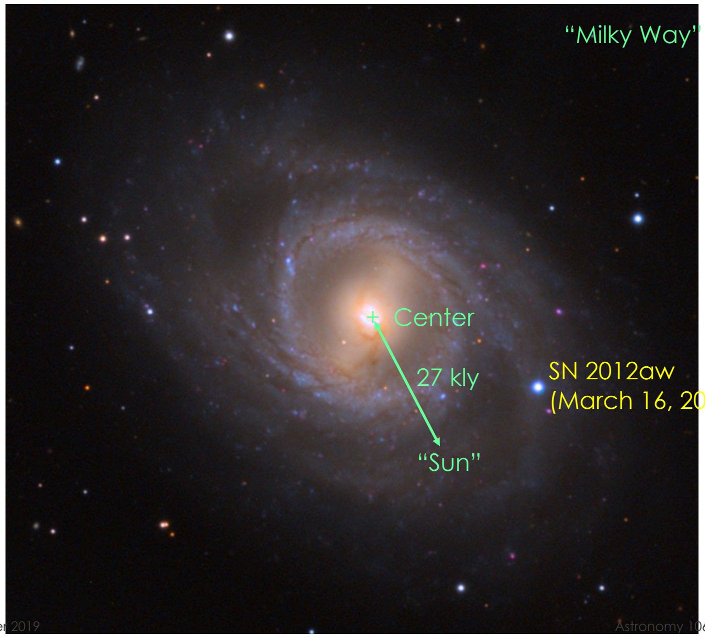


Adam Block, Mt. Lemmon SkyCenter, U. Arizona

## How far to the next civilization?

The Sun lies $R = 27{,}000$ ly = **27 kly** from the Galactic center.

Most stars are closer to the center than the Sun.

We cannot actually view our galaxy from the outside, so we will use the nearby galaxy M95 as our working example, as it is quite similar to the Milky Way.



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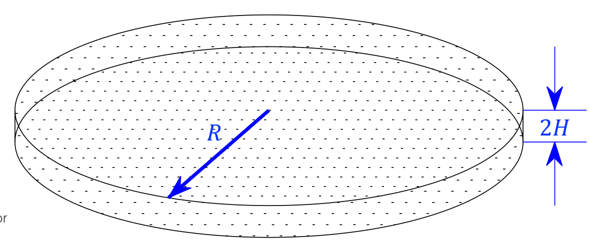
# How far to the next civilization?

Suppose that you calculate a value for $N$ and find that $N \gg 1$. Approximately how far apart are the civilization-hosting stars?

To first approximation, let us assume that these $N$ stars are uniformly distributed throughout the disk. (They are actually concentrated toward the center and the mid-plane.) Let us define $n$ to be the number of stars per unit volume:

$$n = \frac{N}{V} = \frac{N}{\pi R^2 \times 2H}$$

The volume of space **per star** is $1/n$.



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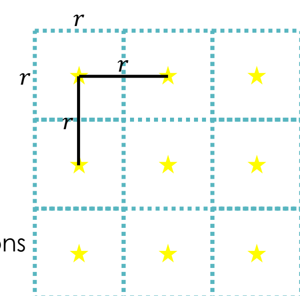
# How far to the next civilization?

If we imagine that each civilization-hosting star occupies an identical cubical volume with dimensions $r \times r \times r$ (where $r$ is small compared to $2H$), then the centers of the cubes – and the planetary systems that they contain – are separated by that same distance $r$:

$$r^3 = \frac{1}{n} = \frac{2\pi R^2 H}{N} \implies \boxed{r = \left(\frac{2\pi R^2 H}{N}\right)^{\frac{1}{3}}}$$




Example: Take $R = 27$ kly, $H = 330$ ly, and $N = 3\times10^6$, as above:

$$r = 80 \text{ ly}$$

$r$ is indeed small compared to $2H$.

This tells us that an optimist would say that communicable civilizations are typically close to 80 ly apart.





# How far to the next civilization?

If, on the other hand, there are only a few civilizations, then their typical separation may be much larger than $2H$. We would then have to imagine that each star is confined to a box with dimensions $r \times r \times 2H$, for which:

$$2Hr^2 = \frac{1}{n} = \frac{2\pi R^2 H}{N} \implies \boxed{r = R\sqrt{\frac{\pi}{N}}}$$

Example: Now use $N = 2$, with the other values the same as before:

$$r = 34 \text{ kly}$$

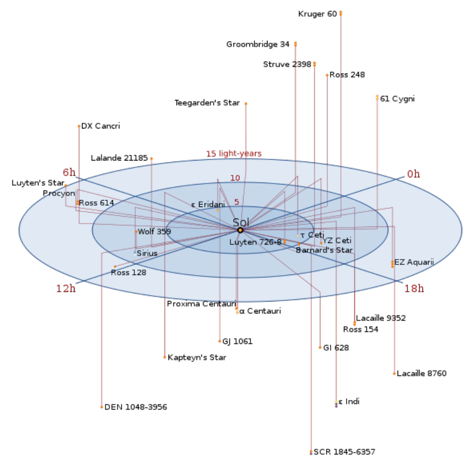
$r$ is indeed large compared to $2H$ – a rather long way apart.

# Finding & visiting other civilizations

The main issues:

- Most stars are far away. The closest system is the triple star $\alpha$ Centauri: $r = 4$ ly.
- There are a lot of them, though: there are 20,000 stars within 50 ly of us.
- Neither information nor astronauts can travel any faster than the speed of light:

$$c = 2.99792458 \times 10^{10}\ \mathrm{cm/s}$$
$$= 1\ \mathrm{ly/yr}$$




The 32 nearest stars



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# Finding & visiting other civilizations

At present, we cannot get astronauts to speeds anywhere near $c$; the fastest current spacecraft (NASA *New Horizons* / Pluto-Kuiper Express) cruises at $2.3{\times}10^6$ cm/s $\approx 8{\times}10^{-5}c$.

So **the first thing to try is communication** rather than visits. As we will see, this is also considerably less expensive.

And until we find a civilization with which to communicate, we should both talk and listen…

…and account for the extreme delay between responses, on the scale of our usual attention spans. Even for relatively nearby civilizations, "conversations" would take many human lifetimes. (It would take 100 years just to say "Hi!" and receive a reply for a civilization only 50 ly away.)



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# Communication with other civilizations

### How would we communicate?

One thing seems clear: communication will involve **light**.

The precise wavelength of light at which the communication would be reasonable, though, is *not* naturally determined. The electromagnetic spectrum covers many orders of magnitude of wavelength, and a *signal* would cover a very small range of wavelengths around some central wavelength.



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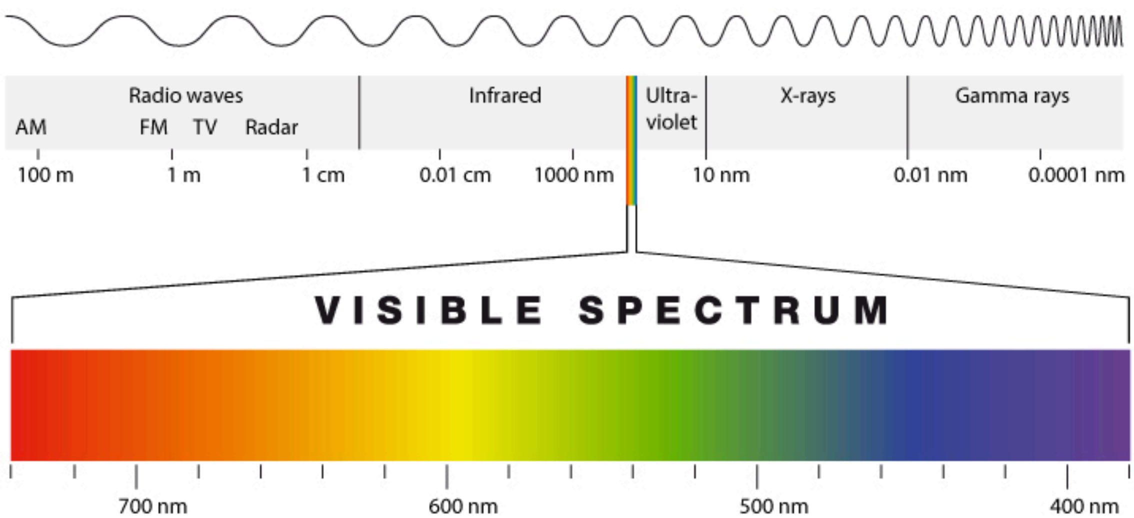
# The electromagnetic spectrum (light)

Visible light is only a tiny part of the spectrum of light.



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# Communication with other civilizations

Issues which decide communication wavelength:

- Need to generate lots of broadcast power
- Need to broadcast that power in a narrow beam aimed at the specific stars. (It is wasteful to broadcast in all directions.)
- Need to detect and identify very small signals against natural backgrounds and noise.
- Need to avoid confusion with natural sources of light.
- Presuming at least some of the communications need to reach the surface of the habitable planets, the wavelength should be one at which the atmospheres are transparent.
- Our broadcast would probably attract more attention if it were near a wavelength of astrophysical significance, so that the astronomers of other civilizations have a higher probability of noticing it. Other civilizations might be thinking along these same lines as well.





# Detection – the ideal frequency

We want to use a signal in the wavelength range that is most likely to be detected by other intelligent life-forms.

- On Earth, all life with sight has developed a sensitivity to **visible light**. (This is also the range in which our Sun is brightest; this is not a coincidence!)
- Our atmosphere is transparent to **radio frequencies**.

Stars shine very bright in the infrared and visible wavelengths.

To avoid our signal being drowned out by natural sources of electromagnetic radiation, the best option here is **radio** (assuming that other planets' atmospheres are also transparent in the radio).

# Getting noticed

The 1-30 cm (radio) band is already largely free of strong local interference, since stars are not bright at these wavelengths, but it is still a lot of wavelength space to cover.

Special locations that astronomers would notice the signal:

- **The water hole**. Two of the brightest spectral lines from interstellar gas, the 21 cm line of atomic hydrogen (H) and the 18 cm lines of hydroxyl (OH), would undoubtedly attract the attention of extraterrestrial astronomers. Frank Drake and Carl Sagan used to draw attention to the gap between them as a result. (H + OH = water)
- **The real water hole**. Bright, natural maser emission from water itself at 1.3 cm, would certainly attract attention.

But there are zillions of important spectral lines in the band.



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# The broadcast itself

We cannot just send a steady wave at a given wavelength – we must **modulate** the wave so that a stream of information at longer wavelengths / lower frequencies is obtained by removing the steady **carrier**. This is how all optical and radio transmission works.

- In radio, the carrier is modulated at audio – voice – frequencies.
- AM and FM refer to the methods of modulation common in radio.



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# What do we look for?

Artificial signals pulse with a constant frequency, while natural signals normally vary in their modulations.

- Pulsars (fast-spinning neutron stars) were originally named "Little Green Men" because no natural emission mechanism could be imagined at the time to produce such a regular pulse.
- Such natural occurrences of regular pulsation are extremely rare.

The most difficult signal to filter out is our own.

- If an alien's signal had a period matching one of our units of time (second, minute, etc.), then we would probably miss it because we would assume it had a terrestrial origin.





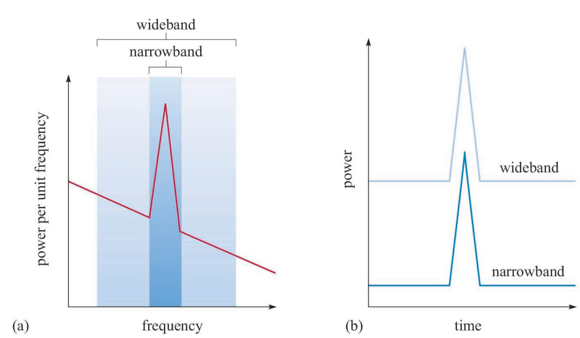
# The signal's bandwidth

**Wideband** – Spread the total energy in the signal out over a wide range of frequencies

- Advantage: Receiver tuning is less crucial
- Disadvantage: Signal is not as strong relative to the background

**Narrowband** – Concentrate the total energy of the signal in a narrow range of frequencies

- Advantage: Signal is very strong
- Disadvantage: Easy to miss if receiver is not looking at the exact signal frequency



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We also need to broadcast a **primer**: something that could help de-cypher our modulations.

- This is best if it is related to natural or mathematical concepts, like prime numbers or the periodic table.



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| Symbol | Value | Meaning |
|---|---|---|
| $\pi$ | 3.14159… | Ratio of a circle's circumference to its diameter |
| $e$ | 2.71828… | Euler's number, used in exponential function and natural logarithms |
| 1,2,3,5,7,11,13,… | | Prime numbers |
| 1,2,3,8,16,32,64,… | | Powers of 2 |
| 0,1,1,2,3,5,8,13,… | | Fibonacci sequence ($F_n = F_{n-1} + F_{n-2}$) |
| $c$ | $3\times10^{8}$ m/s | Speed of electromagnetic radiation in a vacuum |
| $m_e$ | $9\times10^{-31}$ kg | Mass of the electron |
| $m_p$ | $1\times10^{-27}$ kg | Mass of the proton |
| 76/24 = 3.17 | | Mass ratio of hydrogen to helium in early Universe |
| $M_\odot$ | $2\times10^{30}$ kg | Mass of the Sun |

## With what do we communicate?

Despite not knowing anything about the other intelligent life forms, if we can communicate via radio waves, then we must share some **common knowledge**.

Any quantity whose value depends on the units is problematic.



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# How do we send these numbers?

Whatever information we want to communicate to another civilization to break through the language barrier must be somehow **encoded** in the radio signal pulses that we send.

- The most natural number system we have on Earth is the **binary** system: 1 or 0 (on or off, yes or no, nothing or something).

The only issue that remains is to hope that the other civilization reads the sequence of 1s and 0s from left to right (the order in which we encode the signal). If they read from right to left, hopefully they will realize that the translation does not make sense and try it the other way.

So, we need to look for general signs of structure in messages from other systems instead of searching for particular numbers.



# Where to look?

This depends on whether we want to detect intentional or unintentional transmissions.

- **Unintentional transmissions** – Random EM radiation broadcast from a distant civilization
  - Very weak, since they would be spread out in many directions (unfocused)
  - Limited to the nearest star systems (small number of targets to check!)
  - Covers a broad range of frequencies / wavelengths
- **Intentional transmissions** – EM radiation sent as an advertisement
  - Strong signal, since the beam would be pointed directly at us
  - Can see much further away (long list of targets)
  - Very narrow frequency / wavelength coverage

Searching for intentional transmissions is much more time-consuming, but the potential for a conversation is much higher.

# From how far away would we notice ourselves?

The Arecibo 305-m radio/radar telescope can broadcast about 2 MW at 2.4 GHz, which is equivalent to broadcasting about 20 TW (trillions of watts) in all directions (to those at which the signal is pointed).

Averaging this message for a period of 8 hours, we would adequately detect our own message from a distance of about **50 lyr**.



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# The search for extraterrestrial life

SETI is thus proceeding through targeted broadcasts and searches (mostly the latter) at radio frequencies. This is the main effort of the SETI Institute, the professional home of Frank Drake and Jill Tarter.

Most notable: observations with the Arecibo 305-m telescope in the direction of 800 sunlike stars with $r < 200$ lyr, 1998-2004.

Search through the data for signals by a vast array of PCs in the hands of amateurs: SETI@Home

No detections yet. We would have definitely heard about it if there had been.



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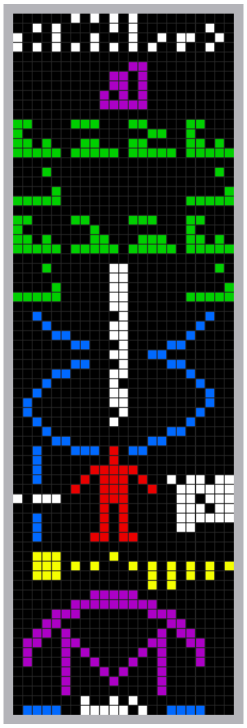

Numbers 1-10

Atomic numbers of H, C, N, O, P

Formulae for sugars and bases in DNA nucleotides

Number of nucleotides in DNA

Double helix of DNA

Human being
Height of human being
Human population of Earth

Solar system

Arecibo telescope transmitting message
Diameter of the telescope

## Our first message

Sent in binary from Arecibo in 1974 by Drake.

There are 1679 bits in the message. 1679 is divisible by only two numbers (besides itself and 1): 23 & 73. These indicate the dimensions of the image.



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# SETI

We are currently decently equipped to detect extraterrestrial signals at radio wavelengths, though the effort is traditionally underfunded and little appreciated.

Although the culture of radio astronomy is changing, most of the depiction of SETI in the movie *Contact* still applies: PhD thesis advisors do not like to see their students going into SETI.

The ongoing search for extrasolar planets – especially projects like NASA's *Kepler*, *K2*, and TESS, which search for habitable planets – will provide more and better targets to which to broadcast, and toward which to search for signals.

And sensitivity, bandwidth, and analysis power will continue to improve.



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# Space flight

By contrast with communication, we are technologically far from being able to explore for extrasolar system civilizations both in person and robotically. The means that we can contemplate for travel are:

- Spacecraft which use thrust to accelerate up to near-light speed ($c$) and to decelerate at the end of the trip. We will call this conventional space flight.
- Thrust involves imparting the spacecraft with the momentum of molecules or particles in a propellant or external beam.
- Spacecraft which employ gravitational acceleration and specially-made shortcuts through spacetime called warp drive or wormholes.

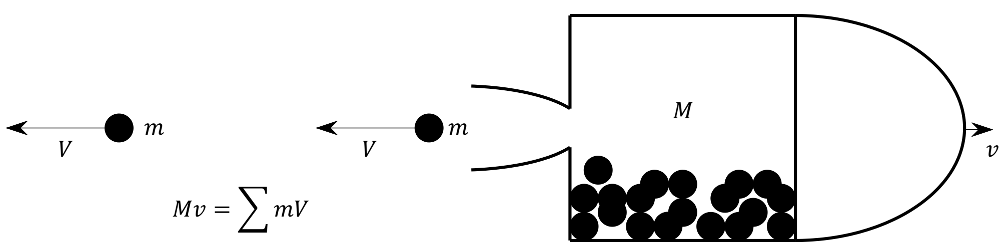
*Launch of the STS-92 mission to the ISS (Discovery, 11 October 2000)*





# Space flight

Thrust can be provided by ejection of onboard propellant, usually atoms (mass $m$) produced by burning molecular fuel and being expelled through a nozzle at some very high speed $V$.

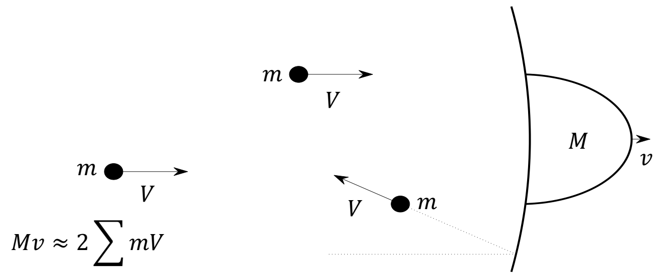



$$Mv = \sum mV$$

The mass $M$ of the spacecraft decreases with time if onboard propellant is used.

# Space flight

In principle (i.e. has not yet been done), thrust can also be supplied externally in the form of a beam of light or high-speed ($V$) energetic particles (mass $m$), which bounce off the back side of the spacecraft.




Not obliged to pack fuel in this case, but can be very inefficient unless the beam can be kept from diverging (particles miss the spacecraft).



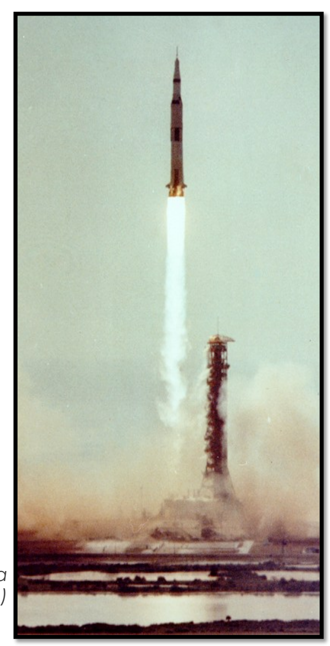


# Space flight

Along with instruments, communication equipment, fuel, and gifts for the leaders of the civilizations that we expect to encounter, the spacecraft has to carry either

- Nothing, if it is unmanned
- Many years of food and life-support systems for human passengers, if it is manned

These life support systems must include artificial gravity and immense radiation shielding in order to keep the passengers alive.



*Launch of Apollo 11 in 1969 on a mighty Saturn V booster (NASA)*

# Space flight

When designing an interstellar spacecraft, two restrictions immediately apply:

- Solar panels provide negligent power when the spacecraft is far from a star. Therefore, a long-lived power source needs to be packed.
  - Like NASA's SAFE-400 nuclear reactor: 100 kWe, 512 kg.
  - For similar reasons, the "beam" form of thrust is currently considered extremely impractical for long trips.
- The interstellar medium is very poor in material of any sort, particularly of anything that would make a good propellant. A sufficient supply of your own propellant must also be packed.
  - Some propellant schemes – the ion-drive sort – would demand additional onboard power generation.



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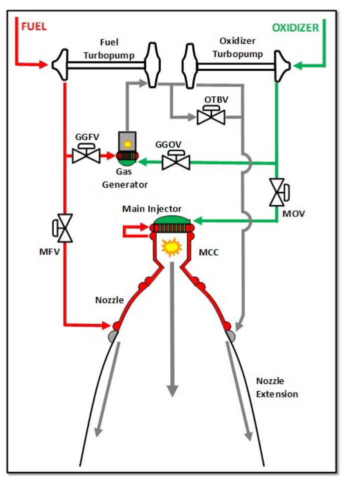
# Conventional space flight

There are two primary propulsion systems currently in use:

1. **Thermal impulsive thrust generation** (a.k.a. **rocket drive**), in which a fuel is ignited and the released heat accelerates the propellant.
   - So far, only chemical fuels have been used (liquid hydrogen / liquid oxygen, hydrazine ($N_2H_4$) / liquid oxygen, ammonium perchlorate ($NH_4ClO_4$) / aluminum / liquid oxygen)
   - Pros of rocket drive:
     - Can generate a great deal of thrust and thereby launch substantial payloads from Earth
     - Power source and propellant are the same thing; no other power source needed
   - Cons of rocket drive:
     - Rather low efficiency
     - Generation of large **specific impulse** (high speed) requires prohibitively large amounts of fuel




Schematic diagram of the J-2X rocket motor (NASA)



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# Conventional space flight

2. **Electrostatic or electromagnetic thrust generation** (a.k.a. **ion drive**), in which the propellant is accelerated by electric and/or magnetic fields.
   - Propellant = heavy, easily ionized gas (xenon: $Z = 54$, $A = 132$)
   - Acceleration voltage (1280 V) maintained by electric power source, in most current cases solar powered
   - NASA NSTAR modules: 2.3 kW gives 0.02 lb thrust
   - Pros and cons of ion drives are the opposite those of rocket drives
     - Efficient relative to other propulsion mechanisms
     - Cannot generate much thrust, but can generate very large specific impulse, simply because they can run almost indefinitely on a reasonable supply of propellant

Hybrid approach: *Dawn* was launched with a rocket but maneuvers from orbit to orbit with an ion drive.

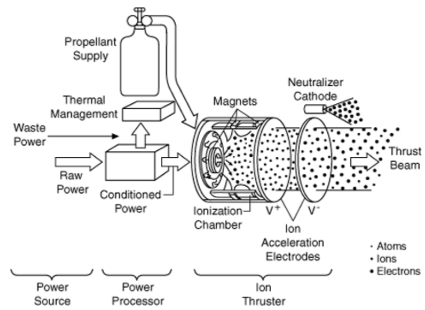



*Diagram of Dawn's ion drive (JPL/NASA)*





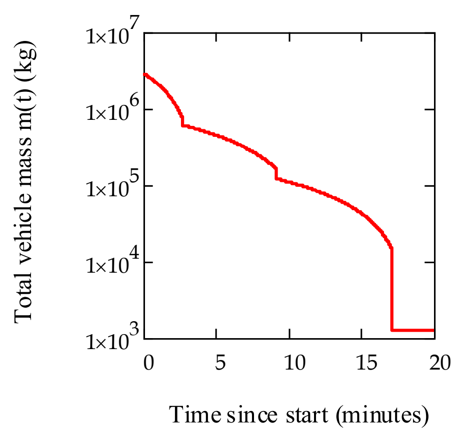
# Ion drives v. rockets

Start the two vehicles with the same mass

- 43 NSTAR ion drives and a SAFE-400 reactor
- Saturn V rocket

Accelerate as long as they are producing thrust

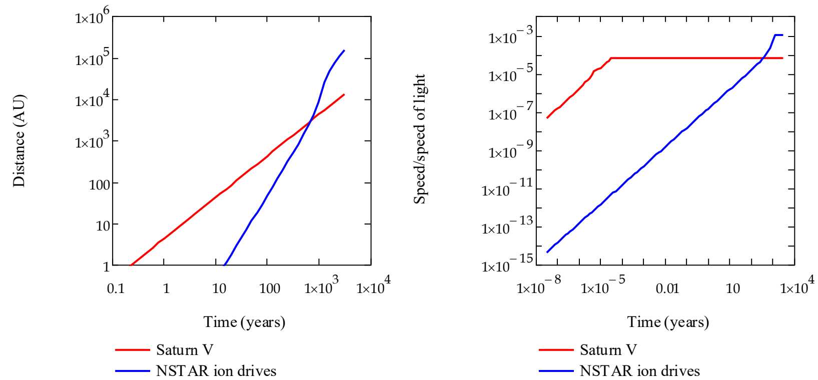
- Their masses decrease as they go and use up fuel, so the acceleration changes with time




*Mass of the rocket-powered vehicle, as the Saturn V expends and ejects its three stages*

# Ion drives v. rockets

Result: the Saturn V can get anywhere within the Solar System faster than the *current* NSTAR ion drives, but eventually the ion drive goes further and flies faster.

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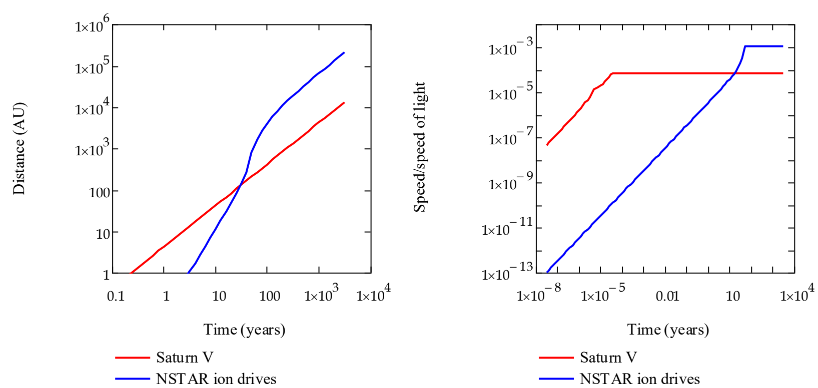
# Ion drives v. rockets

Ion drives have much more room for improvements than rockets. Here are the results for NSTAR drives that can run on 100 W of electrical power:

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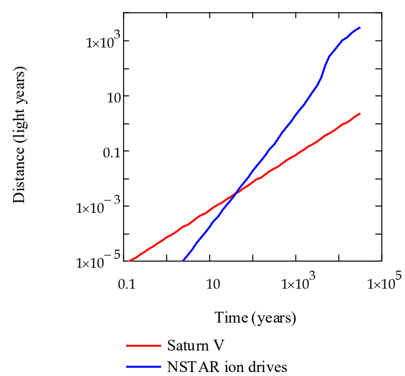
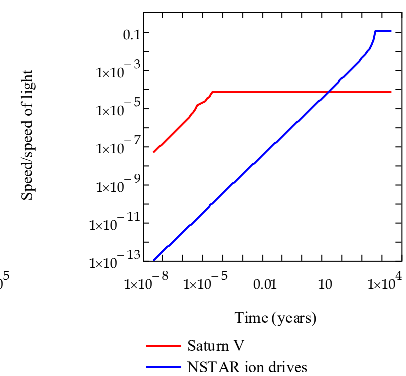
# Ion drives v. rockets

In addition, if the ion drive's electric field could be made 10,000 times larger, the ion drive's top speed begins to look respectable (10% the speed of light) and gets to the nearest stars in about 1500 years.






# Conventional space flight

The fastest we have been able to travel so far is $8\times10^{-5}c$ via a combination of impulsive thrust and gravity boost on a small unmanned spacecraft.

This is the NASA *New Horizons* mission to Pluto, Charon, and a random Kuiper belt object, 2014 MU69. This spacecraft weighs about 1,000 lb in total.

- Thrusters are insufficiently powerful to insert the spacecraft into orbit around Pluto; it merely conducted a flyby.

Of course, much more energy (and thrust) per gram of fuel would be liberated by using the fuel's **nuclear energy** instead of its chemical energy.

Several proposals for nuclear-blast-propelled spacecraft have been fleshed out. We will discuss one (Project Orion).

# Nuclear-propelled space flight

Example: Liberate energy in the form of either heat or light from 1000 kg (1 metric ton) of anthracite coal.

- Chemical energy: burn it (turns it all into $CO_2$ and $H_2O$):
$$\Delta E = 4.3 \times 10^{17} \text{ erg} = 10 \text{ t}$$
- Nuclear energy: maximum-efficiency fusion in the core of a star (turns it all into iron):
$$\Delta E = 4.1 \times 10^{24} \text{ erg} = 100 \text{ Mt}$$

This point has not been lost on scientists trying to invent better means of propulsion.

- The ultimate means of impulsive thrust: controlled explosion of nuclear weapons, specifically high-yield H bombs.



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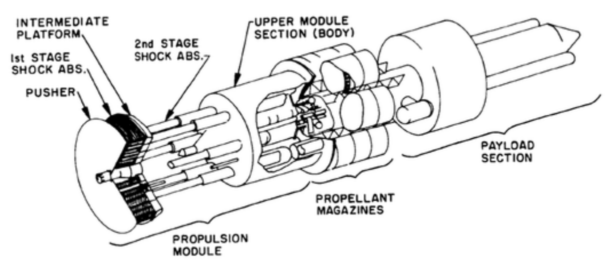
# Nuclear-propelled space flight: Project Orion

Physicist and Manhattan Project veteran Stan Ulam was the first to promote nuclear explosions as a means of spacecraft propulsion (1947). He recruited Ted Taylor to run the project, who in turn recruited Freeman Dyson to lead a study of how it could be done. This was called Project Orion (1958).

The idea: Detonate a nuclear device (with a bunch of refuse, to provide more momentum) about 60 m behind the spacecraft. Catch a large portion of the blast with a shock-absorbed "sail" to accelerate the spacecraft. Repeat.



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# Project Orion

**Upsides**

- Relatively inexpensive, since bombs are not very pricey
- Achieves both great thrust *and* large specific impulse. Ordinary rockets can do the former but not the latter, and ion drives can do the latter but not the former.

**Downsides**

- No one will let you use that many nuclear weapons to launch from the ground
- Or even space, owing to the Limited Test-ban Treaty of 1963
- Current designs still only reach 1000 km/s ($0.003c$)

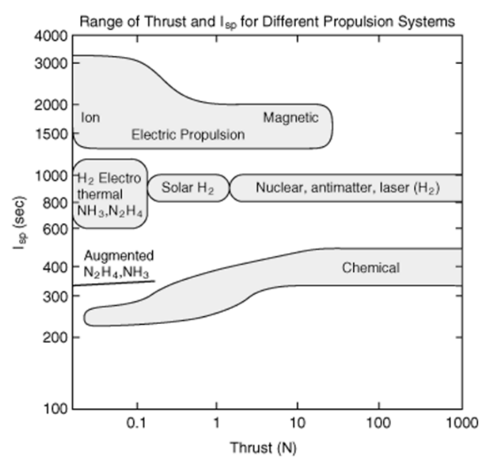




# Conventional space flight

If we had to do it tomorrow, we would use

- Rocket-powered launch vehicles to assemble spacecraft in orbit
- Nuclear-blast propulsion to escape solar system
- Ion drive, powered by an onboard nuclear reactor, to accelerate up to a fair fraction of the speed of light




*Thrust and specific impulse for various propulsion schemes (JPL/NASA).*

# Unconventional space flight

Even if all of this works, it takes many years to even get to the nearest stars. What of the bold ideas proposed by science-fiction writers for faster-than-light travel, like warp drive and wormholes? Are they plausible?

**No.** But, if you insist…

In principle they work and provide a means to travel the Galaxy on the time scale of human lives.

They hinge upon warping space-time to provide shortcuts through space-time, with acceleration and deceleration provided by gravity: no propulsion required.

Unfortunately, they all require **exotic matter** – matter with negative energy density – and we have no idea how to make this unless we have a black hole in hand.



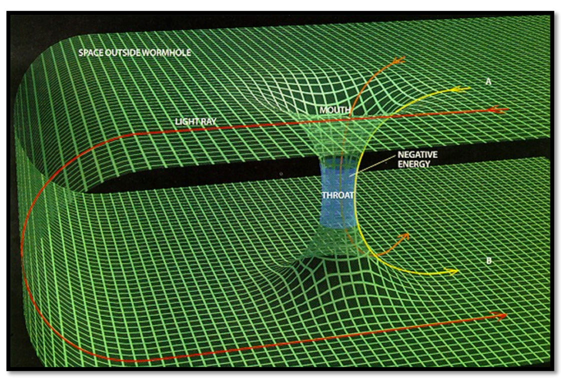


# Wormholes

Wormholes are the solutions to the Einstein field equations of general relativity that (potentially) involve shortcuts through spacetime.

- If a wormhole has mouths in two locations, traveling between these locations through the wormhole can be **orders of magnitudes faster** than traveling "beside" the wormhole at the speed of light.
- One way to think of wormholes: a special overlap between the interiors of widely-spaced black holes.
- We cannot manipulate black holes – for which masses start at a few solar masses – and thus have no empirical evidence that this is possible.

For more information, consult the relevant parts of AST 102, available next semester. The next few pages are just for those curious about wormholes, i.e. **not on the exam**.



# Traversable, constructible wormholes

Advising Carl Sagan in the writing of *Contact* got Kip Thorne and his graduate student Mike Morris interested in how an advanced civilization might build wormholes for transportation. They wrote a set of instructions based on the following principles:

- For simplicity, the wormhole's geometry is taken to be spherical and static.
- It must represent a solution to the Einstein field equations, one which is stable against small perturbations.
- It must have a throat that connects two regions of flat spacetime so that it can be used to connect places in our Universe. Thus, its equatorial-plane embedding diagram looks like the classic "hyperspace tunnel."
- There should be no horizon.
- The tidal forces and accelerations experienced by a traveler must be bearably small; they took $< 1$ Earth $g$.



# Traversable, constructible wormholes

- A traveler must be able to cross the wormhole in a finite time in both the traveler's frame and in a frame of reference at rest with respect to the wormhole's mouths; they took $< 1$ year.
- The matter and fields that generate the wormhole's spacetime curvature must be physically reasonable.
- It should be possible to assemble the wormhole: it should require energy must less than the mass of the Universe times $c^2$, and take time much less than the age of the Universe.

The most difficult constraints turn out to be the material that generates the curvature:

- It must be able to withstand enormous tension: the pressure represented by this tension turns out to be approximately

$$P = \begin{pmatrix}\text{pressure at the center of the}\\ \text{most massive neutron stars}\end{pmatrix} \times \left(\frac{20\text{ km}}{\text{circumference of throat}}\right)^2$$

- This tension turns out to exceed the material's mass density, and there is no such material known.

# Traversable, constructible wormholes

- In fact, if it were to have this property and be part of the structure, from the viewpoint of a distant observer, it would appear to have a negative energy density: it is exotic matter.
- There does not seem to be any way to avoid exotic matter in the construction of a traversable wormhole. All they could do was consider ways to minimize the amount.

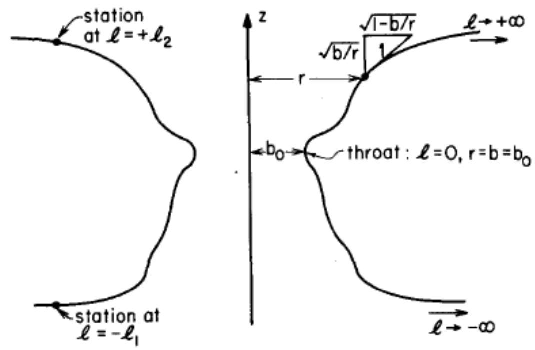



Fig. 2. Embedding diagram for a general wormhole, as seen in profile. (The diagram must be rotated about the vertical z axis to make it complete; cf. Fig. 1.).

Morris & Thorne (1988)





# Traversable, constructible wormholes

Properties of the minimum-exotic-matter solution:

- Exotic matter provided as a spherical shell slightly larger than the throat of the wormhole. All the other matter is non-exotic.
- Characteristic size of the mouths is rather large (600 times the size of the Solar System) in order to keep the accelerations modest.
- Acceleration no greater than one Earth *g*, small tidal forces, so traversing it would be perfectly comfortable.
- It would take 200 days to traverse the wormhole.
- How long it is in physical space determines the total mass.

So all we need is the exotic matter! And lots of it…

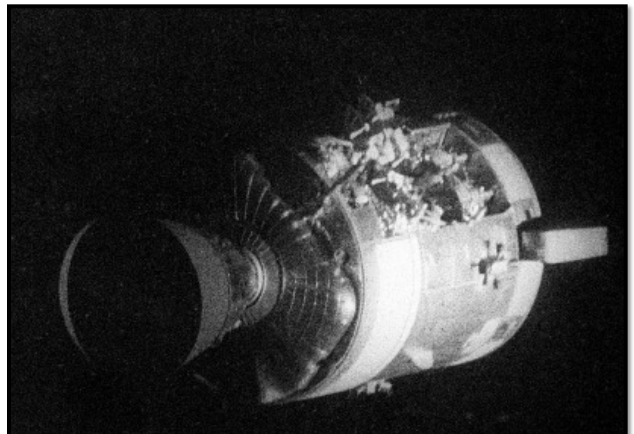
# Space is a hostile environment

574 humans, from 38 countries, have been in outer space:

- 12 suborbital, 562 in Earth orbit
- 24 beyond low Earth orbit
- 12 walked on the Moon
- 150.3+ person-years in space
- 191 person-days of spacewalks

This has led to at least 22 deaths, and a large and incompletely-recorded number of injuries and illnesses.

- 98% of astro/cosmonauts have reported "medical events."



*Apollo 13's damaged service module, after jettisoning (NASA JSC)*





# Space is a hostile environment

The relevant concerns of space medicine:

- **Environmental** →
- Physiological
- Psychological
- Occupational
- Social/cultural
- Communicational

Microgravity
Oxygen requirements
Hypothermia/hyperthermia
Water requirements
Nutritional requirements
Waste disposal – trash management
**Radiation**

*Ureles (2010)*

# Space is a hostile environment

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Acceleration, vibratory, acoustic
Weight loss
Fluid shifts
Vestibular
Loss of muscle mass
Osteopenia-osteoporosis
Slow wound healing
Hematologic changes
Immunological
Microbiological
Endocrine

*Ureles (2010)*



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Stress
Anxiety
Fear
Lack of privacy
Depression
**Sleep disorders** →
Maladaptation
Psychosexual

Sunrise/sunset *q* 90 minutes (Shuttle)
Excitement
Position
Mechanical & human noise
Circadian rhythms – light/dark – cortisol
Insomnia – cognitive impairment
Sedatives v. melatonin

*Ureles (2010)*

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Trauma: in-cabin crowding, floatation

Work overload: fatique

**Space walking: art, balance, dangers**

Competition: numbers v. opportunities

Suit puncture: loss of consciousness in 9-12 s, death within 2 min

*Ureles (2010)*