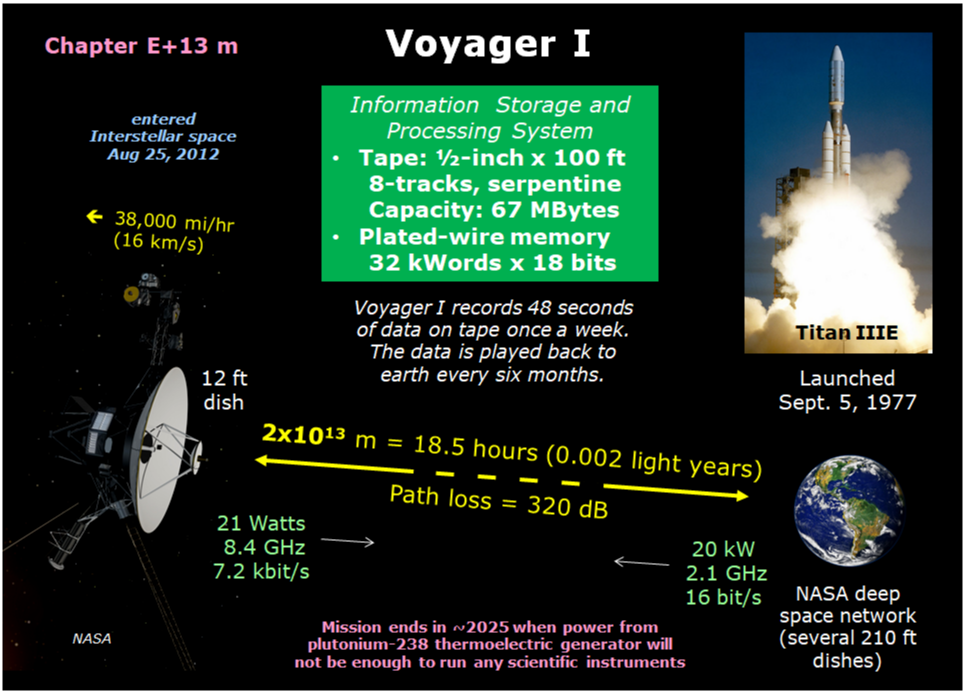
Chapter +13: The Loneliest Spacecraft



Our journey must surely start with the Voyager-1. We've dubbed this *the loneliest spacecraft*. At the time of writing in 2018, Voyager-1 is over 20 billion[1] kilometers (13 billion miles or 142 AU[2]) from home and destined to wander the galaxy indefinitely with no hope of ever returning. Not only is Voyager 1 *the* most distant man-made object, it is, in fact, well beyond all the known natural objects in the solar system including all the known Kuiper belt objects (this includes the dwarf planets: Pluto, Eris, Makemake, etc.). The next object we would come to beyond Voyager is Proxima Centauri, which is the nearest star. Voyager-1 actually has an identical twin, Voyager-2, which was launched a few days earlier. The two spacecraft tracked each other closely until reaching Saturn but were then

[1] This is the US or short-scale billion which is 1,000,000,000 or 10^9 in scientific notation
[2] AU is Astronomical Unit, a measure of distance equal to the mean distance from the Earth to the Sun. It is a handy yardstick for measuring distances in the solar system. Voyager-1 is 142 times further from the Sun than is the Earth (in 2018). This factor of 142 appears several times in this chapter as the basis for several simple calculations.

sent on different trajectories. Not only is Voyager-1 20 billion kilometers from Earth, it is now separated by even more than that distance from its identical twin. Voyager-1 truly qualifies as the *loneliest spacecraft*.

The Voyager-1 spacecraft is over 40 years old but it is still very much 'alive and kicking' (in 2018). Every six months a command is sent from Earth to wake up the Voyager tape recorder. The data that has been accumulated on the tape is then transmitted back towards Earth to be received by NASA's deep space network of antennas. Voyager-1 is so far away that even at the speed of light, the round-trip communication takes over a day-and-a-half to complete. While the total value of all the information Voyager has sent during those 40 years cannot be overstated, its environment today, far beyond the solar system in interstellar space, is about as bleak and sterile and unchanging as you can possibly imagine.

Deep Space

For a moment, let's imagine you are in your spacesuit sitting on Voyager's 12-foot dish antenna dangling your feet over the edge with your back towards (facing away from) the direction of flight. In every direction lie blackness and the myriad unblinking stars. The constellations are familiar and unchanged. The big dipper or Plough is overhead and the Southern Cross is below your feet. To your right is Cassiopeia (the W-shaped one), the vain queen of Greek mythology. Ahead, Orion the Hunter with his giant bow and starry belt is followed across the sky by his faithful Big Dog, Canis Major. The bright jewel of Sirius hangs around the dog's neck. But one thing is very different. Sirius at magnitude[3] -1.5, the brightest star in Earth's night sky, is outshone by a much much brighter star (magnitude -16) lying at Orion's feet. This star is bright enough to cast shadows like our Moon (magnitude -12.6). The Latin name of the star is "Sol", but we know it simply as "The Sun". As of 2018, Voyager is at a distance of 142 AU from the Sun - a distance that increases by 3.6 AU per year[4]. That

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[3] The brightness of stars and planets is measured on a logarithmic scale (like earthquake magnitudes). Stellar magnitude is given by $-2.5\log_{10}(F/F_{Vega})$ where F is the brightness of the object being described and F_{Vega} is the brightness of the reference star, Vega. Note that fainter stars have bigger numbers. Magnitude 6 stars are the faintest that can be seen with the naked eye. Brightness is defined as visible optical power received per unit area.

[4] https://voyager.jpl.nasa.gov/mission/status/

means Voyager-1 is 142 times further away from the Sun than is the Earth. (Remember that number, 142, as it appears in several calculations in this chapter) So the sunlight here is 142-squared or about 20,000 times weaker. The Sun is now just an extremely bright star and not nearly strong enough for solar panels to be useful. Voyager-1 runs on nuclear power.

Still looking in that same direction, where is home? Voyager-1 was put together in Pasadena, California, which certainly won't be visible. But surely planet Earth is visible? We need to look for a tiny blue speck within 1/142 radians[5] (about ½ a degree) of the Sun. But the reality is that it has been many years since it would last have been visible to the naked eye. In fact, at this distance, none of the planets are easily visible to the naked eye. Even the gas giants, Jupiter and Saturn, are fainter than magnitude 5 and are barely visible. We are actually far far beyond the orbits of the eight planets. Voyager has high resolution telescopes on board that revolutionized our knowledge with groundbreaking surveys of the Jovian and Saturnian systems (see later). But even these powerful telescopes no longer have anything useful to focus their attention on and have been switched off for many years.

Behind you, in the direction Voyager is heading, are the constellations of Hercules and Ophiuchus (the serpent bearer). You are traveling at about 16 km/s or 38,000 miles per hour although you cannot sense any motion. This sounds fast, but it is quite slow compared to the speed of other spacecraft and planets and stars. If you wait patiently - for about 40,000 years, Voyager 1 will pass in the vicinity of the star Gliese 445 which, by that time, will have wandered away from its own constellation Camelopardalis (the Giraffe) and into the path of Voyager.

A Bleak Environment

Still in your spacesuit, you might wonder about the other attributes of Voyager's environment. Obviously you are in a vacuum (don't take your

[5] A radian is the scientific measure of angle. There are 2π radians in the 360 degrees of a circle, so 1 radian = 57.3 degrees. It is a particularly convenient unit for dealing with small angles. For example, the diameter of the moon divided by the distance to the moon is equal to its angular width in the sky, 3474 km / 384,400 km = 0.0090 radians = 0.52 degrees. Similarly, Earth viewed from Voyager must lie within 1 AU / 142 AU = 0.007 radians = 0.4 degrees of the Sun.

helmet off! You'll lose consciousness in about ten seconds and be dead a few minutes later). And it is an extremely good vacuum at about one ten-billionth of Earth's atmospheric pressure with just a few atoms per cubic centimeter. The average distance that an atom travels before colliding with another atom (mean free path) is something like 10,000 km (i.e. the size of a small planet like Earth). This vacuum is better than almost anything that can be produced on earth. The typical CRT vacuum tube (Cathode Ray Tubes were common in televisions and computer monitors in the 20th century) would operate at about a billionth of atmospheric pressure and yet still will approach a billion atoms per cubic centimeter. The massive vacuum deposition machines used in processing heads and disks for Hard Disk Drives (HDD) are capable of similar or better vacuums but usually operate at perhaps 1/10,000 of an atmosphere with a plasma[6] created by electrical discharge in a deliberately introduced pure gas such as Argon.

Most of the atoms in interstellar space are in the form of molecular hydrogen but about a quarter of them are helium atoms. There will be only very faint traces of oxygen, nitrogen, water-vapor, carbon-dioxide and other gases familiar on Earth. Many of the atoms are ionized and form a plasma. Plasmas not only respond to electric and magnetic fields but, in responding, they also create further magnetic and electric fields. This leads to very complex behavior and structures. These structures can exist on a truly gigantic scale. We will talk in the next chapter about the huge magnetosphere that surrounds Jupiter and later in this chapter about the corresponding heliosphere that envelopes the entire solar system.

Interstellar space is also bathed in significant high-energy ionizing radiation in the form of gamma rays (electromagnetic radiation) and charged particles. Voyager is well instrumented to measure these over a very wide range of energies (see a description of Voyager instrumentation later in the chapter). The very highest energy particles are bare atomic nuclei stripped of electrons and traveling very close to the speed of light. Such particles are known as cosmic rays. Their origin is still very much a matter of debate but they are believed to be generated by supernovae in our galaxy and in the active cores of distant galaxies. The Apollo

[6] Plasmas are the most common form of matter in the universe. A plasma is a gaseous form of matter but with many of the atoms or molecules ionized (missing electrons and thus positively charged) and correspondingly with many unattached negatively-charged electrons present (cathode rays). Plasmas respond strongly to electric and magnetic fields.

astronauts on their trip to the moon reported seeing bright flashes of light every few minutes even when trying to sleep. Such flashes were later shown to correlate with cosmic rays passing through the astronauts' eyes and optic nerves. The highest energy cosmic ray ever reported[7] had an energy of 48 Joules[8], comparable to a 60 mph (26 m/s) baseball or cricket ball. Though the majority, thankfully, have a billion times less energy. Exposure to high energy radiation like this is definitely not good for health and is a major issue for human space travel such as a proposed mission to Mars that would last many months.

If it's not already obvious that this is not a very hospitable environment for humans, we should perhaps mention that the temperature at this distance from the Sun is decidedly chilly. The absolute temperature of an object in the solar system will vary very roughly inversely as the square-root of the distance from the Sun[9], so Voyager-1 should be at about 300 Kelvin[10] (approximate room temperature, 17°C) divided by the square-root of 142 or about 25 K or -248°C. (recall that Voyager is 142 times further away from the Sun than is the Earth.) However this frigid existence is certainly not the case for Voyager 1 which radiates many kilowatts of heat from its triplicate nuclear power sources and uses much of the electrical power they generate to keep its equipment cozily close to room temperature.

Space is also permeated with gravitational, electric, and magnetic fields though humans are not well equipped to sense the last two of these. The Sun's gravitational field[11] follows Newton's famous inverse-square law (as does the Sun's brightness) and is thus 142-squared or 20,000 times

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[7] https://en.wikipedia.org/wiki/Oh-My-God_particle

[8] A Joule is the kinetic energy in a 1 kilogram mass traveling at √2 meters per second. It is also the energy required to heat one gram of water by 0.239 degrees Celsius.

[9] The incident radiation absorbed from the Sun follows an inverse-square law, but the power radiated back out into cold space varies as the fourth-power of absolute temperature. $P \propto 1/r2 \propto T^4$ hence $T \propto 1/\sqrt{r}$ (where $\propto$ means proportional to).

[10] This is a unit of temperature named after the British Physicist, William Thompson who was elevated to become Lord Kevin for his work on thermodynamics. A Kelvin (abbreviated K without the °) is the same size as a degree Celsius (or 9/5 of a degree Fahrenheit), but the scale is offset so that absolute zero temperature is 0 K and the freezing point of water is 273.2 K (instead of -273.2°C and 0°C)

[11] Gravitational fields cause an object with a certain mass to experience a force or weight but the units reduce to the equivalent acceleration. The gravitational field at the Earth's surface is thus 9.8 m/s^2 or 32 $feet/s^2$, which is often referred to as 1 "g".

weaker than the Sun's gravitational field at the Earth's orbit. The Sun's gravitational field at the Earth's orbit is 6 mm per second per second, i.e. less than 0.1% of the Earth's own gravitational field with which we are so familiar. At the distance of Voyager-1, the Sun's gravitational field is only 0.3 micrometers per second per second[12] or a meagre thirty-millionth of a g. So an average person (50 Kg) would weigh about 1.5 milligrams or one twenty-thousandth of an ounce. Voyager-1's current mass of 733 Kg is like a small car but at this distance the Sun's gravitational field would give rise to an almost imperceptible force or weight about 24 milligrams or one thousandth of an ounce. However, these gravitational fields cannot, by definition, be sensed on board Voyager-1 since, as Einstein would have emphasized, it is an object in continual free-fall.

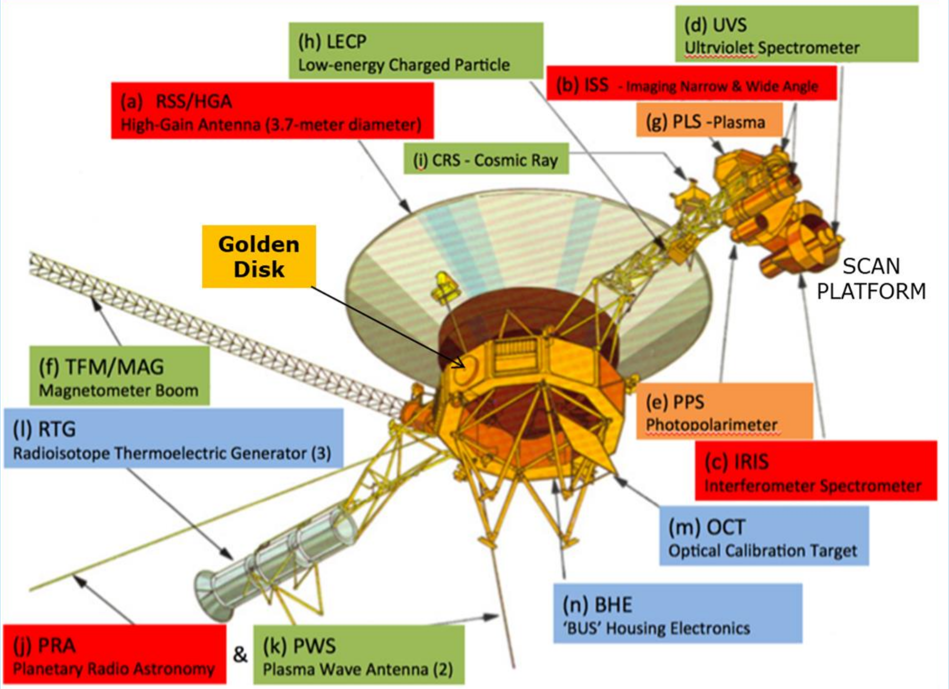
Year by year, Voyager-1 is gradually slowing as gravity pulls it back towards the sun. Even tiny accelerations can build into large velocity changes when taken over years or decades. That leads to the question: will Voyager-1 escape? Escape velocity varies inversely with the square root of distance (same way as temperature behaves). Actually escape *speed* is more correct since the direction doesn't matter. The escape speed from Earth is a respectable 11.2 km/s (7 miles/s). However, Solar escape speed[13], even at the distance of Earth's orbit, is much higher at 42 km/s (compare these to a rifle bullet at about 1 km/s). At Voyager-1's distance of 142 AU, Solar escape speed will be $42/\sqrt{142} = 3.5$ km/s. Voyager-1 is traveling at 17 km/s and greatly exceeds escape speed. So Voyager-1 is destined to wander the galaxy for eons guided on a chaotic path by gravitational fields from nearby stars as it journeys.

Although the gravitational field cannot be measured, there are many other properties of space that Voyager-1 is able to measure and report back to

[12] This gravitational field is given by either Newton's law, GM_{Sun}/r^2, or equivalently by the acceleration of Earth towards the Sun, $\omega^2 r$, as it moves in its nearly circular orbit. The first expression involves "Big G", the universal gravitational constant, and the mass of the Sun. The latter expression just involves the angular velocity of the Earth around the Sun (360 degrees per year = 0.2×10^{-6} radians/second) and the distance to the Sun (93 million miles = 150×10^9 m) and is much more accessible: $\omega^2 r = 6 \times 10^{-3}$ m/s^2

[13] Escape speed is given by the formula $\sqrt{(2GM_{Sun}/r)}$. This is derived by equating kinetic energy with potential energy falling from infinity. The velocity in a circular orbit is given by $\sqrt{(GM_{Sun}/r)}$ derived from the footnote above. i.e. kinetic energy for escape is twice the kinetic energy of orbit. Velocity of the Earth in its orbit is $\omega r = 30$ km/s. Solar escape speed is therefore a factor of $\sqrt{2}$ larger at 42 km/s.

earth. These include the magnetic and electromagnetic fields and the properties of a wide range of particles. The figure below, titled **Voyager**, illustrates the spacecraft structure and the main sensors and measurement instruments that it possesses. The differing requirements for these various sensors plus the radioactive power supply and communications antenna conspire to dictate the spacecraft's rather ungainly figure[14].



Voyager: Structure and key instruments. Major features include the large parabolic communications dish and the nuclear power supply. Several telescopes and directional instruments are clustered on a scan platform that can be oriented independently of the spacecraft. The highly sensitive magnetometer is on the end of a long boom to keep it away from magnetic devices such as the motors on the scan platform and in the tape recorder (picture courtesy NASA) http://voyager.jpl.nasa.gov/spacecraft/instruments.html, with additional labeling: red for disabled, green for active, orange for defective (as of 2016) https://upload.wikimedia.org/wikipedia/commons/d/d2/Voyager.jpg.

[14] R. Heacock, "The Voyager Spacecraft", James Watt International Gold Medal Lecture https://ntrs.nasa.gov/search.jsp?R=19810057725

The Voyager Spacecraft

Continue to imagine that you are sitting on the edge of the dish facing toward Earth. Below and behind you extends the structure of the spacecraft. There is a large ten-sided circular structure 1.8 m (6 feet) in diameter. This is the "bus" containing the electronics. One of the ten segments houses the radio transmitters and another houses the tape recorder. Anchored to the bus there are several very elongated structures or "booms" extending in several directions. (This is certainly not a streamlined spaceship as you might imagine from the movies). This was obviously not the configuration when Voyager was packed inside its launch vehicle. These booms were deployed once the spacecraft was released and cleverly extended themselves. For example, the delicate fiber-glass boom that holds the ultra-sensitive magnetometer far away from the spacecraft body is initially packed into a 2 foot canister (0.6 m) before it is released to extend itself to a full length of 43 feet (13 m). Similarly, the two orthogonal 10 meter antennas made of springy beryllium-copper automatically unwind themselves rather like the opposite of a self-retracting tape-measure.

Nuclear Power

On one of the shorter booms are stacked the three RTGs (Radioisotope Thermoelectric Generators)[15] that power the spacecraft (it is too far-away from the Sun for solar panels to be an option). Each RTG contains radioactive Plutonium-238 as the heat source and a thermoelectric convertor (a bi-metallic thermocouple). Note that this is not the fissionable Plutonium 239 isotope used in nuclear weapons. Plutonium-238 decays by the emission of alpha particles (Helium nuclei) which are absorbed by the Plutonium container and with the energy turning into heat. This heat is transmitted through the thermocouple array and finally radiates into space from the outer surface of the RTG. The thermocouples produce electricity directly by virtue of the difference in temperature between the very hot inner end of the thermocouple near the plutonium and the cooler end close to the outer surface. The overall process is highly inefficient with only about 5% of the heat turning into electricity and the other 95% or several

[15] https://en.wikipedia.org/wiki/Radioisotope_thermoelectric_generator

kilowatts being radiated into space. In return for the poor efficiency, RTGs provide a very long lifetime source of power with extreme reliability (no moving parts and no electronics). The RTGs generated about 470 watts of power at 30 volts at the time of launch. The power output of the RTGs declines over time (due to the 87.7-year half-life of the fuel and degradation of the thermocouples), but the craft's RTGs will continue to support some of its operations until around 2025. As of 2016-07-31, Voyager-1 still has 73.5% of the plutonium-238 that it had at launch but the power has dropped below 250 Watts because of degradation of the thermocouples.

The launch of spacecraft including RTGs with was controversial at the time and their use continues to be so. The RTGs contain plutonium which is highly radioactive and highly carcinogenic and there is a non-zero risk, during launch or during a flyby of Earth, that the radioactive material could be released into the atmosphere. This controversy came to a head with the Galileo spacecraft. The trajectory of Galileo depended on a gravity-assist from a *very* close pass by Earth. In the next chapter, we will hear more about Galileo and its 8-year visit the Jovian System and the controversial use of the Plutonium-fueled RTGs.

Telescopes and Spectrographs

On one of the shorter booms is a scan-platform that can be pointed independently of the spacecraft orientation. On the scan-platform are mounted several instruments including the two telescopes or cameras that were put to such good use during the Jupiter flyby and the Saturn flyby. The larger, high-resolution telescope has a 7-inch lens (176 mm) allowing an angular resolution at optical wavelengths (around 500 nm) of around 3 microradians[16]. This means 3 kilometers at a distance of one million kilometers. The Titan flyby at was at a distance of 6,400 km and, but for the thick atmospheric haze, would have allowed features around 20 meters in size to be distinguished. Much more than the other instruments, the high resolution telescope requires the camera platform to be pointed very accurately and the spacecraft attitude (orientation) to be correctly

[16] Angular resolution of a system is given approximately by the wavelength divided by the diameter of the objective lens or mirror. This is just as true for parabolic radio dishes as it is for lenses or mirrors in optical telescopes.

maintained during the relatively long exposure times necessitated by the low light levels. The high-resolution telescope has a focal length of 1.5 m so, in camera terminology; it is at f/8.5[17], which relates to the required exposure time or 'speed'.

Also on the same rotatable platform is a wide-angle camera with a 67 mm lens and a 200 mm focal-depth, f/3. For both cameras, there is a choice of eight possible filters that can be rotated into the optical path. In both cases a vidicon camera tube is used to scan the image formed by the telescope. The vidicon would be considered very old fashioned now. It is based on cathode ray tube (CRT) technology and was used in television studios worldwide until, in the 1980s, when it was displaced by semiconductor charge coupled device (CCD) technology and CMOS sensor technology now ubiquitous in all cameras and cell-phones.

The scan platform also includes an instrument that can examine polarization of scattered sunlight at optical and near ultra-violet wavelengths (PPS) and two further instruments that cover infra-red and ultra-violet wavelengths (IRIS and UVS). These last two instruments are spectrometers meaning that they are able to take the incoming infra-red or ultra-violet light and spread out the different frequency or wavelength[18] components into a spectrum (or 'rainbow' for visible wavelengths). Although the angular resolution of these instruments may be quite poor (i.e. fuzzy vision), the spectrum of what is being observed can be developed with very high resolution such that very narrow spectral absorption lines can be discriminated and associated with particular gases or chemical compounds. During the flyby of Jupiter and Saturn, all these instruments on the scan platform were invaluable in taking images and analyzing the composition and temperature profiles of the atmospheres of the planets and their moons. By now, as mentioned earlier, out at a distance of 142 AU, there is nothing to focus on. These optical scanners, other than UVS, have long been disabled to conserve power.

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[17] The f-number is the ratio of the focal length to the lens diameter. It describes the intensity of light at the image plane. The usual notation is to preface the number with f/.

[18] In empty space, the frequency, f, and the wavelength, λ, of electromagnetic radiation are simply related by $f\lambda = c$, where c = 300,000,000 m/s is the speed of light. This relationship is true for all electromagnetic radiation all the way from radio waves with wavelengths of many meters and frequencies in the MegaHertz to gamma rays with picometer wavelengths and frequencies beyond the ExaHertz (10^{18}) range.

Particles and Plasma Waves

As might be guessed from the earlier comments about radiation and cosmic rays, Voyager instrumentation includes three sensors specifically designed to detect particles in different energy ranges. The three instruments are referred to as PLS, LEPC and CRS (see figure 1).

The Plasma Spectrometer (PLS) uses two Faraday-cup detectors that catch charged particles and analyze the resulting current flow. One detector is pointed along the Earth-spacecraft line (close to the Earth-sun line) and is used to investigate the velocity, density and pressure of the plasma ions in the Solar wind. The other is at right angles to this line and focusses on the measurement of electrons in the low energy range from 5 eV to 1 KeV[19]. Unfortunately, this important instrument has failed on Voyager-1 though it continues to work on Voyager-2.

The Low Energy Charged Particle (LECP) instrument consists of two solid-state detector[20] subsystems: the low-energy magnetospheric[21] particle analyzer (LEMPA), and the low-energy particle telescope (LEPT). These are optimized for high and low particle-flux environments, respectively. The LECP looks for particles over the broadest range of energies of all of the particle sensors. These devices have very fine time resolution of about 50 ns and also offer some limited angular resolution in sensing the direction of arrival or particles. The LECP was especially valuable in the harsh radiation environments of the planetary encounters.

The Cosmic Ray System (CRS) consists of a High-Energy Telescope System (HETS), a Low-Energy Telescope System, and an electron telescope, all using arrays of solid-state detectors and covering several ranges from 10 KeV to more than 30 MeV per nucleon. The CRS looks for very energetic particles in plasma, which can often be found in the intense radiation fields surrounding some planets (like Jupiter), as well as particles with the highest-known energies-from other stars.

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[19] An electron-Volt or eV is the energy of an electron accelerated through a potential difference of 1 Volt. It is a tiny amount of energy but very appropriate for measuring particle energies. One electron-volt is 1.6×10^{-19} Joules or 4.4×10^{-26} kiloWatt-hours

[20] These devices are essentially reverse-biased semiconductor diodes. Spikes in the leakage current announce ‘hits’ by an ionizing particle or photon. Using multilayer structures, the depth of penetration and hence energy of the particle can be assessed.

[21] Magnetospheric (adjective) - pertaining to a magnetosphere

Voyager-1 also sports a pair of 30 foot (10 meter) whip antennas mounted perpendicular to each other and perpendicular to the direction of travel. These antennas are linked to two experiments, the PRA and the PWS: The Planetary Radio Astronomy Investigation (PRA) utilizes a sweep-frequency radio receiver covering two frequency bands, 20.4 to 1300 KHz[22] and 2.3 to 40.5 MHz (primarily for studying radio-emissions from Jupiter and Saturn). It uses the antennas as a pair of orthogonal monopoles.

The Plasma Wave Subsystem (PWS) uses the two antennas to form a vee-type balanced electric dipole and measures electric field components of local plasma waves over the frequency from 10 Hz to 56 kHz which includes the range that humans can hear (approximately 30 Hz to 30 KHz) even though these are electrical signals and obviously not sound waves[23]. An electron plasma oscillation, like a simple harmonic oscillation of a mass-spring system, gives a sharp peak in the received spectrum. The peak frequency, or the pitch of the oscillation, helps scientists determine the density of the plasma. This is one of the primary tools for studying the magnetospheres of Jupiter, Saturn, and the Sun (heliosphere) and now the interstellar environment.

However, one cannot sensibly study a magnetosphere without a decent magnetometer. Voyager's extremely sensitive magnetometer is mounted at the end of the long trellis boom to minimize the effects of fields from the rest of the spacecraft. Even so, the fields from the spacecraft are much larger than the interstellar fields now being measured. The Triaxial Fluxgate Magnetometer (TFM) or MAG was designed especially to investigate the magnetic fields of Jupiter and Saturn, the solar-wind interaction with the magnetospheres of these planets, and the interplanetary magnetic field out to the solar wind boundary with the interstellar magnetic field and beyond. Its primary job is to measure the changes in the Sun's magnetic field with distance and time, to determine if

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[22] The Hertz is the unit of frequency named after the German physicist Heinrich Hertz who first proved the existence of electromagnetic waves. One Hertz (abbreviated Hz) is one cycle per second.

[23] http://www-pw.physics.uiowa.edu/plasma-wave/voyager/v1pws_interstellar_update.html http://www-pw.physics.uiowa.edu/plasma-wave/voyager/ssr/PWSINST.HTM#Equation%203)

each of the outer planets has a magnetic field, and how the moons and rings of the outer planets interact with those magnetic fields. The investigation was carried out using two high-field and two low-field triaxial fluxgate magnetometers. Data accuracy of the interplanetary fields was plus or minus 0.1 nanoTesla (nT), and the range of measurements was from 0.01 nT to 2.E-3 T[24]. (Earth's field is about 50,000 nT). Despite the long boom, the fields from the spacecraft far exceed the fields to be measured. So every few months, measurements are made while the entire spacecraft is rotated 360 degrees around its roll axis in an effort to calibrate out the stray spacecraft fields.

Leaving the Heliosphere

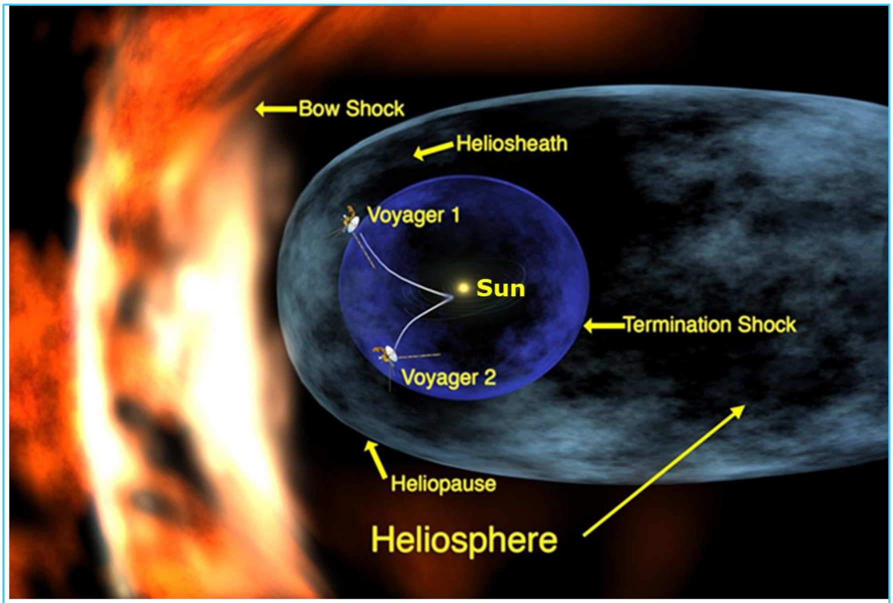
The magnetometer, the particle detectors, and the plasma wave subsystem, were central to the announcement on August 25th, 2012, that Voyager-1 had left the heliosphere and was now in interstellar space.

The heliosphere is a bubble-like region surrounding the sun and solar planets. It extends far beyond the orbit of Pluto. The solar wind, an outward flow of plasma from the sun, creates and maintains this bubble against the opposing flow of the interstellar medium that permeates the Milky Way Galaxy. The heliosphere travels along with the solar system as the sun orbits the galactic center with an average speed of 230 km/s or 514,000 mph. However, the artistic rendering as shown below (**Voyager's travels**) has been changing over time. The data from Voyager 1 keeps challenging scientists to reconsider the actual shape of heliosphere, the location of its boundary, the heliopause, and how exactly the solar wind interacts with the interstellar medium at that boundary. The same questions will arise for the sister spacecraft, Voyager-2, which does not yet appear to have entered interstellar space (as of 2018).

Going from the heliosphere to interstellar space, scientists expected to see a shift in the direction of the magnetic field at the boundary between interstellar space and the heliosphere. They also expected to see a sharp

[24] T stands for Tesla, the unit of magnetic flux density. By definition a flux-density changing at one Tesla per second threading a conducting loop will induce exactly one volt in the loop. In a vacuum, either magnetic flux-density or field can be quoted since they are directly proportional and related by the universal constant, μ_0, the permeability of free space. See also the tutorial box "Connecting magnetism and electricity".

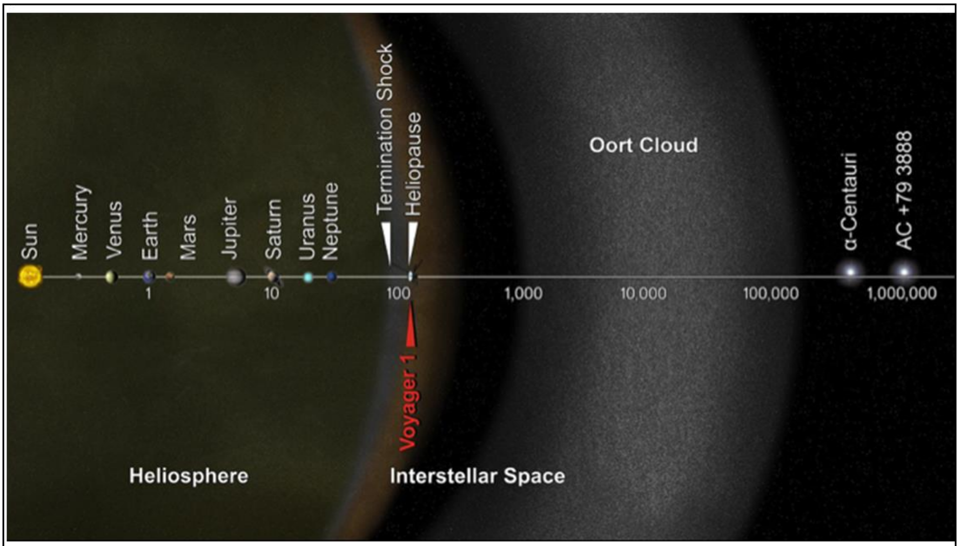
drop in the presence of charged particles from the sun and a rise in cosmic radiation from interstellar space. In May 2012, the particle detector systems LECP and CRS detected a drop in charged particles and a jump in cosmic rays. Those changes accelerated around July 28, 2012, but the levels soon returned to normal. But by Aug. 25, all the particles identified as originating inside the heliosphere dropped dramatically and cosmic ray levels skyrocketed — and the levels stayed that way. The magnetometer (MAG) detected a closely correlated increase in the magnetic field intensity. However, the fact that it did not detect the expected significant field direction change raised doubts about whether Voyager 1 had indeed reached the heliopause.



Voyagers' travels: Artistic rendering of the two Voyagers exiting the Heliosphere and the Solar System around 2005. http://www.nasa.gov/vision/universe/solarsystem/voyager-interstellar-terms.html)

This question could have been resolved more quickly if the PLS, the instrument that directly measures plasma density, had not stopped working in 1980. It could have confirmed whether there is a transition from the hot (~10^6 K) and lower-density heliosheath plasma to the cooler (10^4 K) high-density interstellar plasma. The PWS can also derive plasma density from the electron plasma oscillation frequency as mentioned earlier. But it did not pick up any signal at the time. It's not too surprising as such oscillations do not occur frequently. Just like a mass and spring that needs a gentle pull in order to oscillate, the plasma oscillations are usually excited by energetic solar events or shock-waves from planetary magnetospheres.

Not until April 9, 2013, did the PWS detected strong oscillations that corresponded to a 40 times increase of plasma density as expected for interstellar medium. This unexpected gift was from the sun. A coronal mass ejection, or a massive burst of solar wind and magnetic fields, erupted from the sun in March 2012 on St. Patrick's Day but took 13 months to reach Voyager 1's location. The plasma wave science team reviewed its data and found an earlier, fainter set of oscillations in October and November 2012. When they extrapolated both events back, they deduced that Voyager had first encountered this dense interstellar plasma in August 2012, consistent with the sharp boundaries in the charged particle and magnetic field data on August 25.



Solar system distances : shown on logarithmic scale with approximate position of Voyager-1. The scale is measured in Astronomical Units (AU). Note: log scales can be visually very misleading on relative distances.
http://www.jpl.nasa.gov/news/news.php?release=2013-278, (Sep 2, 2013)

With this additional confirmation, the Voyager team concluded that Voyager 1 has indeed entered interstellar space. However it is still in a transition region where there is still solar influence on the magnetic field and plasma. By 2025, scientists believe that Voyager 1 will reach a more "pristine" region of the interstellar medium where the solar wind no longer has any significant influence on the interstellar magnetic field.

Depending on the definition, Earth's most distant spacecraft can still be considered as inside the solar system since it has about 300 years until it reaches the inner edge of the hypothesized Oort cloud where icy comets are born. The journey through the vast Oort cloud could take another 30,000 years, until finally we will reach a region where the Sun's gravitational field is no longer dominant. The figure above (**Solar System Distances**) shows the distances of various objects. Note that all these have to be plotted on a logarithmic scale which can be visually very misleading with respect to relative distances.

The Grand Tour

So how did the two Voyager spacecraft get to their current positions and how were they able to visit and gather information on so many different planets and moons?

In 1964, Gary Flandro[25], at the Jet Propulsion Laboratory, recognized that there would be a rare alignment of planets occurring in the late 1970s that would allow a single spacecraft to visit Jupiter, Saturn, Uranus, and then Neptune – the so-called "Grand Tour". With very careful choice of timing and trajectory, a spacecraft could take advantage of gravity-assist from each successive encounter to complete the journey in just 12 years. Without this fortuitous alignment, visiting all four planets in any reasonable time-frame would be completely impossible. This was a once in a life-time opportunity that could not be missed (not to occur again until around the year 2150). (We will talk more about gravity-assist in the next chapter discussing the Galileo spacecraft)

In August and September of 1977, two identical spacecraft were launched from Cape Canaveral, Florida, on a powerful Titan-Centaur rocket. Voyager-2 was launched first then followed 16 days later by Voyager-1. The official plan for both spacecraft was to do a flyby of Jupiter and then a flyby of Saturn. However the launch-date and trajectory never precluded the Grand Tour – assuming the spacecraft survived that long. After success with the Jupiter encounter and with both spacecraft looking good,

[25] http://www.pbs.org/the-farthest/science/man-behind-mission/

the new plan became official. Voyager-2 was to complete the grand tour of the four giant planets. Voyager-1 was to visit just Jupiter and Saturn but, in particular, would perform a close fly-by of Saturn's large moon, Titan. This large moon was of special interest as it had long been known to have a thick atmosphere. Voyager-1's trajectory was optimized for the Titan fly-by and precluded subsequent visits to Uranus and Neptune.

The Voyager missions proved to be one of the greatest ever successes of space exploration. Both spacecraft contributed immensely to our knowledge of the Solar System. For the first time, detailed images were obtained of Jupiter and its storm systems and of the larger moons, Io, Europa, Ganymede, and Callisto – each moon being dramatically different from its neighbors (see next chapter). Similarly the Voyagers obtained unprecedented images of Saturn and its rings and moons. Voyager-1 provided valuable information about the composition of Titan's atmosphere but the high-resolution images proved anticlimactic because the ubiquitous atmospheric haze obscured any detail. Voyager-2 continued the grand tour to rendezvous successfully with Uranus then Neptune. It is still the *only* spacecraft to have visited and provided detailed images of the two ice-giants!

As a result of these two last encounters (Voyager-1 with Saturn/Titan and Voyager-2 with Neptune) both spacecraft were deflected well out of the plane of the ecliptic that all the planets follow closely. Voyager-1 was thrown at 35 degrees towards the north and Voyager-2 a similar angle towards the south (see figure above, **Voyagers' travels**). The net result is that the twin spacecraft are actually separating from each other faster than they are leaving Earth behind. As a result of the gravity assists from the giant planets, both spacecraft have velocities well in excess of solar escape velocity. Voyager-1 is the faster of the two and is the object with second highest hyperbolic velocity[26] in the Solar system. The fastest object is Oumuamua[27], the only known the interstellar asteroid, with an asymptotic velocity (at infinity) of 26 km/s, almost twice that of the two Voyagers.

[26] Hyperbolic velocity refers to the asymptotic velocity an object will reach when far from the source of gravitation (the Sun in this case). Objects that exceed escape speed have open hyperbolic trajectories rather than closed elliptical orbits.

[27] Oumuamua (meaning 'scout' in Hawaiian) is understood to be an interstellar comet or asteroid. It was discovered in 2017 just after its closest approach to the Sun. It is the only such object to have ever been identified. It is a small, 100 m, elongated reddish object.

None of these objects have enough excess velocity to escape from our Milky Way galaxy.

How to Phone Home?

So how does Voyager-1 phone home? A dominant feature of the Voyager spacecraft is its large parabolic dish antenna (figure **Voyager** near beginning of chapter,). It goes without saying that this *must* be kept pointing back towards Earth otherwise communications may be permanently lost. There are several mechanisms that allow the spacecraft to sense its attitude (orientation in three dimensions) including gyroscopes and celestial navigation (Sun sensor and Canopus[28] star tracker). Errors in attitude are corrected by short bursts from some combination of the 16 hydrazine thrusters (reaction wheels were not used on the Voyagers) to maintain pointing of the high-gain antenna toward Earth. At the frequencies of 2.1 and 2.3 GHz used for commands and simple telemetry, the wavelength is about 14 cm (5 inches), so the resolution of the 3.7 meter (12 foot) antenna dish is roughly 14/370 radians or 2 degrees. Should the spacecraft inadvertently lose orientation, it is independently capable of locking on to the Sun and Canopus and automatically re-orienting to much better than 2 degrees and thus re-establishing communications with Earth.

Cell phones or Mobile phones operate on similar frequencies to Voyager (their main band is just below 2 GHz). So how is it that cell phones only work over a few tens of miles or kilometers but Voyager can communicate over a distance a billion times greater than that? Furthermore, power falls off as the square of distance, so it’s perhaps a billion-billion (10^{18}) times more difficult! Admittedly Voyager doesn’t have to compete with interfering signals from other cellphones and there are no obstructions from buildings or terrain. Part of the secret lies in the power levels and data-rates used. A cell phone transmits at less than a Watt, whereas Voyager uses about 20 Watts. A cell-phone can transmit many Megabits each second whereas the Voyager commands and telemetry are at a few

[28] Canopus is the second brightest star in the sky after Sirius, the Dog Star. Canopus is well separated from other bright stars and so is a preferred reference point for spacecraft navigation. Coincidentally, in Greek mythology, Canopus, was a navigator for Menelaus, king of Sparta.

tens of bits per second (more energy in each bit). Another important factor is the use of cryogenic receivers at the down-link end on Earth. These operate at an effective temperature just a few degrees above absolute zero. This reduces the thermal noise generated locally in the receiver to a level similar to that of the microwave background radiation (2.7 K). This drops the receiver noise-level by about a factor of one-hundred below a typical receiver operating at room temperature.

However, the biggest factor in communicating over such a huge distances is the use of very large directional antennas at both ends of the link. A corollary to the high-resolution or narrow beam-width of a dish antenna is its high gain in the preferred direction. On the transmitting end, all the energy is directed along a narrow path and, on the receiving end, the antenna effectively scoops up all the energy intercepted by the area of the dish. The Voyager antenna is 3.7 m (12 feet) in diameter and NASA's Deep Space Network (DSN) boasts multiple 70 m (230 feet) and 35 m (120 feet) antennas that can be ganged together. (The gain of the antenna built into a cell-phone is effectively zero since it is small and as omnidirectional as possible.) The power gain of an antenna[29] goes roughly inversely with the square of its angular resolution or directivity, λ/D, (see earlier footnote on optical telescopes) and the antenna gains at both ends of the link get multiplied together. So the total antenna gain in this case is a factor of six billion or more depending on how many DSN antennas are linked together. Voyager's 2.3 GHz down-link carrier is always being transmitted making it easier to acquire and accurately point the DSN antennas at Voyager and to correctly phase-align the signals from several antennas.

As well as the simple telemetry from Voyager which is transmitted at 16 bits/s, larger quantities of scientific data can be read back from tape at various tape-speeds and with data-rates in the Kbit/s regime. These much higher data-rates mean that there is even less energy per bit available. To overcome this loss, the higher-speed data is transmitted on a carrier at 8.4 GHz. The wavelength at this frequency is only 3.6 cm (one-and-a-half inches) or about a quarter of the wavelength used for telemetry. As a

[29] The power gain of a circular parabolic antenna is $(\pi D/\lambda)^2\varepsilon$, where D is the diameter, λ is wavelength, and ε is a factor of 0.5 to 0.7 representing the efficiency with which the dish is illuminated by the feed. In this example, $(\pi 70/0.14)^2 0.6 \times (\pi 3.7/0.14)^2 0.6 = 6\times10^9$

consequence, the antennas on each end have much narrower beam-widths (which makes accurate pointing much more critical), but, conversely, they do provide 16 times more gain at each end of the link for a total gain of 256 and thus enabling the scientific data to be downloaded to Earth much more rapidly.

Imagine again that you do happen to be sitting on the Voyager dish in your spacesuit. If you are there at exactly the right time, you might hear (through the seat of your pants, since no sound travels in a vacuum) a faint click and a whirring noise as the tape recorder spools start rotating. The spacecraft itself will start rotating very very slightly in the reaction to the rotating tape spools (conservation of angular momentum), though not enough to easily discern. However, it's quite possible that there might be a popping sound as one or more of Voyager's hydrazine[30] thrusters give a millisecond burst of correction. (Earlier in the journey, these corrections were absolutely necessary to avoid smearing when the high resolution telescopes were taking images of the Jovian and Saturnian moons and the tape recorder was running). These faint noises signify that six months' worth of accumulated scientific data is now being spooled off the tape recorder and transmitted back to Earth, although it will take another 19 hours before it is finally hits the giant dishes of NASA's deep space network.

Data Storage

So finally we get to talk about data-storage on Voyager-1. Perhaps we should first apologize to the reader for making such a circuitous journey in getting here, but Voyager-1 represents such a remarkable and fascinating achievement in engineering and human ingenuity, that it was difficult for the authors to resist the temptation. Before we plunge into the data-storage topic, please be reminded that everything we've talked about so far on the spacecraft including everything in the data-storage systems is over forty years old. Nevertheless, there is much that can be learned as we discuss this.

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[30] Hydrazine, N_2H_4, is a colorless liquid with a density similar to water. It is highly flammable and highly toxic, but it is a preferred rocket fuel since it needs no oxidant and reliably self-ignites with the help of a catalyst such as iridium. There's about 25 litres or 6½ gallons of fuel left on Voyager .

There are three data storage technologies to discuss. First comes the famous “Golden Disk” attached to the outside of the Voyager bus (figure **Voyager**). Second are the computer systems and their plated wire memory. Third is the tape recorder, though detailed discussion of magnetic tape recording will occur in later chapters.

The Golden Record

The Golden Record is a 12-inch (30.5 cm) phonograph record intended as a message from humanity to whomever or whatever might come across it, possibly billions of years into the future. It is purely passive, not actively linked in any way to the spacecraft’s activities but it provides an excellent example of an important popular technology that extended through much of the twentieth century. The Golden Disk is attached to the side of the spacecraft and housed under an aluminum cover. On the cover is a sample of ultra-pure Uranium 238. Uranium 238 is radioactive with a half-life of 4.5 billion years that will allow possible alien recipients to assess the age of the spacecraft quite precisely. Also on the cover are etched diagrams with instructions on how to play the record. This is to be done using the needle provided and with the record rotating at $16^2/_3$ rpm. The cover also has instructions on how to assemble images out of 512 × 8 millisecond waveform segments recorded on a portion of the record. The time reference is the 704 picosecond period (1.4204 GHz) corresponding to the hyperfine transition[31] of the hydrogen atom and is also indicated by a diagram. This naturally also provides the unit of distance 21.11 cm (8.3 inches) which is the distance light travels in a 704 picosecond period.

Certainly carving or etching pictures or diagrams onto a stone tablet or onto the cover of the golden disk is about as basic as it gets for data storage. The oldest rock carvings go back tens of thousands of years and more detailed diagrams and writing systems started about 8,000 years ago.

[31] Hydrogen atoms have a single proton and a single electron each of which have a quantum spin or magnetic moment. The state with the proton and electron spins parallel has very slightly lower energy than the antiparallel state. The “hyperfine” transition from one state to the other emits radiation at the 21 cm wavelength. The transition is very infrequent and cannot be easily observed in the laboratory but is readily observed on an astronomical scale and is widely used in radio astronomy for studying hydrogen clouds.

If it's longevity you're after, physically carving something into rock or ceramic or noble metal is about as good as it gets.

And so it goes with the golden disk itself. A single groove is cut spiraling from the outside of the disk towards the center. Information is recorded in analog form onto the rotating disk by laterally vibrating the tool that is cutting the groove. Playback is achieved by placing a needle or stylus in the groove and allowing it to vibrate in sympathy with the groove as the record rotates. The bandwidth extends to about 30 kHz, more than sufficient for high quality audio and the images. The disk is made of gold-plated copper and, barring any close encounters, will wander the galaxy at a temperature a few degrees above absolute zero, unchanged potentially for billions of years.

Phonograph technology was invented by Thomas Edison in 1877. Note that this predates the invention of electronic amplification. No electronics is required to create or playback a phonograph recording. The ancient Greeks could possibly have put together a system to make phonograph recordings on beeswax cylinders. The invention and popularization of disks rather than cylinders and lateral or 'zig-zag' vibrations rather than 'hill and dale' recording was due to Emile Berliner who coined the name "Gramophone" in 1887.

There has recently been a resurgence of interest in "old fashioned" vinyl records. These are 12-inch records run at 33-1/3 rpm mass produced by squashing or "pressing" a vinyl "puck between two high-quality metal masters. The puck flattens out into the thin disk and at the same time replicates the fine grooves on the masters. The master is created on a precision metal lathe. Modern disks are in stereo format. This is achieved by employing zig-zag or side-side motion of the groove for the sum channel and "hill and dale" or depth modulation for the difference channel (alternatively one can think of the left and right stereo channels being impressed into the left and right walls of a 90 degree V-shaped groove)

The contents of the Golden record were selected by a committee chaired by Prof. Carl Sagan of Cornell University and include images, sounds, brain-waves, written messages and even Morse code[32]. The 115 images

[32] Sagan, Carl (1978). Murmurs of Earth. New York: Random House. ISBN 0-394-41047-5 https://en.wikipedia.org/wiki/Voyager_Golden_Record

include some scientific basics, humans undertaking daily activities, and various animals and landscapes. Many of the pictures are annotated to indicate the scale. The sounds include human greetings in various languages, human song and music (both classical and modern), and various animal and natural sounds. The brain-waves were of Ann Druyan (the creative director for the project and Carl Sagan's then future wife). The short written messages were from US President Jimmy Carter and from U.N. Secretary-General Kurt Waldheim. The message in Morse code reads *Per aspera ad astra* (Latin for "Through hardships to the stars").

Computer Control

There are three relatively-independent computer systems on Voyager and each of these is duplicated for redundant reliability. The computers employ magnetic plated-wire for main memory and a magnetic tape recorder is available for bulk data storage. The computers themselves are proprietary, custom-built from CMOS and TTL medium-scale integrated circuits (fewer than 100 gates per chip) and discrete components. The total storage among the six computers is about 64 kBytes – about enough for one small .jpg file from the internet. The three computer systems provide 1) overall Command and Control, 2) Attitude and Articulation Control, and 3) control of the scientific data including operation of the tape recorder:

1) The Computer Command System (CCS) is the central controller of the spacecraft and contains fixed routines such as command decoding and fault detection and corrective routines, antenna pointing information, and spacecraft sequencing information. It comprises two 18-bit-word, interrupt-type processors with 4096 words each of plated-wire non-volatile memory. During most of the Voyager mission the two CCS computers on each spacecraft were used non-redundantly to increase the command and processing capability of the spacecraft.

2) The Attitude and Articulation Control Subsystem (AACS) controls the spacecraft orientation, maintains the pointing of the high gain antenna towards Earth, controls attitude maneuvers, and positions the scan platform. The AACS is two 18-bit word machines with 4096 words each, similar to the CCS.

3) The Flight Data Subsystem (FDS) configures and controls the various scientific instruments. It also collects engineering and science data and formats the data for transmission. The FDS comprises two 16-bit word machines with modular memories and 8198 words each. The Digital Tape Recorder is used to record high-rate signals. Currently this includes the plasma-wave electrical signals (PWS) from the pair of orthogonal 10 meter whip antennas. Earlier in the voyage it would have included the images from the telescopes' vidicon TV cameras.

Plated Wire Memory

In the Voyagers, both the main computer memory and the bulk data storage are based on the use of magnetism. This is in sharp contrast to more recent spacecraft such as New Horizons (explored Pluto in 2017) that rely entirely on solid-state semiconductor devices for both main memory and bulk storage. In Voyager, even the main computer memory is magnetic. The control computers use plated-wire memory which we will talk about in some detail in this chapter and the bulk data storage is on a reel-to-reel tape-recorder that we will talk about briefly here but discuss in more detail in the following Chapter +12 on the Galileo probe that explored the Jovian system.

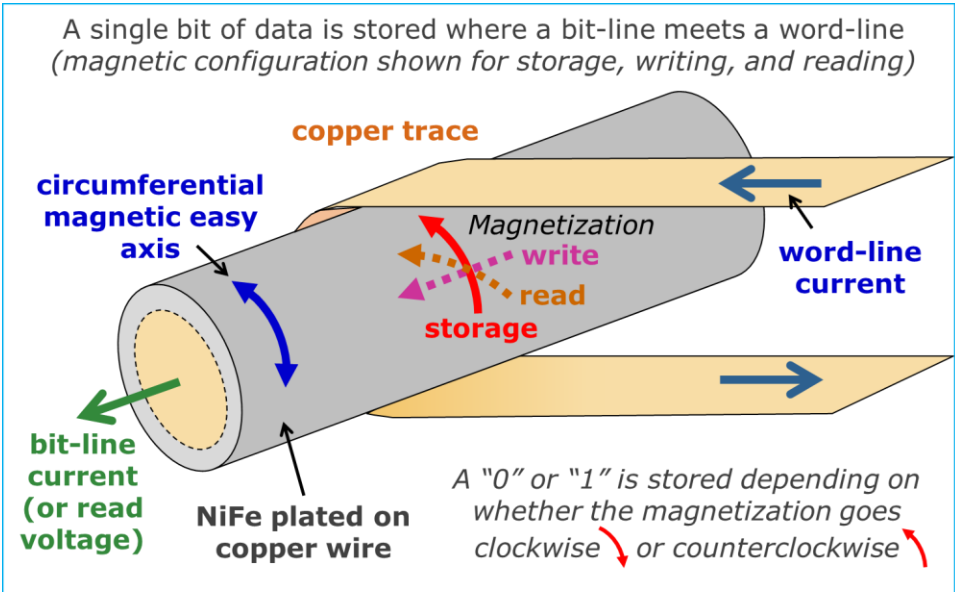
Plated wire memory[33] is a variant on the more famous "core memory" that will be discussed in Chapter +9 on the Apollo lunar lander program. These types of memory predate the development of non-volatile semiconductor memories. They are inherently very robust against ionizing radiation – and important factor for Voyager-1's rendezvous with Jupiter. Plated wire memory has the advantage over core memory in having non-destructive readout. It also can be made lighter and more compact than core memory – again an important factor in spacecraft design.

The figure below "**Plated Wire Memory**" shows the principle of operation. The storage medium is a thin layer of Permalloy (a soft magnetic NiFe alloy) plated onto a copper wire. The plating is done with an electric current passing through the wire. During plating, the circular magnetic field from the current induces a circumferential magnetic

[33] http://www.technikum29.de/en/devices/plated-wire-storage (retrieved Jan 21, 2017) G. Fedde, "Thin film plated wire memory", US Patent 3371326, 27 Feb 1968

anisotropy in the Permalloy. The effect is that the magnetization prefers to wrap around the wire circumferentially and resists being oriented along the length of the wire. The magnetization can wrap around the wire in either a clockwise or a counter-clockwise direction equally happily, thus storing either a "1" or a "0".

To write data into the plated wire memory, a large current is passed through the word-line. The magnetic field from the current causes the magnetization to swing round from the 'easy' circumferential direction and saturate along the 'hard' direction along the bit-line. When the word-line current is released, the magnetization relaxes back to its preferred circumferential orientation. However, if at this time, there is a small positive or negative current present in the bit line, the corresponding circumferential magnetic field can steer the magnetization to relax back into either a clockwise or a counter-clockwise configuration - thus storing one bit of information.



Plated Wire Memory: Showing one bit of a plated wire memory. The manner of operation is described in the text. . In practice, there are many bits threading each word-line and many word-lines wrapping each bit-line.

To read back the data, a smaller current is passed through the word-line. The field from this current rotates the magnetization by a small amount from its stable circumferential configuration. When this current is released, the magnetization relaxes safely back to its original configuration, (note that the data is not erased by this operation). As the magnetization rotates, its circumferential component drops in magnitude. Conversely, when the current is suddenly removed, the circumferential magnetization will quickly relax to its full value. This sudden change in the magnetization circulating around the wire causes a small voltage pulse (Faraday's law) to appear on the bit-line. (see also the blue tutorial boxes at the end of this chapter). The polarity of the pulse depends on whether the original bit was magnetized clockwise or counter-clockwise. Thus, with a sensitive amplifier on the end of the bit-line, the polarity of each stored bit can be read by activating the corresponding word-line.

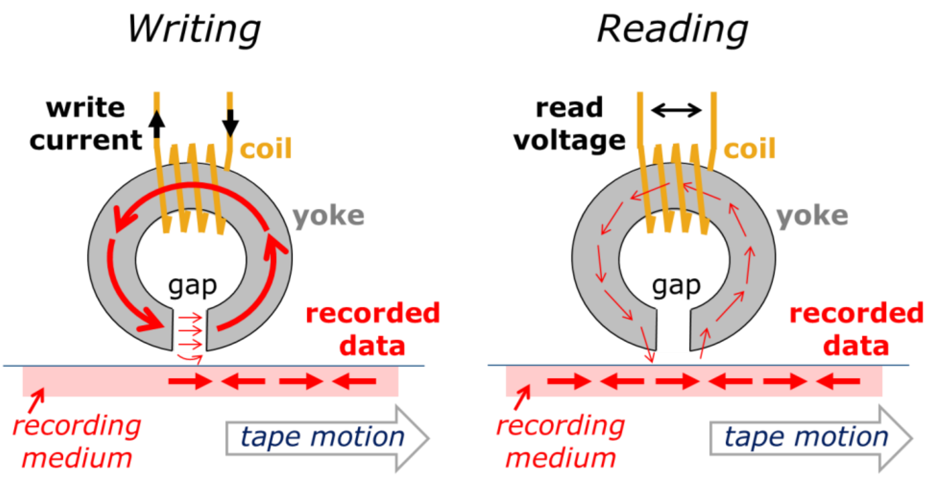
In practice, on each layer, there are many bits threading each word-line and many word-lines wrapping each bit-line. Then many layers of memory are stacked together to form a rigid three-dimensional block of storage. The manufacturing process still involves some manual assembly but avoids the painstaking threading of individual ferrite cores as required for core memory. In addition to the magnetic structure, separate semiconductor devices are required to create and steer the appropriate current pulses to the selected word and bit lines and to amplify and detect the tiny voltages during read. Plated-wire memory was used in limited applications in the 1960s and 70s as a replacement for core memory and prior to the advent of inexpensive semiconductor memory.

Tape Recording

Historically, magnetic tape recording dates back almost as far as phonograph recording (Edison 1877) yet it still shows no sign of being supplanted by any newer technology. The first example of tape recording comes from Valdemar Poulson in 1898[34]. Poulson was a Danish engineer who was actually more famous for his contributions to early radio transmission. Poulson's invention actually used steel wire rather than tape but operated on the same principle. At that time, electronic amplification was not an option (Lee De Forest did not invent the vacuum tube amplifier until 1907). Recordings were made directly from a carbon granule microphone and listened to through a moving-coil headset. In the 1920s,

[34] https://en.wikipedia.org/wiki/Valdemar_Poulsen
http://www.computerhistory.org/storageengine/poulsen-records-voice-on-magnetic-wire/

steel-tape replaced wire and in the 1940's this was replaced in turn by paper tape coated with iron oxide. The reasons for the shift away from steel tape included cost but also the significant danger involved in handling a fast-moving thin steel tape. Today's tapes are similar in concept but employ a polyester tape with a magnetic coating, typically, of iron alloy particles or iron oxide particles.



Tape Recording: Showing writing and reading processes with an inductive head (a gapped soft magnetic yoke wound with a copper coil). The recording medium is typically of iron oxide particles embedded in a plastic binder and coated onto a polyester tape substrate.

The principles of operation are shown in the figure above (**Tape Recording**). Both writing and reading can be done with the same "inductive" head, but often, for data recording, two separate heads are used. The function of the head is to convert the rather diffuse Amperian magnetic fields from the current in the copper windings into an intense very-localized field across the small gap in the soft[35] magnetic ring structure. The word "soft" here implies that the structure is a very good conductor of magnetic flux so that nearly all the magnetomotive force from the coil current ends up across the narrow gap. To write, the moving tape is brought into contact with the gap and the intense head fields leave a

[35] The word "soft" implies a material that conducts magnetic flux easily (has high permeability) but does not retain the magnetization. The word "hard" here suggests that flux does not flow easily and the material is difficult to magnetize (high coercivity). However if the material does become magnetized, it will retain that magnetization.

permanent magnetic impression on the hard magnetic coating. Read back is accomplished by moving the tape past the gap such that the magnetization in the recording medium links with the head yoke and with the copper coil. As the tape moves, the magnetic flux changes and a corresponding small voltage is induced in the coil.

Tape recorders for spaceflight must operate in hermetically sealed containers. It is especially important to maintain humidity and temperature within a certain range to avoid degradation of the tape material and failure of the head-tape interface. Nitrogen is typically used to fill the container and the humidity carefully allowed to settle to a prescribed value (most of the water content resides in the tape packs themselves). An electric heater is required to continuously control the temperature of the sealed unit within a narrow range around room temperature.

The Voyager-1 tape recorder is belt-driven and capable of four tape speeds. The magnetic tape is 1075 feet long (328 meters) and divided into 8 tracks that are written sequentially one after the other. Data can be written and played back at 57.6, 33.6, 21.6 or 7.2 Kbits/s. Lower data-rates can be achieved by padding the data (tape recorders of this era have a minimum speed dictated by their use of inductive readback heads). Total storage capacity of the tape is 67 MegaBytes. At the time of writing, the tape recorder records about 48 seconds of data on tape every week and then, once every six months, the accumulated data is played back to Earth. The Voyager-1 tape recorder has been operating now for four decades – an amazing testament to the quality of the original design and engineering.

This concludes our interstellar chapter. Our next factor-of-ten leap takes us to 10^{+12} meters (one billion kilometers) - well within the Solar system and into the vicinity of the two gas giants.

Further Reading

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https://voyager.jpl.nasa.gov/

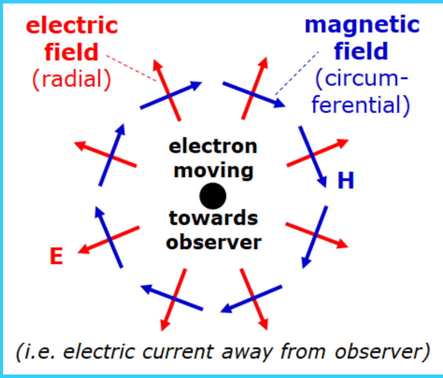
https://en.wikipedia.org/wiki/Voyager_1

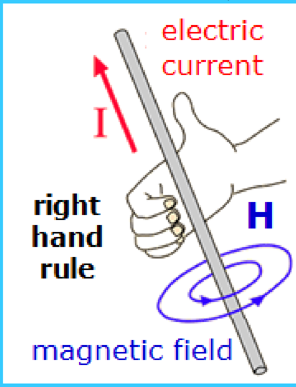
(Note: tutorial boxes below in blue)

Magnetic Fields and Magnetic Materials

There are two fundamental sources of magnetic fields: a) moving electric charges and b) 'spins' of elementary particles.

a) **Moving Electric Charges** (electric currents): Gravitational fields, electric fields and magnetic fields all obey the inverse square law with respect to distance from a point source. However, magnetic fields differ in that the point source has a direction of movement or a "flow" associated with it. In contrast to electric and gravitational fields that are directed radially away from or towards a point source, magnetic fields circulate around the vector direction of the source (they also have an additional factor proportional to the sine of the angle between the source vector and the position vector). The inset diagrams illustrate the fields from a moving electron (say) and also the so-called "right-hand rule" that is a helpful reminder for the direction of circulation of the field around a current in a wire. Note the field from the current in a long wire drops inversely with distance from the wire (the inverse-square law applies to a short current element).





b) **Atomic Spins:** Magnetic fields also arise from the intrinsic magnetic moment or spin of electrons and atomic nuclei. These spins can be considered as tiny current loops or tiny magnets. The magnetic field from a spin has exactly the same form as the electric field from a tiny electric dipole and varies as the inverse cube of distance from the source. In some solid materials, notably Co, Fe, & Ni, the atomic spins naturally tend to align with each other. In this case their individually tiny magnetic fields can all add together to create a large macroscopic field. In 'hard' permanent magnets, a large external field is required to align the spins, but, once set, the magnetization is retained (as in a tape recording medium). So-called 'soft' magnetic materials do not retain magnetization but can act as good conductors of magnetic flux (such as in a tape recording head).

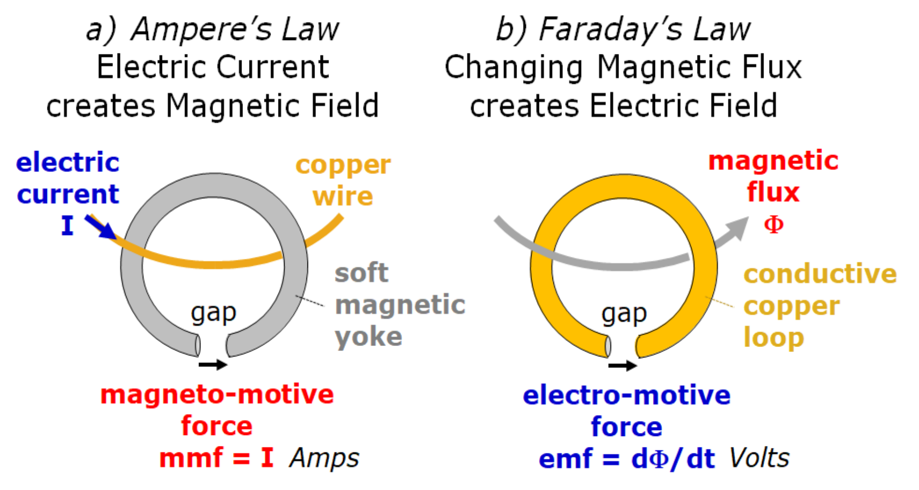
Connecting Magnetism and Electricity

There are two very fundamental ways in which magnetism and electricity interact: a) Ampere's circuital Law describes how a magnetic field arises from an electric current and b) Faraday's Law describes how an electric voltage can arise from changing magnetic flux-density.

a) **Ampere's Circuital Law**: The integral of the magnetic field around a closed path is given by the electric current enclosed by that path. The integral of magnetic field is referred to as magnetomotive force (mmf) and is thus measured in Amperes. Accordingly, the magnetic field has units of Amperes/meter (in SI).

b) **Faraday's Law:** The voltage or electromotive force (emf) induced in a wire loop is given by the rate of change of the magnetic flux threading the loop. Magnetic flux thus has units of Volt-seconds or 'Webers'. Correspondingly, flux-density within the loop is measured in Webers per square meter or 'Tesla'.

The ratio of flux-density to field-strength is known as permeability. The value for vacuum is $\mu_0 = 4\pi 10^{-7}$ and is typically quoted in Henrys per meter. A Henry is a unit of inductance equal to one Weber of flux per Ampere of current.



Ampere's Law and Faraday's Law illustrated here with complementary structures analogous to writing and reading with inductive heads in a tape-recorder. The magnetic-yoke or wire-loop serves to concentrate all the magnetic field or electric field, respectively, across a small gap (incidentally performing the implied circular integral). The field-strength in the gap is roughly given by mmf or emf divided by gap-length.