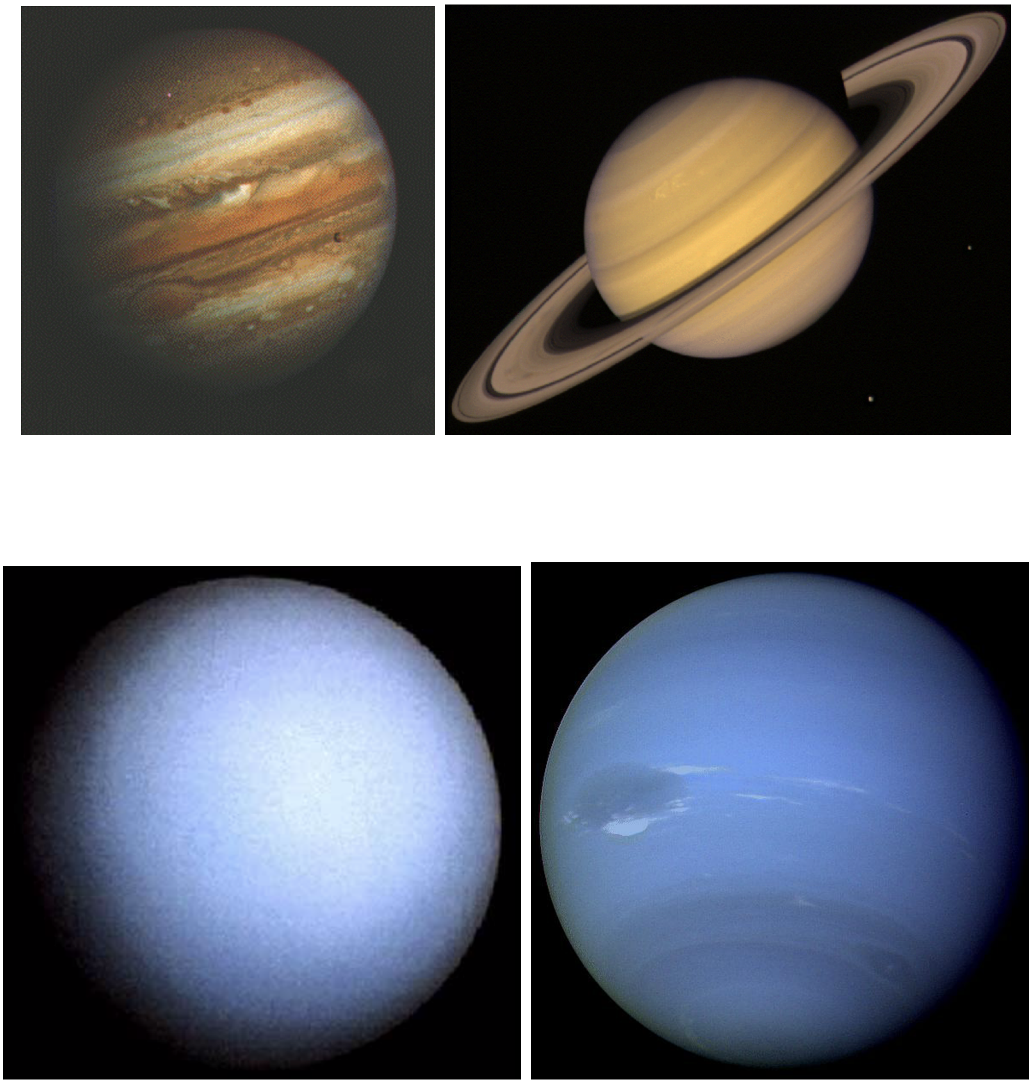
Pioneers and Voyagers
Exploring Space Beyond Mars.
(Including a dynamic example of a 3 body solution)



NASA Images of Jupiter, Saturn, Uranus and Neptune

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Preface.

Following the success of the Mariner series of spacecraft during the decade from the early 1960's, NASA decided to extend knowledge of the outer Solar System beyond Mars, by exploring out to Jupiter, Saturn and further. The final Mariner 10 mission (Earth-Venus-Mercury) had demonstrated a technique whereby an infinitesimally small piece of Venus's gravity was "stolen" to accelerate and hence change the orbit of the spacecraft to enable a rendezvous with Mercury. Well, NASA did not exactly use the word "stolen", the term "gravity assist" was used. By sheer coincidence this technique had been proven just a few years before a favourable alignment of Jupiter and Saturn would allow 'The Grand Tour" of Voyager 1 and Voyager 2. However what has drifted beyond memory is that there were also two Pioneer missions, 10 & 11 which served as the initial pathfinders to Jupiter and Saturn.

I have published two prior works on the Mariner 4 & 9 Mars exploration missions. What is obscure knowledge, to most, is that the Voyagers were originally planned and named the Mariner 11 & 12 1977 missions to Jupiter and Saturn , in March 1977 they were renamed Voyager 1 & 2, thus the genesis of this family, as that of the Pioneers may be traced back as far as 1958. The name Voyager may also be traced back before 1964 to a planned Mars Lander to be launched on a Saturn V, see NASA doc NASA-CR-69566 on the NTRS server. Funding was only available in the early 1970's for the Pioneer 10 and 11 missions plus the two Voyagers to explore Jupiter and Saturn. It would not have been envisaged in the 1970's, that at this date of writing, that the Voyagers are still sending back useful scientific data. Following the initial successes of Voyager 2 it was decided to further fund the mission to encompass an extension to Uranus and subsequently a further extension to Neptune. The technology in space was of course already there and thus free, however continued funding was essential to maintain a ground mission team plus tracking and data relay support and of course continued interest from the academic community in being able to continue analysis of the data and thus gain new knowledge. The orbital calculations for potential opportunities and mission variations had, of course, been well considered long before launch.

This brief exercise aims to set some historical context to these missions as well as explore the orbit designs of the Voyager missions and the scientific experiments carried by both Pioneers and Voyager platforms.

Cover images show some enhanced post processed images from the Voyager missions.

Some specifically useful texts are shown in Appendix 2:

We have to thank NASA and it's associates for allowing this information and images into the public domain, at the time of the missions some of the technical information would have been very highly classified.

`http://rayhillwrites.com//`

This document was prepared using LaTeX.

Overview

The historical context was that the USA was using NASA to demonstrate to the world its superior technology over the USSR. Some might argue that it was done purely on a scientific basis, but personally I do not feel that finance would have ever been provided had it been for science alone. In my opionion cold war politics played the major part in NASA's continued funding at that time. Following the Apollo missions and subsequent continuing expenditure on the Space Shuttle a variety of planned missions were scrapped to meet evolving budget constraints. This in itself is not new, the ambitions and dreams of scientists and engineers often ran in front of commercial reality in this period and continue to this day. However it is these dreams and ambitions that frequently and ultimately drive scientific progress forward.

The aforementioned planetary alignment was simply too good an opportunity to miss and the successes of Pioneer 10 to Jupiter and Pioneer 11 to Saturn meant that further exploration could effectively exploit and build on existing mature technology and evolving new technologies. This favourable planetary alignment only occurs every 175 years.

The key timelines are as follows :

1. March 1972 : Pioneer 10 launched toward Jupiter using an Atlas/Centaur launch system. Closest approach to Jupiter was 132,252km (82,178 miles) on December 3, 1973. Contact was lost 15 years after launch on January 23, 2003.

2. April 6th 1973, Pioneer 11 launched, again using the Atlas/Centaur system. Closest approach to Jupiter was on December 3rd 1974 from where it proceeded to its closest approach to Saturn 210,000km (130,000miles) on September 1st 1979. Contact was lost on September 30th 1995.

3. August 20th 1977, Voyager 2 launched from Canaveral, again using a Titan IIIE launcher. Flyby of Jupiter 570,000km (350,00 miles) on July 9th 1979. Flyby of Saturn 101,000km (63,000 miles) on August 25th 1981, flyby of Uranus 81,500km (50,600 miles). January 24th 1986. Finally a flyby of Neptune 4,951km (3,076 miles) on August 25th 1989. At time of writing (2020) it is considered to have passed into interstellar space. Power is expected to maintain transmission until around 2025.

4. September 5th 1977, Voyager 1 launched from Canaveral using a Titan IIIE launcher. Flyby of Jupiter was on March 5th 1979 at a distance of 349,000km (217,000 miles) and then, using gravity assist, arrived closest to Saturn 124,000km (77,000miles) on November 2nd 1980. It also“stole” some of Saturn's gravity and by 2012 had escaped through the heliopause into the interstellar medium. In 2017 NASA carried out a trajectory correction manoeuvre, at the date of writing (2018) NASA engineers estimate that its sensors will operate until 2025.

The science from the Voyagers and the quality of images far exceeded that of the Pioneers, however, had the Pioneers failed who knows if funding for the Voyagers would have been continued. It is also appropriate that at launch the Voyagers benefitted from far superior imaging capability (both pre and post processing) and also far better communications (particularly data rates) than had been available for inclusion, five years earlier, within the Pioneer programme.

A few points from above; firstly note that the flyby distance of the larger planets (Jupiter and Saturn) is much larger than for the smaller planets (Uranus and Neptune), secondly by 2025 the Voyagers will have been flying for 42 years with power to provide communications. They do in fact carry small nuclear reactors. Finally an anecdote : Voyager 2 was fitted with a golden disc carrying information about the human race. Since 1977 our recording technology has moved from cellular cine film and plastic LP discs, to cassettes, CD/DVDs and onto MP3 memory sticks. I hope any aliens that may find it in thousands of years time can decode how to understand technology which by then may be far older than the whole of recorded human civilisation. The real point here is that when Voyager was planned in the early 1970's no-one on Earth could have possibly envisaged how far data storage and communications technology would have progressed by the end of the millenium. Even if they knew, any delay would miss that all important once in every 175 year window of opportunity.

The Voyager missions (orbit profiles and flyby trajectories) were also cleverly designed so as to enable the carrying out of comprehensive surface imaging and detailed study across many of the planetary moons that were also within reasonable flyby distance.

In technology terms the key challenges to these missions were orbital planning, production of scientific instruments and data communications. The latter totally essential to allow us to actually receive useful information on Earth. Without communication capability none of this would have been possible or even worthwhile. A further historical context is that, in this era, computing and telecommunications technology had been leaping ahead in massive bounds thus enabling ever improving image processing of data received. My earlier work on Mariner 9 goes into this in some detail. I have to say that data-communications and data storage technology was a hugely significant and rewarding part for around 30 years of my own working career.

Image above is a NASA photo of the Voyager 1 launch on top of the Titan IIIE with Centaur second and third stages. The actual spaceship at the top is much smaller and is enclosed by an aerodynamic shroud.

Flying to another planet

The process of going anywhere in the known universe essentially involves designing orbits around gravity sources. When we go to the Moon we move from a gravitationally dominant orbit around Earth into another gravitationally dominant orbit around the Moon, simply when we get closer, the gravity of the Moon becomes stronger than that of Earth. By far the largest gravitational effect within our Solar System always comes from the Sun, which according to Newton's law of gravity extends out to infinity but with increasing distance its effect becomes vanishingly small (a calculus of space). Gravity is however also the glue that holds galaxies together, of which we are an extremely small part. So when we go to another planet we move from an orbit dependant on the "Sphere of Influence (SOI)" of the Earth to a point where the Sun's SOI dominates, hence we move into an orbit around the Sun which is designed to intercept any chosen planet in its orbit at a required time. To do this requires that our vehicle is accelerated to an escape velocity which is always planetary mass/gravity dependant. As we get closer to a planet, e.g. Jupiter, its relative SOI becomes greater than that of the Sun so the orbit naturally adjusts into a Jovian one. Jupiter is a massive object and hence also has massive gravity which means that even as we approach, well before the SOI boundary, Jupiter will cause us to be accelerated toward it, therefore our ships solar orbit will slowly evolve into a Jovian one. The really clever part is making sure that the angle of approach is designed so that we either flyby, or go into an orbit around Jupiter. Both of which require precise approach angles and velocities. An alternative way of thinking about this is that as we pass into the SOI we enter a gravity bubble which captures us and we are then sucked toward the centre of the planet, the only way to escape from this bubble is by accelerating to a velocity which is greater than the unique escape velocity for each heavenly body, so basically the approach orbit design requires that Jupiter accelerates us (that is "gravity assist") to a velocity at which we then can escape it, without using engines. If we design and use it properly any planet always freely gives us a helping hand for escape. The alternative approach is to carry massive amounts of fuel, in fact so much that the launch vehicle necessary to take it all up from Earth would be prohibitively expensive and with chemical rocketry virtually impossible.

Galileo, with his telescope, saw the moons of Jupiter, which are often referred to as the Galilean system. Each of these moons is quite large and hence exert their own gravity which will also change our path of travel close to and within the Jovian system. These moons and also the rings around Saturn, may be quite easily seen on a clear night through a reflector telescope costing less than a TV set. The position of heavenly bodies is calculated in a table called the epheremides and it is possible to look at both past and predicted future positions for most bodies within the Solar System. For these missions NASA had calculated the epheremides for the moons that would be close to the entry path and hence were able to plan the trajectory to take account of the changes that the moons would cause and also to give favourable near miss distances for each moon so that camera imaging angles would be optimal. They obviously did the same for Saturn and beyond. One of the aims of the missions was actually to improve the accuracy of the ephemerides information for the moons because there were significant error bars in that knowledge at the time of launch.

If we know the cordinates of Earth and Jupiter at given times we can use the planetary epheremides (which may be found online at NASA Horizons) to design a transfer orbit between their respective SOI's. This orbit will depend on using conical mathematics, or computer models of dynamic simulations. According to Kepler the velocity will vary along its conical path, the only power is gravity. In fact at the beginning and toward the end of a journey (to a much larger planet than Earth) we will probably only ever use a part of whatever ellipse or hyperbola is generated from the design process. We therefore need to know at what point we wish to intercept Jupiter's SOI, so we need to calculate Jupiter's SOI against that of the Sun. Herein this part of the journey (from Earth) is referred as the JTO (Jovian Transfer Orbit)

We won't go into the details of conic mathematics here, but to calculate the radius (R) of an SOI (which, ignoring planetary oblateness, or flattening at the poles, approximates to a sphere) requires that we need to know the semi-major axis (a) from the Sun. This dimension varies throughout an elliptical orbit but for demonstration at this level may often be approximated to a circle, (a) thus becomes a simpler radius so is a fixed value.

The equation below simply states, in English, that the radius of Jupiters SOI is equal to the ratio of the mass of Jupiter and the Sun and the product ot the radial distance , all this to the power of 2 over 5.

$$R_{jsoi} = a(\frac{m_{jupiter}}{M_{sun}})^{\frac{2}{5}}$$

We can then input the ratio of the mass of our required planet over that of the Sun. Mass of Jupiter and the Sun in kilograms are : 1.89813×10^{27} and 1.98855×10^{30}. The average distance from Jupiter to the Sun is 5.2044AU so : $a = 5.2044$

$$= 5.2044(\frac{1.89813 \times 10^{27}}{1.98855 \times 10^{30}})^{\frac{2}{5}}$$
$$R_{jsoi} = 0.3223AU$$

Now 1 AU is the average distance from Earth to the Sun, $1.496 \times 10^{11}m$, or 93 million miles. Therefore for some comparisom the SOI radius of Jupiter is approximately a third of that value, so about $0.5 \times 10^{11}m$.

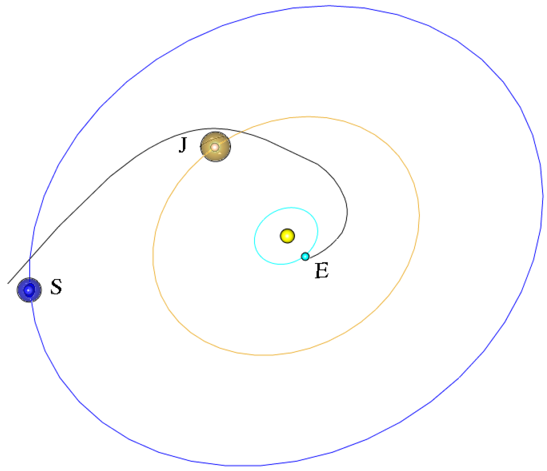
The implication of the above is that to intersect with the Jovian SOI we need the arrival point of our Jupiter transfer solar orbit to be somewhere close to $5.2044 - 0.3223 = 4.8821AU$ from the Sun. This throws in the additional question of what is the velocity of our vehicle at that point and how long will it then take to travel across, as it rapidly accelerates through that final 0.3223AU. Additionally the planet is also a moving object, so the velocity of that needs factoring in. On arrival we also need to design another parabolic or hyperbolic approach orbit to the planet based on our required target velocity and altitude at defined closest arrival point. We might choose to call this the JAO (Jovian arrival orbit). The detail of how the moons might affect this will not be covered here, but for some insight, the JAO might not actually be one mathematical orbit but a seqeunce of orbits, patched together, designed to hop around moons and arrive at the correct planetary point so the next orbit evolves into that required for the next destination. Voyager 2 used a gravity assist at Jupiter to alter its orbit out toward Saturn (and then ultimately onto Uranus and again Neptune) so the velocity and near points of arrival orbits needed to be accurately maintained. Accuracy was essential since the vehicle itself did not carry enough fuel to make major orbit/velocity changes under its own power. Achieving all this for each planet and their moons was in my opinion the major unique achievement of the whole mission, which ultimately facilitated such a rich feast of scientific planetary data collection to be gained from the whole programme.

To intercept, or leave any planet we need to know its velocity vector at chosen points on its orbital path and the escape velocity required to break away from its gravitational field at various distances. We will first calculate the escape velocities for Jupiter and Saturn. In the following calculations G is the unversal gravity constant, $M\&R$ are the planet's mass and radius. Now the basic equation gives the answer at the surface of the planet, if we add a required missed distance or orbital altitude to the planetary radius we can save a second step in doing this, defined below by h.

$$
\begin{aligned}
V_{escJupiter} &= \sqrt{\frac{2GM_{Jupiter}}{R_{Jupiter}+h}} \\
&= \sqrt{\frac{2 \times 6.673 \times 10^{-11} \times 1.8982 \times 10^{27}}{(69,911+570,000) \times 10^{3}}} \\
&= 19,864.44ms^{-1}
\end{aligned}
$$

$$
\begin{aligned}
V_{escSaturn} &= \sqrt{\frac{2GM_{Saturn}}{R_{Saturn}+h}} \\
&= \sqrt{\frac{2 \times 6.673 \times 10^{-11} \times 5.6834 \times 10^{26}}{(58,232+101,000) \times 10^{3}}} \\
&= 21,825.51ms^{-1}
\end{aligned}
$$

At the closest point we need to be at least at or above these velocities to escape the gravity and flyby the planet towards our next destination. Points E, J & S on the diagram below approximate to points where planetary escape velocities were attained



If we now compare the above with the required in orbit velocities at those altitudes.

$$
\begin{aligned}
V_{orbitJupiter} &= \sqrt{\frac{GM_{Jupiter}}{R_{Jupiter} + h}} \\
&= \sqrt{\frac{6.673 \times 10^{-11} \times 1.8982 \times 10^{27}}{(69,911 + 570,000) \times 10^{3}}} \\
&= 14,906 ms^{-1}
\end{aligned}
$$

$$
\begin{aligned}
V_{orbitSaturn} &= \sqrt{\frac{2GM_{Saturn}}{R_{Saturn} + h}} \\
&= \sqrt{\frac{6.673 \times 10^{-11} \times 5.6834 \times 10^{26}}{(58,232 + 101,000) \times 10^{3}}} \\
&= 19,374 ms^{-1}
\end{aligned}
$$

So, at these velocities and altitudes and right up to escape velocity we would orbit the planet, any slower and we would eventually crash. So this previous step showed lower velocities and as such was a valuable commonsense check against the escape velocities from the previous steps. So these two sets of calculations have set some boundary conditions which may be used to interpret the success or otherwise, of subsequent work. You may have noticed that although Saturn is smaller its escape and orbital velocites are higher than for Jupiter, this is determined by the h value.

We can calculate the velocity of a planet, with respect to the Sun, through a similar method to above, however more accuracy may be obtained if we know the planet's velocity vectors at a given point in time. Sounds difficult? Well actually, no, all we need to know is our target arrival date and time and use the velocity vectors which we look up from NASA's ephemerides system `https://ssd.jpl.nasa.gov/horizons.cgi#top`, then the next steps are simply good old Pythagoras.

The ephemerides data below shows the X, Y & Z position vector components in units of AU, this is all given with Sun at the centre. VX, VY & VZ are the velocity vector components in units of AU/day. For simplicity and for easier reading we will ignore references to the Z axis and just work in 2D space (i.e. assume every planet's orbit is precisely on a flat plane). For clarification of the negative values , -VX is when the X component is moving to the left of the X axis and -VY is for motion down the Y axis. Positive X is configured to point from the Sun toward the first point of Aires. Note that epheremides data is supplied to 13 decimal places, for this text all data will be simplified to 4 decimal places.

For Jupiter July 9th 1979 22:30
$X = -3.9293662001580AU$, $Y = 3.5913956361882AU$
$VX = -5.1763448523621 \times 10^{-3}AUday^{-1}$, $VY = -5.2223811415995 \times 10^{-3}AUday^{-1}$

$$\begin{aligned} V_{Jupiter} &= \sqrt{(-5.1763 \times 10^{-3})^2 + (-5.2224 \times 10^{-3})^2} \\ &= 7.3531 \times 10^{-3}AUday^{-1} = 12,723ms^{-1} \end{aligned}$$

A worthy point to note here is that both position and velocity vectors for X&Y are of similar magnitude, X is negative Y is positive so Jupiter on a map (where positive X points to the first point of Aries) is on the upper left hand quadrant , so the hypotenuse of the velocity vectors must be about 45 degrees.

For Saturn August 25th 1981 03:24
$X = -9.384918133243751AU$, $Y = -1.942986292275135AU$
$VX = 8.339297576096664 \times 10^{-4}AUday^{-1}$, $VY = -5.472528095240905 \times 10^{-3}AUday^{-1}$

$$\begin{aligned} V_{Saturn} &= \sqrt{(8.3393 \times 10^{-4})^2 + (-5.4725 \times 10^{-3})^2} \\ &= 7.1831 \times 10^{-3}AUday^{-1} \end{aligned}$$

From hereon we will specifically look at the journey of Voyager 2 to Jupiter. Launch was on 20th August 1977 14:29 UTC and nearest point to Jupiter was on 9th July 1979 22:29 UTC , which is 688.3 days. Tha arrival point may also be considered as to where the subsequent journey to Saturn began, for which to succeed required that the spacecraft be travelling faster than the escape velocity, previously calculated above as $19,864.44ms^{-1}$.

We have already discussed the need for a Heliocentric transfer orbit and on arrival, due to the gravity of Jupiter, the velocity will increase massvely during the final JAO stage, to almost precisely what we need to go on to Saturn. However what was calculated was the theoretical minimum, not the velocity that Jupiter will actually give us as its gravity causes us to accelerate ever closer. The question thus arises, how long do we spend once inside the SOI to get to the nearest point? We know that to escape and continue to Saturn we need to attain $> 19,864.44ms^{-1}$ at the planned nearest point of arrival and we also know the radius of the SOI but so far we have no idea of of the likely ship velocity or position vectors upon arrival at Jupiter's SOI. Furthermore we have been looking at time of closest arrival (9th July) but what we need to do is find time of arrival at SOI plus position and velocity vectors for both planet and ship. For this we need to get an idea of time between entering SOI and closest point and then wind the epherimedes clock back to a previous date and time.

For simplicity, at this point, I will conveniently ignore the fact that Jupiter's gravity will have been altering our heliocentric trajectory a long time before we ever reached the SOI boundary. The next difficulty is that if we leave Jupiter too fast we will miss Saturn and pass ahead of it, by contrast if we leave too slowly we will again miss Saturn and pass behind it. I hope you are getting a real sense now of how complex designing these orbits must have been all those decades ago and remain so even now.

Using a method which is outlined in "More Spaceflight Theories", I have previously calculated a sample JTO which gives ship velocity magnitudes of $38,126.33ms^{-1}$ at the departure point from Earth's SOI and $6,602.84ms^{-1}$ upon arrival at Jupiter's SOI. Now these numbers are velocities with respect to the Sun, however the escape velocities are with respect to the planet, which is moving at $12,723ms^{-1}$. There is another twist here in that these velocities are simply magnitudes, to get a sense of direction and relative velocity we must look at the components of each velocity vector. So from Jupiter's ephemerides we have $VX = -5.1763448523621 \times 10^{-3} AUday^{-1}$, $VY = -5.2223811415995 \times 10^{-3} AUday^{-1}$ and the calculation from the orbit app for the spacecraft gave us $V2X = -1,121.3ms^{-1}$ and $V2Y = 6,506.93ms^{-1}$.

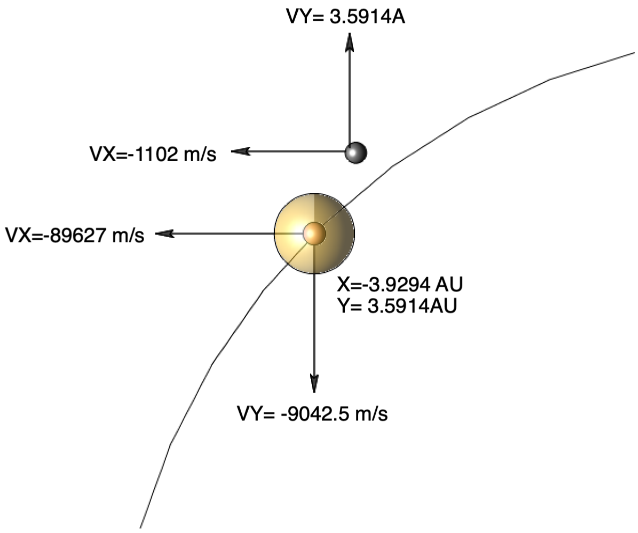
For Jupiter VX is negative and for the spacecraft V2X is also negative (so they both travel in the same X direction) VY is also negative but V2Y is positive so motion along the Y axis is opposite). The ephemeris tables gave us values in $AUday^{-1}$, whilst the app' delivered its results in ms^{-1}. Since spacecraft velocities are calculated to accuracies of ms^{-1}, we must now normalize the planet's velocity components to be in the same units.

From earlier : $1AU = 1.496 \times 10^{11} m$. Therefore :
$VX = -5.1763 \times 1.496 \times 10^{11} = -7.7437 \times 10^{8} mday^{-1}$ and
$$\frac{-7.7437 \times 10^{8}}{86,400} = -8.9627 \times 10^{3} ms^{-1}$$

$VY = -5.2224 \times 1.496 \times 10^{11} = -7.8127 \times 10^{8} mday^{-1}$ and
$$\frac{-7.8127 \times 10^{8}}{86,400} = -9.0425 \times 10^{3} ms^{-1}$$

Putting these two results into Pythag' gives us a resultant velocity at that point in Jupiter's orbit of $12,731.69ms^{-1}$.

We now need to know the relative velocity between Jupiter and our spaceship upon arrival at it's SOI. It helps here to look at the relative position and velocity vectors.



$VX + V2X = -8962.7 + -1,121.3 = -7,841.4$
$VY + V2Y = -9,042.5 + 6,506.93 = 15,549.43$

If we subtract the previously calculated Jupiter escape velocity $(19,864.44ms^{-1})$ from the arrival velocity $(6,602.84ms^{-1})$ and divide by two we get an approximation to an average velocity across the SOI of $6,630.8ms^{-1}$, the SOI of Jupiter is $0.327AU = 4.9289 \times 10^{10}km$ which if divided by the time gives us a flight duration from SOI to nearest point of 23.1 days. This for now will suffice as an approximation for which we can establish the arrival date at SOI as 9/7/1979 22:29 - 23 days 2.4 hours giving us an SOI arrival at 16th June 1979 20:00hrs UTC . We need to refer again to the ephemerides for this event and whilst there also obtain the ephemerides data for the Earth departure. The methods used in the following dialogue are approximations based on using a level of Mathematics that is more accessible to a broader audience i.e. you don't necessarily require a Degree or Doctorate in the subject to follow the mathematics and physics dialogue so most of the content should be readily accessible to older pre-university teenagers onwards to whom mathematics does not present an insurmountable challenge. Having said that I hope my style enables more general readers to simply follow the logic of the dialogue and essentially skip the equations, whilst preserving the general sense of what is going on. Now I should perhaps point out that those position coordinates at Jupiters SOI were largely a random choice and could have been chosen to concide with any longitude/latitude coordinates extended out from the planet to the point of SOI entry which would greatly affect the ship's arrival and departure characteristics. This is another level where further detail would need to be gone into for final development of the optimal mission profile.

Now here it is important to say that the ephemerides data is derived from a real conical orbit, not a circular simplification.

For Jupiter 16th June 1979 20:00hrs UTC, ignoring the Z axis :
X=-3.807848892555832E+00 Y=3.710051679564757E+00

VX=-5.351431011066396E-03 VY=-5.057282555759187E-03
Using X & Y as a baseline for the barycentre of Jupiter we now need to derive the X,Y coordinates for it's SOI at this time. We simply plug the above X,Y values into Pythagoras to calculate a hypotenuse which relates to the orbital distance of Jupiter from the Sun.

$$\begin{aligned} R_{Jupiter} &= \sqrt{(-3.8078)^2 + (3.7101)^2} \\ &= 5.3164AU \end{aligned}$$

we now subtract the radius of the SOI

$$5.3164 - 0.3297 = 4.9867AU$$

Now taking the ratio (derived to be used as a scaling scaling factor) and multiplying against the original X, Y coordinates

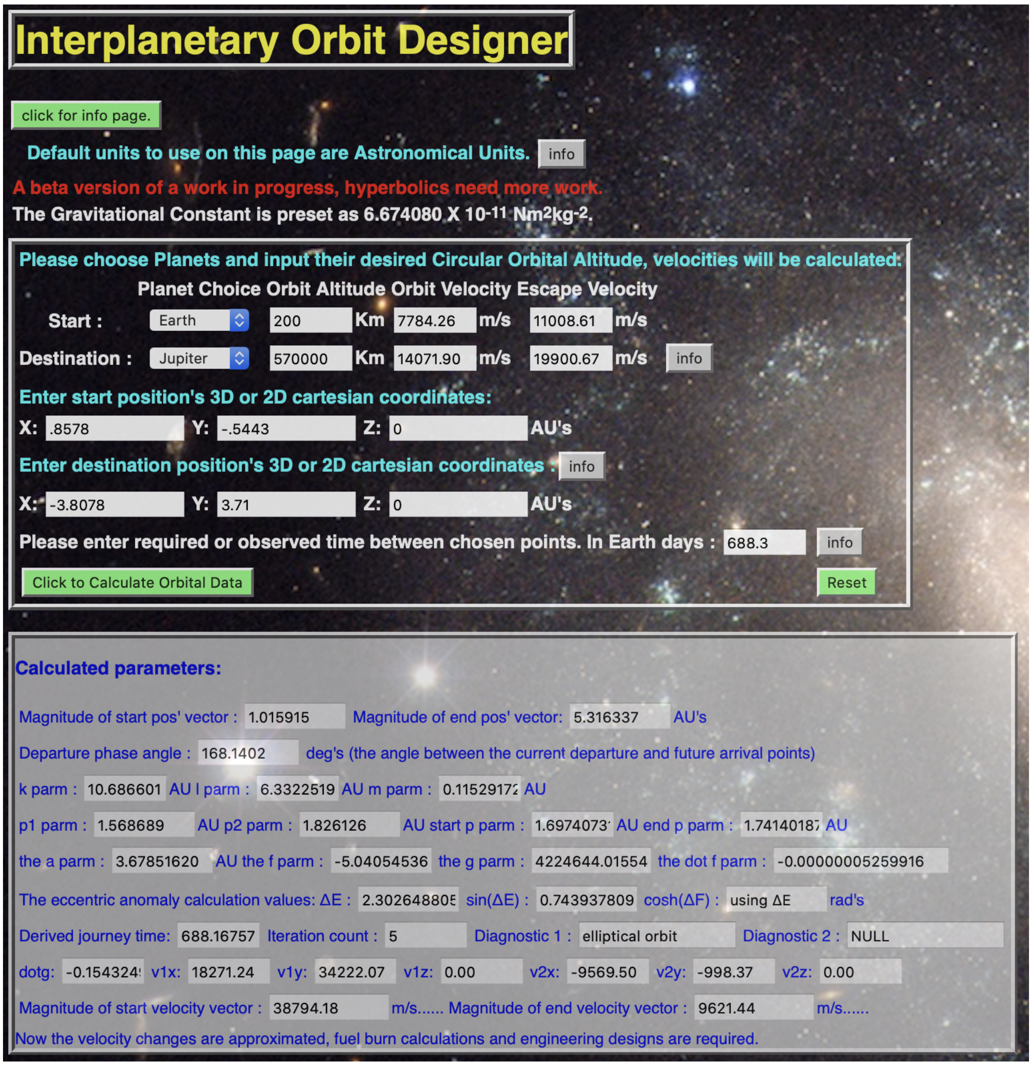
$$\begin{aligned} \frac{4.9867}{5.3164} &= 0.938 \\ X_{SOI} = -3.8078 \times 0.938 &= -3.5717AU \\ Y_{SOI} = 3.7101 \times 0.938 &= 3.4801AU \end{aligned}$$

These represent the 2D coordinates from the Sun for the point of arrival at the SOI.

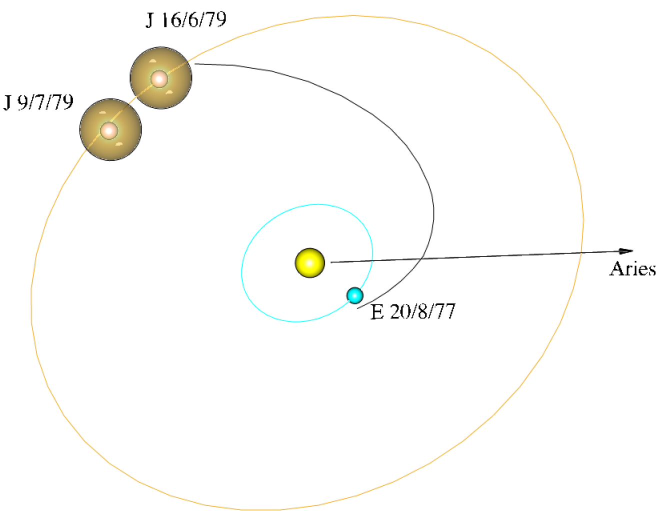
Earth departure 20th August 1977 14:29 UTC, ignoring the Z axis :
X = 8.578265504145067E-01 Y =-5.443016826865910E-01
VX= 8.905443368587378E-03 VY= 1.449097483788280E-02

For brevity I will ignore the fact that a real mission would calculate the departure point of a hyperbolic exit orbit as it crosses Earth's SOI and injects itself into the Heliocentric/elliptical JTO. The distance to this point is miniscule compared to the overall distance to Jupiter, however "in the real world" accuracy of both direction and velocity injection into the JTO was essential for the success of the mission.

Now combining the required SOI coordinates with the Earth exit coordinates and using the required journey time $688.3 - 23.1 = 665.2days$, I can plug this into my Javascript program (`http://rayhillwrites.com/orbits.html`) and evaluate the required orbit. Which gives us a departure velocity of $38,162.33ms^{-1}$ but more importantly, for the arrival phase, an arrival velocity of $6,602.84ms^{-1}$, having vector components $VX = -1,121.3$ & $VY = 6,506.93ms^{-1}$. The signs are very important in allowing us to understand the arrival angle, relative to both the Sun and the planet. The screenshot below shows the full results. To use this application generically simply select the start and end planet plus add required orbital altitudes, the velocity on the top two lines will later autocalculate. Then using the ephemerides information, from above, enter the x, y & z coordinates for the start and end point. Finally in the bottom right enter your ideal transit time, please be realistic, use some known past mission data. Finally click the green calculate button. Most of the output on the grey panel is interim results/diagnostic for the patch conic calculation steps. They key results are on the last three lines, journey time should be close to your orginal input, iteration count is just how many program loops it took for the result to converge to your journey duration target. The next line v1(x,y,z) gives start velocity vector magnitudes and v2(x,y, z) gives destination velocity vector magnitudes. Plus and minus values offer a sense of vector component direction. Therefore the last lines offer the required size of the start and end resultant velocity values which can then be used to evaluate the change in velocity that your spacecraft needs to be able to achieve at each end. From this last step you can then separately calculate the fuel burn and hence required size and mass of booster assemblies (see Spaceflight Theories for further information).



The before and after situation is approximated below.



The relative velocity vectors at SOI arrival are for Jupiter :
$VX_J = -0.005314AU/day = -9,201.1ms^{-1}, VY_J = -0.050573AU/day = -8,756.1ms^{-1}$
and for our spacecraft :
$VX_S = -9,368.14, VY_S = -1,802.8ms^{-1}$
If we now use normalised units and deduct the difference we obtain the relative velocities between Jupiter and our spacecraft.

$$\begin{aligned} VX_{JS} &= VX_J - VX_S \\ &= -9,201.1 - -9,368.14 \\ &= 167.04ms^1 \\ VY_{JS} &= VY_J - VY_S \\ &= -8,756.1 - -1,802.8 \\ &= -6,953.3ms^{-1} \end{aligned}$$

Then combine the results using pythagoras

$$\begin{aligned} V_{JS} &= \sqrt{167.04^2 + (-6953.3)^2} \\ &= 6,955.31ms^{-1} \end{aligned}$$

At the moment Jupiter appears to be racing away from us at $6,953ms^{-1}$, but for us to escape from its gravity field we need a difference of $> 60,000ms^{-1}$ at its surface, we are in fact a long way out so we can re-calculate escape velocity for the distance at SOI edge.

$$\begin{aligned} V_{escJupiter} &= \sqrt{\frac{2GM_{Jupiter}}{R_{Jupiter} + R_{SOI}}} \\ &= \sqrt{\frac{2 \times 6.673 \times 10^{-11} \times 1.8982 \times 10^{27}}{69,911 \times 10^3 + 49,322,418}} \\ &= 2,264ms^{-1} \end{aligned}$$

so we are in fact slowly being drawn toward it . As we get drawn in further our relative velocity will move through zero and then into negative values as we get ever closer.

JAO, the Hyperbolic approach orbit

At this point in time we know the relative velocities of the spacecraft and target planet and from history the nearest point r_p (periapse/perijove), we also know the mass of Jupiter and the gravitation constant. The formula below allows one to calculate the velocity magnitude at any point on a conic. Since we know our relative entry velocity and SOI radius we can re-arrange to calculate the semi-major axis, a

$$v = \sqrt{GM[\frac{2}{r} - \frac{1}{a}]}$$

Which may be arranged as :

$$a = \frac{-GM}{v^2} + \frac{r}{2}$$

Using known values of v and r :

$$\begin{aligned} &= \frac{-6.673 \times 10^{-11} \times 1.8982 \times 10^{27}}{6955.76^2} + \frac{0.3297 \times 10^{11}}{2} \\ &= 2.4662 \times 10^{10} metres \end{aligned}$$

We may now calculate the eccentricity, r_p is the given historical closest point.

$$\begin{aligned} e &= 1 + \frac{r_p}{a} \\ &= 1 + \frac{570,000,000}{2.4662 \times 10^{10}} \\ &= 1.0231 \end{aligned}$$

The distance from focus of the ellipse (Jupiter) to the orgin of the hyperbola is calculated as follows

$$\begin{aligned} J_0 &= ae \\ &= 2.4662 \times 10^{10} \times 1.0231 \\ &= 2.5232 \times 10^{10} metres \end{aligned}$$

Let r_p be the distance from planet to vertex (perijove)

$$\begin{aligned} r_p &= ae - a \\ &= 2.5232 \times 10^{10} - 2.4662 \times 10^{10} \\ &= 570,000,000 metres \end{aligned}$$

This may alternately be calculated using :

$$r_p = a(1 - e)$$

So the last value is the perijove which matches precisely the published history of nearest point. Which is very encouraging because it validates the correctness of the math' process used so far.

We now need to calculate the angle η, of the arrival asymptote to the origin along the hyperbolic x axis.

$$\begin{aligned}\eta &= \arccos \frac{1}{e} \\ &= \arccos \frac{1}{1.0231} \\ &= 167.8 degrees\end{aligned}$$

Conics have a construction line known as the semi latus rectum (or parameter) which is often useful.

$$\begin{aligned}p &= a(1 - e^2) \\ &= 2.4662 \times 10^{10}(1 - (1.0231^2)) \\ &= -1.1532 \times 10^9 metres\end{aligned}$$

The angle from the planets hyperbolic νx axis to the arriving body is calculated :

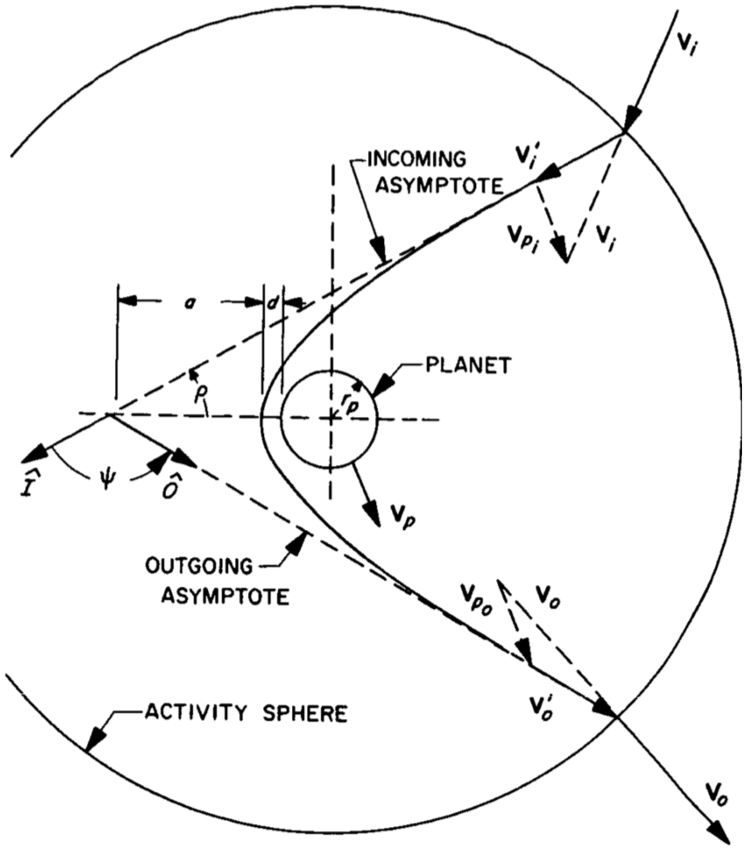
$$\begin{aligned}\nu &= \arccos \left[\frac{a(1-e)^2 - r_p}{er_p}\right] \\ &= \arccos \left[\frac{2.4662 \times 10^{10}(1 - 1.0231)^2 - 570,000,000}{1.0231 \times 570,000,000}\right] \\ &= 162.71 degrees\end{aligned}$$

From the above results we can do a hyperbolic drawing of the approach path. An actual NASA one is shown in the next section.

Gravity Assist

By the 1970's space launches had mainly become routine affairs, however required fuel and hence the size of boosters will forever remain an issue. The use of gravity assist avoids the need to carry excessive fuel so actually enables such missions to be affordable. To understand this we need to look at some orbital mechanics, yup, sorry you can't avoid the higher math' but the ongoing dialogue should also describe it well enough.

Whilst researching this topic I came across a key historical document from 1965, which discusses the possibilities for a grand tour of the outer planets, which really illustrates the ambitions of the time. I would urge you to look at this which can be found at `https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19660004267.pdf`, where pages 12-22 are relevant to this subject, but it is also worth scanning the table of contents which offer many historical insights into a far broader range of topics such as deep space communications, guidance technologies, etc. Unsurprisngly, for the period, it was classified. The diagram below is extracted from the original document, now declassified.



In a broader sense we travel in an n-body problem (n implies many gravitational bodies) which after ignoring trivial gravitational effects of all smaller and very distant bodies leaves us with a three body problem concerning the Sun, Jupiter and our spacecraft. The

Sun is still the dominant gravity force, keeping Jupiter in orbit, however as we get closer to Jupiter we can treat Jupiter and our spacecraft as a single subset system in which physical quantities (energy etc) are conserved, i.e we get back (reduce the problem) to a 2 body system which just happens to be moving in its own frame of reference around the Sun. So if we have, for the whole system, a momentum value as we arrive, the departure value must be the same, although,as will be shown, not necessary in the same parts of our system. So using $M_s \& M_j$ as masses of our ship and Jupiter and $V_{si}, V_{sf}, V_{ji} \& V_{jf}$ as initial and final velocities of each mass we can use Newton and momentum conservation then simplify by dividing by M_j as follows :

$$M_s V_{si} + M_j V_{ji} = M_s V_{sf} + M_j V_{jf}$$
$$V_{jf} - V_{ji} = \frac{M_s}{M_j}(V_{si} - V_{sf})$$

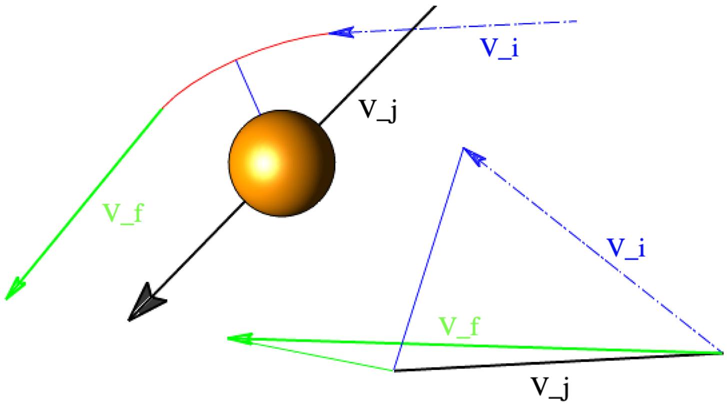
The mass ratio is very small, in the Jupiter case around 10^{-24}, so :

$$V_{jf} = V_{ji} = V_j$$

The above didn't really tell us very much apart from justifying the fact that any changes to Jupiter's velocity are trivial and may be ignored. However if there is any change at all, which we intuitively know there must be because of acceleration due to gravity, there would be a very noticeable affect on the velocity vector of our ship whereby $V_{sf} \approx V_{si} + V_j$, which at least helps us set a likely boundary condition indicator. As we might have previously expected, the baseline velocity of Jupiter doesn't change, at least for a small part (a few days) of its overall 11 year (near circular elliptical) orbit, which may therefore be simplified and considered to be an arc of circle, but in the limit approximating to a straight line.

Now in conservation of energy and momentum, the mass of all bodies must be invariant. But we do know that final velocity increases so clearly the ship must be adopting some of the velocity of Jupiter as gravity accelerates it towards the planet. This implies that only the variant quanties of velocity have changed so Jupiter must have slowed down, but as Jupiter is around 10^{24} more massive its velocity change will not be enough to cause a collapse of the current harmony of our solar system. As a rough approximation, if the ship is arriving at Jupiter at $10Km^{-1}$, with respect to the Sun, and Jupiter's motion around the Sun is around $12Kms^{-1}$, we might be temped to expect our ship will adopt a velocity relative to the Sun of $22Kms^{-1}$, however as it passes Jupiter it will be slowed down fighting for its escape from the SOI. So that was a fairly simple explanation of the dynamics, but it would be nice, in fact essential. if we could calculate the final velocity and angular changes so we know where the ship is going next, hopefully toward Saturn.

We need to bear in mind that as the ship approaches Jupiter, within its sphere of influence, the path with tend from being a straight line asymptote into a hyperbolic flyby of the planet. Providing the velocity is greater than escape velocity (for a given altitude), the final departure will also be an asymptote which later tends toward a curve as the effect of Jupiter's gravity decreases and that of the Sun again becomes the dominant force. The subsequent velocity out to the next planet should always be greater than the ship's escape velocity from it's evolving distance from the Sun, otherwise it will curve back toward the Sun before the next planet's gravity is close enough to begin taking effect.



The diagram above approximates the arrival trajectory for Voyager 2 at Jupiter. This can be broken down into two velocity vector triangles for both the initial and final phases, using Jupiter's velocity vector as a common baseline. Here the velocity vector of Jupiter is modelled as a straight line, but in reality it is curved around the Sun, the level of curvature would be in proportion to the time and distance the flyby takes. The angle between V_i and V_j is labelled α_i that of V_f and V_j is labelled α_f, the difference between these two is the directional change (deflection) that takes place, $\beta = \alpha_i - \alpha_f$.

Now at this point we can go around in many circles trying to patch two orbits together, whilst we can build something that works mathematically, is it truly representative of the situation that actually happens as determined by the forces of nature? Whilst a mathematical solution can provide a pretty good approximation to help us design spaceships and likely fuel burn it becomes extremely complicated to account for the fact that the perfect mathematical orbital path gets progressively skewed as the gravity of Jupiter increasingly distorts the equations that descibe the conical intercept orbit at the start. What is really required is a solution based around incremental time changes that solves the effect that Jupiter has on the orbit as we get progressively closer. What we can do is to take our spaceship's position and velocity vector at a given start point and then calculate how the gravitational forces acting from both the Sun and Jupiter accelerate the ship (negatively and positively) through its journey there and also as it passes its point of closest approach and travels outwards. So what we can do on a computer is to step through time just using Newtonian vector mathematics of forces acting on a single moving object. Were it that simple? There is also the non-trivial problem that Jupiter is also moving. The next section describes a computer model that I built for this topic.

Orbital Dynamics - a 3 body problem

The previously discussed solutions worked well enough for an approximation and are very useful to gain an insight into injection velocities for the JTO and also are thus useful input to the rocketry and fuel aspects of the hardware design. However the limitations are that it while it is highly sophisticated it takes a rigid conic approach evolved from the Ancient Greeks and takes no effect of the way the target planet (plus its moons) will distort that cosy conic orbit as we get ever closer and its pull of gravity becomes increasingly significant. To get greater accuracy we would need to do a whole n-body re-calculation of a new orbit for each time increment, where choice of interval improves accuracy at an ever escalating cost in computation (days, hours, minutes, seconds even into a continuum) . Using this logic it is theoretically possible to build a Newtonian dynamical model of all the major bodies in the solar system going through time and even run the model backwards from a point in the future.

The best way to think of space travel after orbital injection velocity is attained is to treat each celestial object as a gravity well with analogy to a magnet. Each celestial object within the model will also be moving. A further misconception is that the prior methods made the assumption that our Sun is fixed, it isn't! Classically we take a visual approach to such problems, however if we switch the light off and visualize gravity wells in our mind we conclude a different story. Jupiter is huge; it and the Sun engage in a mutual tug-of-war where the barycentre is actually outside the Sun. Both objects therefore revolve around opposite sides of this barycentre. Well, even that is not strictly true as other planets also cause this barycentre to move, consider how that may effect solar events such as flares and mass ejection. The biggest example might be when Saturn and Jupiter are aligned on the same side thus causing the barycentre to move even further from the Sun, so it all becomes a highly complex many body ("n-body") dynamical system. The Earth must also be considered as part of this so as the solar systems barycentre moves so must the orbit of the Earth and it may even get closer to the Sun, meaning more heat and more gravity. The heat is obvious but maybe the gravity change contributes to motion inside the Earth's core which results in it heating up inside, the problem of global warming is probably not 100% due to human activity.

In space physics we usually ignore the mass of a spacecraft because it is infinitesimally small compared to even a moon. Imagining the problem as gravity wells we can consider the physical aspects that are parameters of Orbital Dynamics. These are for each celestial body : Mass, Position vector, Velocity vector and from the spaceship the accumulation of all the gravity vectors at constantly varying distances from the relevant celestial objects which cause it's Position, Velocity, Distance and Gravity vectors to change over time ($\Delta PVDG$).

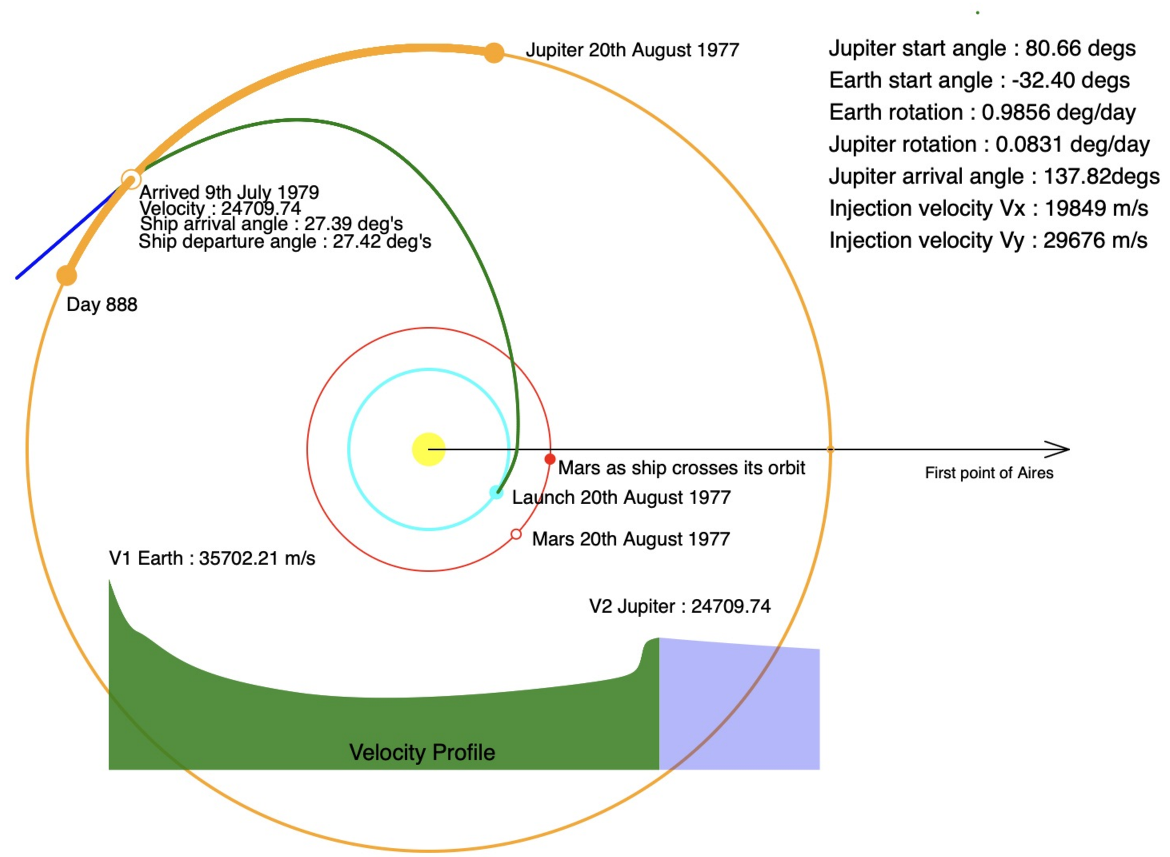
We can calculate each of these over a series of time intervals each of magnitude Δt, if we make this infinitely small we can theoretically model the whole problem as a space/time continuum. I have derived this process without external references to any published process, but doubt that the solution is completely original. Now the good thing about this is that while sounding grand it is also relatively simple and depends solely on a basic mathematical knowledge of vectors, Pythagoras' theorem, trigonometry (mainly excluding tangents) and on the physical side Newtonian gravity plus attributable velocity changes from the acceleration due to all gravity sources. In order to simplify the problem I have again taken historical positional data from NASA's Horizon ephemerides online system which gives the option to use the solar system barycentre as being of fixed reference for each date/time. For simplification I have treated Jupiter's orbit as being circular. I have also taken a 2D (x,y plane) view of the problem, ignoring the 3D z vector plane. Finally I have used $\Delta t = 0.5day$, which thus requires at least 1,378 individual calculations for a 688 day mission, using hourly intervals would require 16,512 calculations, moving closer to a continuum we could do millions even billions of calculations for progressively smaller time intervals. Iterating in a computer program means this is not that onerous a task. There are included other simplificatios such as ignoring solar pressure, gravity effects due to passage close to moons and ignoring the dimishing gravity of Earth as we enter the JTO. These problems are best left to the professionals with their super computer arrays. Wait, won't higher physics such as relativity be required? Well, since orbital injection velocity is a bit less than $3.6 \times 10^4 ms^{-1}$ and lightspeed is $3.8 \times 3 \times 10^8 ms^{-1}$, the difference in magnitude is around one ten thousandth, so we are only travelling around ten thousandth of the speed of light. Now one of the key determining relativity parameters, the Lorentz factor, is $\lambda = \sqrt{(1 - \frac{v^2}{c^2})}$ which after calculation using the above velocity values, $\lambda = 0.99994$, which for the purposes and accuracies within is close enough to 1. So for our purposes we may choose to ignore the relativistic effect. However, if we sat in a spaceship for thousands of years and approached the nearest black hole, life "as we know it, Jim" would become very different, more so as we crossed it's Schwarzchild radius.

The method outlined above is therefore a three body problem where just two of which (ship and Jupiter) are in motion. Creating a 3D solution "simply" involves calculating a complete (x,y,z) vector set for every parameter. As stated earlier the math is relatively trivial however I spent very many hours understanding how parameters moved from postive to negative values as the orbit passed through trigonometrical quadrants , then accounting for sines changing from positive to negative values and gravity of the Sun and Jupiter becoming accumulative instead of subtractive at distances (from the Sun) beyond Jupiter's orbit. This is a solution which also models the hyperbolic approach and gravity assist factors. Description of this method would be difficult for the average person who may not be familiar with computer languages, however it may be visualised at `http://rayhillwrites.com/jupitert3body12hour.html` which shows some of the important values and shows the non-ellipticity as we approach Jupiter and more significant the velocity boost and directional changes as we pass by, onwards to Saturn. The reader is free to save the HTML/Javascript page which may then be opened in a suitable text editor. If anyone wishes to copy and adapt, they are most welcome (there are plenty of improvements that may be made) you will also need the downloadable graphics module from JSGL.ORG placed in the same folder.

I acknowldge that although not a fully accurate solution, I believe the main benefit is to explain one such method to define an orbital trajectory and to build on an individuals understanding of space dynamics. Adapting the existing code and iterating at time intervals of 1 second would yield a far more accurate solution, however the main loop would need to to be iterated over 59,000,000 times. It would also be far better if the real set of coordinates for Jupiter's elliptical orbit (available on a hourly basis) were used, smaller time intervals could then be interpolated from the hourly differences in the X,Y & Z coordinates. However that is a lot of work and unless working on a real mission does not really add that much to our overall high level understanding.

The following diagram is a screenshot of the solution from the website.

The Historical Voyager 2 Mission to Jupiter.
Trajectory is modelled as a 3 body problem, calculated from the dynamic vectors of position, velocity and gravity.
Coordinate data is from NASA ephemerides (with respect to solar system barycenter).
Jupiter start coordinates X: 0.8262 Y: 5.0206 AUs.
Earth start coordinates X: 0.8578 Y: -0.5443 AUs, Journey Time : 688.2 days.
This shows the orbit (in Green to Jupiter, then Blue on to Saturn), after escape from Earth.
Mars distance from ship is always increasing from at least 0.5AU so its gravity is ignored.



So the previous section outlined the required science of orbital dynamics for this type of mission. Focus will now be shitfed to some of the technical aspects of the missions launched during the 1970's.

Power supplies

Without power to drive systems space travel is impossible. For the inner solar system much energy is supplied by solar cells. However received power from the Sun is measured in Wm^{-2}, as we get further away this power diminishes with distance and we can only compensate with larger solar panels to a point, they cannot ever be larger in mass than about 10 % of an Earth based launcher. It is impossible for the spacecraft to carry enough fossil fuel which just leaves us with nuclear power. The incredible thing is that large power stations only began in the mid 1950's, but by the mid 1960's, based on early experiments by Monsanto in 1954, isotopic decay technology had been miniaturised enough to be built into spacecraft. However the key distinction is that these generate energy from radioisotopic decay, not from nuclear fission reactions. The enabling factor is that a less radioactive atomic isotope may be used which requires far less heavy shielding. During my research I found a photo of Al' Bean removing such a unit (SNAP-27) from the Apollo 12 LEM on the Moon. This was required to power some external experiments, which would continue long after the astronauts were back home. However such devices would not yield enough power for a Mars based expedition of many months. Spacecraft also use additional similar systems as heat generators to keep equipment at workable sub-zero temperatures.

This briefly looks at the power units that were built into the Pioneers and Voyagers. Most of the information was taken from a 2006 paper that I found online written by G.L. Bennett for an IECEC conference.

A typical heat source is from the decay of Plutonium 238 which has a half life of 87.7 years, meaning that power output decreases by approximately 0.8 % per year. For the Voyagers the system begain life with an output of 470W, which by 2000 had decreased to about 392W. Thermo-electric generators are used to convert the heat from decay into electrical power, however these have low effciencies of below 7 %.

The Pioneers used 4 devices per spacecraft of model SNAP-19 these generated about 40 watts each, The Voyagers used 3 model MHW-RTG of about 158 watts each. SNAP is an abbereviation of "Systems for Nuclear Auxiliary Power" and MHW-RTG is for " Multi-Hundred Watt Radioisotope Thermoelectric Generator.

The following diagrams show the layout, mass, dimensions and power output of these systems. BOM is an abbreviation for Beginning of Mission

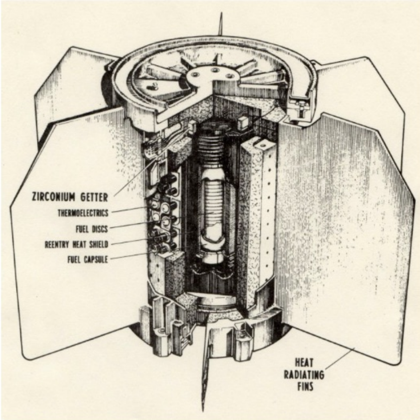


Figure 14. Cutaway of the Pioneer SNAP-19 RTG.
The height was 28.2 cm and the fin span = 50.8 cm.
The average BOM power was 40.3 We per RTG.
(TES)

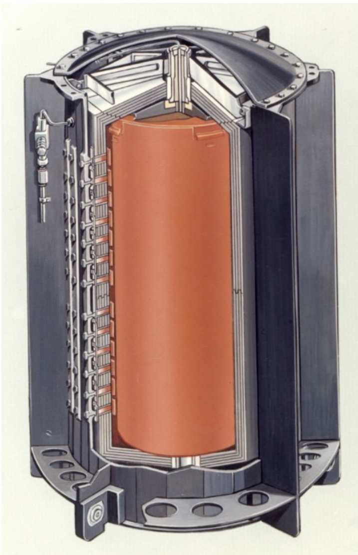


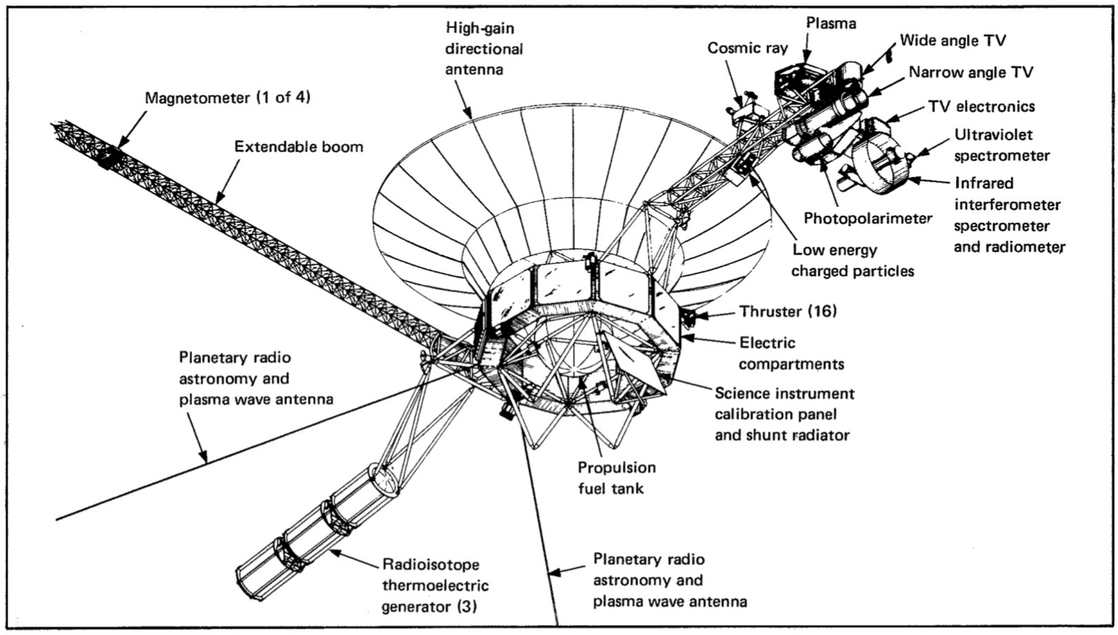
Figure 12. Cutaway of the MHW-RTG.
The length was 58.31 cm and the overall diameter was 39.73 cm. For LES-8/9 the average BOM power was ~154 We per RTG with a mass of 39.69 kg (avg.). For Voyager 1/2 the average BOM power was ~158 We/RTG with a mass of 37.69 kg (average). (GE)

This power is essential to maintain the basic spacecraft flight operation. The mission payback is maintenance of sensor operation, including cameras plus computation and data storage also plus telemetry for incoming flight commands, transfer of outbound status information and that most valuable outbound data transfer of imaging data and other less data intensive scientific sensor measurements.

Data Transfer and propagation delay

A significant problem with most space, travel even to the Moon, is propagation delay. This is dictated by the time it takes an electro-magnetic signal to travel through space at the speed of light. Depending on the distance between Earth and Jupiter, in their respective orbits, such delays are something like 35 to 52 minutes. As we travel further out into space it obviously increases to many hours. The implication here is that realtime command and control is impossible, so by the time we have recieved a status indicator from the craft and sent a suitable response well over an hour will have passed plus further time while we wait to get a response code indicating the success or failure of the command.

My Mariner 9 article covered the technology of transmission in some detail, so I shall not repeat. However, by the time the Voyagers had launched, X-Band technology was available. Success was of course due to the deep space network's ability with the 34 metre receiver dishes to recover and decode the very weak signals from the spacecraft and also to track it. The DSN would also be time-sharing for numerous other missions. Unlike most previous probes the ship's radio dish (3.7 metre) was larger than the spacecraft chassis, looking at the diagram (from a NASA preflight report) below you will see that, plus you will also see the RTGs and other equipment at the end of extremely long booms to keep any signal noise that they might generate as far away as possible from the radio and computing equipment.



The communications system operates in both S and X bands, S band consumes lower power and has a broader beamwidth but less bandwith, so is more suitable for receipt of telemetry data. S band data rate during cruise is from 2,560bps near Earth to 80bps near Saturn, slow yes but still 10 times faster than signals from the 8.3bps of Mariner

4 at Mars over a decade earlier and much closer to Earth. The data rate is increased to 7,200bps for engineering and non imaging science data. Using X-Band at Jupiter the data rate could be as high as 115,200bps and at Saturn 44,800bps, which meant that much better imaging data could be transmitted. When it was not possible to transmit signals in realtime the data was stored on a tape machine and played back later. This had capacity to store about 100 image frames. Communication was an essential part of the mission so redundancy was built in with two receivers, two travelling wave tube (TWT) amplifiers for X-band transmissison, plus a TWT and a solid state amplifier for S-band transmission.

Science packages on the Voyagers

In addition to the radio receivers and transmitters and also the obvious camera/imaging subsystem the package comprised the following instruments to collect data for further scientific investigation. The pre launch narrative within each sub section gives us a useful insight into some of the scientic research objectives, my narratives below are extracts from more detailed official reports produced by NASA/JPL, See appendix for document information.

Infrared Radiation

Infrared radiation comes from planets and their moons both by thermal emission and by the reflection of solar radiation. Beyond Mars, the temperatures of the emitting surfaces or atmospheric layers are so low that most thermal radiation is in the far infrared. Solar radiation is more intense at near infrared and visible wavelengths. Atmospheric gases have various absorption bands throughout the infrared, and the reflected solar radiation shows reduced intensities at some of those wavelengths. The effectiveness of particular absorption bands depends on the chemical composition and on pressure and temperature conditions. It is through these effects that the infrared radiation equipment acquires information on the composition and thermal structure of planetary atmospheres (including that of Titan) to complement that provided by the ultraviolet spectroscopy investigation. Infrared radiation from any moons with tenuous atmospheres contains information about surface composition, temperature, and thermal and optical properties, as well as atmospheric composition information. This package also obtained spectral data from Saturn's rings, permitting studies of their composition and radial structure, and of the size and thermal properties of the constituent matter. This system includes a radiometer that measures the total reflected radiation in the visible wavelengths and a portion of the near infrared wavelengths. In combination with the reflection and thermal emission information derived from the infrared spectra, this permits studies of the energy balances of the planets and their satellites. A prime objective was the investigation of the heat balances of the outer planets. Jupiter is known to radiate about twice as much heat as it receives from the Sun. Recent telescope measurements indicate that Uranus also radiates more heat than it receives, while at present the evidence on Saturn's overall heat balance is conflicting. The existence of an internal heat source such as Jupiter's bears on questions concerning the origin and evolution of the planets as well as the dynamics of deep atmospheres that are transporting heat outward, which in the case of the gas giants is a highly complex problem.

Photo-polarimetry

Non luminous objects become visible by scattering incident light. Imaging science has the function of resolving the scattered light to produce images, the function of photo-polarimetry is to provide information about the properties of light-scattering surfaces or atmospheric particles. It does this by measuring the intensity of scattered light at selected wavelengths and polarization angles. The light that the Sun radiates over a broad band of wavelengths is unpolarized. That is to say that the light waves vibrate equally in all of the infinite number of planes that are perpendicular to the direction of propagation. When this light is scattered by particles in an atmosphere or on a surface, the scattered light is polarized to some extent; i.e., the intensity of the light vibrating in some planes is higher than in others. With light that is completely plane polarized (by means other than scattering), the intensity is zero in the plane perpendicular to the plane of maximum intensity. By measuring light intensities separately through three plane polarizing filters oriented 60 degrees apart, a photo-polarimeter can determine both the degree and the plane of polarization. The Voyager instrument makes its measurements in eight discrete wavelength bands, ranging from 2,350 A in the ultraviolet portion of the spectrum, through the visible, to 7,500 A in the near infrared. It measures at 5 positions of the polarization analyzer wheel, so that a single observation comprises 40 measurements The main purpose of photo-polarimetry is to determine the physical and chemical properties of particulate matter in the atmospheres of the planets and other moons that may have thin atmospheres; and the surfaces of satellites that have little or no atmospheres. The rings of Saturn, which may be partly aggregations of very small satellites, will also contain small amounts of particulate matter.

Ultraviolet Spectroscopy

The outer planets, because of their strong gravitational attractions and low temperatures, retain even the lightest gases in their atmospheres. Thus, the atmospheres are probably close approximations of the original composition of the primordial solar nebula at their respective heliocentric distances. Atmospheric gases emit radiation at certain of the far ultraviolet wavelengths as a result of either the resonance scattering of solar ultraviolet radiation or excitation by bombardment with energetic particles. This “airglow” can be analyzed by a sufficiently sensitive spectrometer. When sunlight passes through the atmosphere, resonance scattering causes a reduction in the transmitted energy at those wavelengths. Most of the gases with which this investigation is concerned also have continuous absorption bands below some characteristic wavelength. A spectrometer aboard a spacecraft that is entering or leaving a planet’s shadow can analyze this atmospheric extinction spectrum by looking at the Sun. The Voyager ultraviolet spectrometer operated in both the airglow and solar occultation modes during encounters with Jupiter, Saturn, Uranus, and some of their moons. The ultraviolet wavelength band of the electromagnetic radiation spectrum extends from about 50 A to 4,000 A. The Voyager ultraviolet spectrometer analyzes the portion of the ultraviolet band between 500 and 1,700 A. This portion is the far ultraviolet. The primary objective of the ultraviolet spectroscopy investigation is to determine the concentration of the main constituents and the structure of the atmospheres of Jupiter, Saturn, Titan, and, possibly, Uranus. The atmospheres are believed to consist mainly of atomic hydrogen, molecular hydrogen, helium, and methane.

Radio Science

The success of these outer planet missions requires new levels of communications and tracking performance. Although the radio equipment is not especially dedicated to this investigation, some requirements have been upgraded to improve capabilities for radio science. Also, the spacecraft trajectories have been designed to provide radio occultations by the planets, the rings of Saturn, and Titan. As a planet is interposed between a spacecraft and Earth, the radio paths can traverse the planet’s magnetosphere, ionosphere, and atmosphere in turn. Each region affects the radio signal characteristics in its own way, so that it is possible to study its structures and disturbances from occultation data. Throughout the missions, the radio paths will be traversing the interplanetary medium. With two spacecraft (Voyager 1 & 2) in the same part of the sky at different distances, the radio signals will permit a study of the flow patterns of solar wind disturbances. When the paths lie near the Sun, the effects of the solar corona and the relativistic signal delay caused by the solar gravity field will be observed. One set of objectives is to investigate the structure of the atmospheres of Jupiter, Saturn, and Titan. This will be done by continuous measurement of the received frequencies and intensities of the radio signals from the spacecraft's S-band and X-band transmitters.

The atmospheric pressure of any planet's atmosphere increases as one descends toward the surface. That is the basis for the use of barometric altimeters in airplanes. The velocity of light (or radio) wave propagation, which is constant in a vacuum, decreases with increasing atmospheric pressure. To put it another way, the atmosphere's index of refraction increases with pressure, light rays passing through an atmosphere are refracted from a straight line path by the variation in pressure. When a spacecraft is entering occultation the rays are increasingly refracted, and the lengthening optical path produces a Doppler shift in the received radio frequencies. Refractive dispersion also reduces the intensity of the received signals as the angle of refraction increases. By cross checking the frequency and intensity measurements, it is possible to derive a profile of the atmosphere's refractivity. Then, with a knowledge of the atmosphere's composition and its temperature at some altitude (from data supplied by the mission's ultraviolet and infrared systems), the refractivity profile can be converted to temperature and pressure profiles.

Cosmic Ray Particles

Primary cosmic rays are charged particles that travel through space at speeds nearly equal to that of light. Most of the particles are protons: nuclei of hydrogen atoms, with a unit positive charge. Other cosmic ray particles are electrons and the nuclei of heavier atoms that have been stripped of all their electrons. Because of their velocities, the particles have very high kinetic energies, many millions or billions of electron volts. However, particles with energies over a billion electron volts are of little interest in space exploration, because they can be observed more conveniently at the Earth's surface. In addition to galactic cosmic rays, other charged particles of somewhat lower energies move through the outer reaches of the solar system. Some originate in the Sun, some in the solar wind, some in Jupiter's magnetosphere. Some, perhaps, come from sources in a nearby region of the galaxy. The Voyager cosmic ray particle instrument sorts the particles by charge, mass, and energy, and measures the variation in their number at different times, places, and arrival directions. This information makes it possible to study the sources of the various particle populations and the nature of the medium through which they have traveled. The objectives with respect to cosmic rays require measurements of the energy spectrum of the electrons, and the energy spectrum, elemental and isotopic composition, and the streaming patterns of the nuclei. Galactic cosmic rays are believed to come from a small number of source regions in our galaxy. The elemental and isotopic abundances among the cosmic ray particles carry information about the process of nucleosynthesis in supernova explosions, as well as information about the average interstellar distance the particles have traversed.

Low Energy Charged Particle

Three investigations study charged particles: the plasma particle, low energy charged particle, and cosmic ray particle investigations. The three complement each other in the energy ranges they can examine, and in the types of data provided. Collectively, they complement the magnetic fields and plasma wave studies in examining the structure of the planetary magnetospheres and the interplanetary magnetic fields. The low energy charged particle (LECP) investigation deals with particles of lower energy than does the cosmic ray particle investigation, although there is some overlap. There is a coverage gap between the low-energy end of the LECP range at about 10,000 electron volts and the plasma particle investigation range of 10 to 5,950 electron volts. Still, the LECP by itself can provide a great deal of information about the flow velocities and temperatures of hot plasmas when their densities are sufficiently high. The objectives of the LECP investigation fall into two broad groups: those concerned with particles in the planetary magnetospheres and near natural satellites; and those concerned with particles in the interplanetary environment. As a result of the Pioneer flybys of Jupiter, the general nature of the Jovian magnetosphere is known. The radiation belts have been located, and their electron fluxes have been observed to be unexpectedly high. The objective here is to fill in details such as the composition, energy range, and angular distribution of the charged particle radiation, to answer such questions as the origin, transport, and loss of the particles, the sources of radio emission, and the effects of the Galilean satellites. Recent observation of radio emissions from Saturn indicates a magnetosphere exists. Objectives of the investigation during the Saturn encounter are to study the extent of this magnetosphere and to determine the compositions, spectral and angular distributions, and fluxes of particles in various regions. The interaction of the magnetospheric charged particles with the satellites and with the material of the rings will be investigated. The nature of the radio emission will also be examined. The existence of a magnetosphere surrounding Uranus is also likely. Because the spin axis of Uranus will be pointing very nearly at the Sun in 1986 (encounter date), the interaction of a rotating magnetosphere with the solar wind should differ considerably from those at Jupiter and Saturn.

Magnetic Fields

Magnetic fields are everywhere in the solar system. Some planets have their own magnetic fields, presumably of internal origin. These include Mercury, Earth, and Jupiter. Recent radio data from the IMP-6 satellite indicate that Saturn, too, has a magnetic field. The interplanetary medium is traversed by streams of charged particles that constitute the solar wind, and by the shifting patterns of magnetic fields that they bring with them. The interaction of the solar wind with the planetary magnetic fields produces the various features of the planetary magnetospheres. Jupiter's inner moons, whose orbits lie within its magnetosphere, must likewise interact with it. Some of the moons of Saturn and Uranus probably do the same. Finally, the solar wind must interact with the particles and magnetic fields of the interstellar medium. The zone where this takes place, the heliopause, is at an unknown distance from the Sun. The magnetic fields investigation will gather data on all the fields encountered in the mission. Because of the extreme differences in the strengths of the planetary and interplanetary magnetic fields, the instrument employs both a low-field and a high-field magnetometer system. An important objective of the investigation is to measure the magnetic fields of Jupiter, Saturn, and Uranus. Since Jupiter's field has already been measured by magnetometers on the Pioneer 10 and 11 missions, the new measurements at that planet can provide a data base for studying any long term changes in the field. Pioneer 11 is expected to make the first measurements of Saturn's magnetic field as well, in September 1979.T

Plasma Particles

A plasma is a gas composed of charged particles. The gas as a whole is electrically neutral, or nearly so, but the positive and negative particles can be studied separately. Since the plasma particle investigation is one of three Voyager investigations dealing with charged particles, it is instructive to consider the differences. The plasma particles have lower kinetic energies than those measured by the cosmic ray particle and low energy charged particle instruments, and there are more of them. Whereas the other investigations are instrumented to count individual particles, the plasma particles investigation is concerned with the collective properties of the plasma's velocity, density, and pressure. The kinetic energy of a large number of particles can be considered as a group velocity. The instrument measures in the energy range from 10 to 6,000 V/charge. This corresponds to velocities up to about 1,000 km/sec for protons, and up to about 50,000 km/sec (one-sixth the speed of light) for electrons. By measuring the variation of group velocity with direction, the instrument determines the plasma flow direction.

Plasma Waves

Plasma waves are low frequency oscillations that have their origins in instabilities within plasmas. The plasma particles study provides information about the bulk properties and composition of the gases of charged particles,the plasmas that constitute the solar wind and the planetary magnetospheres. When examined more closely, plasmas exhibit instabilities of several kinds. There is turbulence in the flow of the particles, and the electrically neutral plasma carries local concentrations of positively and negatively charged particles. When these instabilities become oscillatory, plasma waves are generated. Plasma waves can be categorized as either electrostatic oscillations or as generalized electromagnetic waves of very low frequency. The Voyager plasma wave investigation measures only the electric field component. Although the frequencies of interest extend from about 0.01 Hz to about 100 kHz, the plasma wave instrument itself detects only the range of frequencies between 10 Hz and 56 kHz. The Voyager magnetometer can measure the magnetic vectors of electromagnetic plasma waves below 10 Hz, and the planetary radio astronomy instrument measures plasma waves with frequencies over 56 kHz. The plasma ions and electrons both emit and absorb plasma waves. These particle/wave interactions are known to affect the magnetospheric dynamics of the outer planets and the properties of the distant interplanetary medium, but they have not been directly observed in these regions. In general, they can only be observed by flying spacecraft through the interaction regions. Electrostatic plasma waves only propagate for short distances, and the propagation of electromagnetic plasma waves is also greatly restricted when the frequency is lower than the gyrofrequency (cyclotron frequency) of the ions and electrons. A main objective is to study the role of wave/particle interactions in determining the dynamics of the magnetospheres of the outer planets. Some of the effects are the heating of solar wind particles at the bow shock (the shock front sunward of the magnetopause), the acceleration of solar wind particles that produce high energy trapped radiation, and the maintenance of boundaries between the rotating inner magnetosphere and the streaming patterns in the outer regions.

Planetary Radio Astronomy

This investigation will measure the radio emissions of Jupiter, Saturn, and possibly other planets, both during planetary encounters and cruise. The power and time history of the emissions will be measured in 198 discrete narrow frequency bands in the range from 1.2 kHz to 40.5 MHz. A distinctive feature is the measurement of the polarization of the emissions, with the power in the right hand and left hand circular polarizations determined separately. Broadband planetary and solar radio emissions of thermal origin are noncoherent and unpolarized. The electromagnetic waves have random phase relationships and vibrate in all planes. On the other hand, nonthermal planetary emissions cover narrow frequency bands and are largely coherent. When the waves at a given frequency are in phase, it is possible to determine the direction of their circular polarization: the plane of vibration rotates either clockwise or counterclockwise as successive crests arrive at the antenna. Until the recent observation of nonthermal radio emission from Saturn (and possibly also from Uranus), all examples of planetary nonthermal emission came from the Earth or Jupiter. The polarization of terrestrial emissions is unknown, the Voyager planetary radio instrument will have the first opportunity to observe it. Jupiter's nonthermal emissions have a strong right handed polarization at most observed frequencies. While Earth-based radio astronomy observations commonly include polarization measurements, the Voyagers will be the first spacecraft to do it. A major set of objectives is to locate as closely as possible the sources of planetary emissions at kilometric, hectometric, and decametric wavelengths; and to seek explanations of their origin by correlation with data from other Voyager investigations. The powerful sporadic bursts from Jupiter that are modulated by the moon Io are mainly decametric.

The above is a small snapshot of the larger scientific endeavour encompassed within the programme. Of course the Voyagers are still trackable (as of 2020) and continue to collect data of interest, the latest major event being that of passing through the heliosphere.

Pioneer 10

The following text is extracted from NASA's website. My own notes are in italics.

Pioneer 10 was launched on 2 March 1972 on top of an Atlas/Centaur/TE364-4 launch vehicle. The launch marked the first use of the Atlas-Centaur as a three-stage launch vehicle. The third *(Centaur)* stage was required to rocket Pioneer 10 to the speed of 52,000 kilometers per hour (32,400 mph) needed for the flight to Jupiter. This made Pioneer the fastest manmade object to leave the Earth, fast enough to pass the Moon in 11 hours and to cross the Mars orbit, about 80 million kilometers (50 million miles) away, in just 12 weeks. *The Atlas had two stages(booster and sustainer, the Centaur was the 3rd.*

On 15 July 1972 Pioneer 10 entered the Asteroid Belt, a doughnut shaped area, which measures some 280 million kilometers wide and 80 million kilometers thick. The material in the belts travels at speed about 20 km/sec. and ranges in size from dust particles to rock chunks as big as Alaska. After safely traversing the Asteroid Belt, Pioneer 10 headed toward Jupiter. Accelerated by the massive giant to a speed of 132,000 km/hr (82,000 mph), Pioneer 10 passed by Jupiter within 130,000 km (81,000 miles) of the cloudtops on December 3, 1973. During the passage by Jupiter, Pioneer 10 obtained the first close-up images of the planet, charted Jupiter's intense radiation belts, located the planet's magnetic field, and discovered that Jupiter is predominantly a liquid planet.

Below is one of the first images taken of Jupiter by Pioneer 10, it clearly shows the limitation of the scanning capaiblities of imaging technology at that time.

The launch from Earth was into a solar orbit designed to intercept Jupiter at a pre-planned date and time.

Following its encounter with Jupiter, Pioneer 10 explored the outer regions of the Solar system, studying energetic particles from the Sun (Solar Wind), and cosmic rays entering our portion of the Milky Way. The spacecraft continued to make valuable scientific investigations in the outer regions of the solar system until its science mission ended on March 31, 1997. Since that time, Pioneer 10's weak signal has been tracked by the DSN as part of an advanced concept study of communication technology in support of NASA's future interstellar probe mission. The spacecraft had also been used to help train flight controllers how to acquire radio signals from space during the Lunar Prospector mission. The power source on Pioneer 10 finally degraded to the point where the signal to Earth dropped below the threshold for detection in its contact attempts on 7 February 2003 and 3 March 2006. The previous three contacts had very faint signals with no telemetry received. The last time a Pioneer 10 contact returned telemetry data was on 27 April 2002.

Pioneer 11

The following text is extracted from NASA's website. My own notes are in italics.

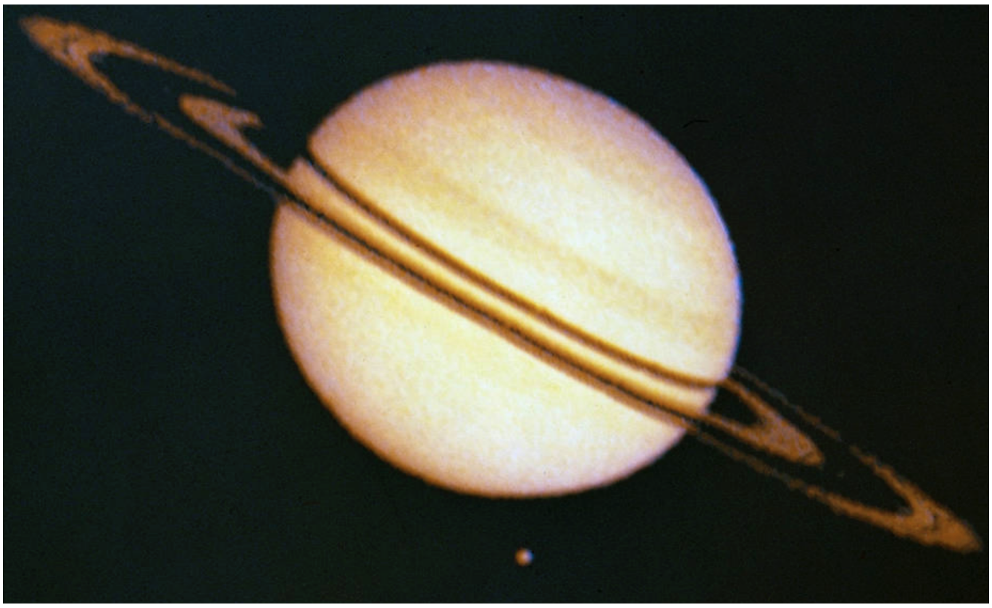
Pioneer 11 was launched on 5 April 1973, like Pioneer 10, on top of an Atlas/Centaur/TE364-4 launch vehicle. After safe passage through the Asteroid belt on 19 April 1974, the Pioneer 11 thrusters were fired to add another 64 m/sec (210 ft/sec) to the spacecraft's velocity. This adjusted the aiming point at Jupiter to 43,000 km (26,700 miles) above the cloudtops. The close approach also allowed the spacecraft to be accelerated by Jupiter to a velocity 55 times that of the muzzle velocity of a high speed rifle bullet - 175,000 km/hr (110,000 mph) - so that it would be carried across the Solar System some 2.4 billion kilometers (1.5 billion miles) to Saturn.

During its flyby of Jupiter on 2 December 1974, Pioneer 11 obtained dramatic images of the Great Red Spot, made the first observation of the immense polar regions, and determined the mass of Jupiter's moon, Callisto.

Looping high above the ecliptic plane and across the Solar System, Pioneer 11 raced toward its appointment with Saturn on 1 September 1979. Pioneer 11 flew to within 13,000 miles of Saturn and took the first close-up pictures of the planet. Instruments located two previously undiscovered small moons and an additional ring, charted Saturn's magnetosphere and magnetic field and found its planet-size moon, Titan, to be too cold for life. Hurtling underneath the ring plane, Pioneer 11 sent back amazing pictures of Saturn's rings. (http://quest.nasa.gov/sso/cool/pioneer10/graphics/lasher/slide4.html) The rings, which normally seem bright when observed from Earth, appeared dark in the Pioneer pictures, and the dark gaps in the rings seen from Earth appeared as bright rings.

Following its encounter with Saturn, Pioneer 11 explored the outer regions of our Solar system, studying energetic particles from our Sun (Solar Wind) and cosmic rays entering our portion of the Milky Way. In September 1995, Pioneer 11 was at a distance of 6.5 billion km (4 billion miles) from Earth. At that distance, it takes over 6 hours for the radio signal (which is traveling at the speed of light) to reach Earth. However, by September 1995, Pioneer 11 could no longer make any scientific observations. On 30 September 1995, routine daily mission operations were stopped. Intermittent contact continued until November 1995, at which time the last communication with Pioneer 11 took place. There have been no communications with Pioneer 11 since. The Earth's motion has carried it out of the view of the spacecraft antenna. The spacecraft cannot be maneuvered to point back at the Earth. It is not known whether the spacecraft is still transmitting a signal. No further tracking of Pioneer 11 was scheduled.

Below is a processed image of Saturn, below which is it's moon Titan. Taken by Pioneer 11, at a range 2.8 million km.



The Voyagers

The recorded source documents from NASA on the Voyager program runs to very many thousands of pages, I expect there is an equally similar quantity filed at participating academic institutes. For me it is a fair bit of largely pointless piece work to duplicate what already exists so I would urge people to download the referred to documents from NASA's ntrs server. The information there is obviously of original source quality so conveys much more useful information than I could justifiably do here on this short work. I admit to not having read them all and have simply scanned many just for specific information. Most of these documents are very readable and can be followed by people who do not necessarily need to follow the technical information.

Rather than summarise each spacecraft these extracts compile results from the whole programme.

Here is an extract from NASA's pre-launch summary document NASA-SP-420.

Foreword

THIS publication briefly describes the National Aeronautics and Space Administration's Voyager mission to explore the giant planets of the outer solar system–Jupiter, Saturn, and possibly Uranus. Our Pioneer 10 and 11 missions to Jupiter have already given us a brief glimpse of the majesty of that giant planet and its satellites. Based on that reconnaissance, the two Voyager spacecraft will now explore in more depth the characteristics of the Jovian system and make the first concerted reconnaissance of Saturn, its satellites and mysterious rings. If all goes well, we may get our first close look at Uranus almost eight years from now, extending man's presence nearer to the edge of our solar system. Just as Voyager is building upon results from Pioneers 10 and 11, these missions in turn will pave the way for orbital and atmospheric-probe explorations in the 1980s.

Voyager is an important incremental and sequential step in mankind's quest for knowledge about himself and his place in the universe. By comparing the outer planetary systems with each other, and with the terrestrial planets Earth (and its Moon), Mars, Venus, and Mercury, we will better understand how the solar system was formed, how it evolves, how life originated, and how the planetary environments are affected by the Sun.

NOEL W. HINNERS
Associate Administrator
for Space Science

June 21, 1977

Here is an extract (Page 127)f rom NASA's 1980 Voyager post Jupiter report NASA-SP-439.

JUPITER – KING OF THE PLANETS

A Star That Failed

More massive than all the other planets combined, Jupiter dominates the planetary system. The giant revealed by Voyager is a gas planet of great complexity; its atmosphere is in constant motion, driven by heat escaping from a glowing interior as well as by sunlight absorbed from above. Energetic atomic particles stream around it, caught in a magnetic field that reaches out nearly 10 million kilometers into the surrounding space, embracing the seven inner satellites. From its deep interior through its seething clouds out to its pulsating magnetosphere, Jupiter is a place where forces of incredible energy contend.

At its birth, Jupiter shone like a star. The energy released by infalling material from the solar nebula heated its interior, and the larger it grew the hotter it became. Theorists calculate that when the nebular material was finally exhausted, Jupiter had a diameter more than ten times its present one, a central temperature of about 50 000 K, and a luminosity about one percent as great as that of the Sun today.

At this early stage, Jupiter rivaled the Sun. Had it been perhaps 70 times more massive than it was, it would have continued to contract and increase in temperature, until self-sustaining nuclear reactions could ignite in its interior. If this had happened, the Sun would have been a double star, and the Earth and the other planets might not have formed. However, Jupiter did not make it as a star; after a brief flash of glory, it began to cool.

At first Jupiter continued to collapse. Within the first ten million years of its life, the planet was reduced to nearly its present size, with only a few percent additional shrinkage during the past 4.5 billion years. The luminosity also dropped as internal heat was carried to the surface by convection and radiated away to space. After a million years Jupiter emitted only one-hundred thousandth as much radiation as the Sun, and today its luminosity is only one-ten billionth of the Sun's.

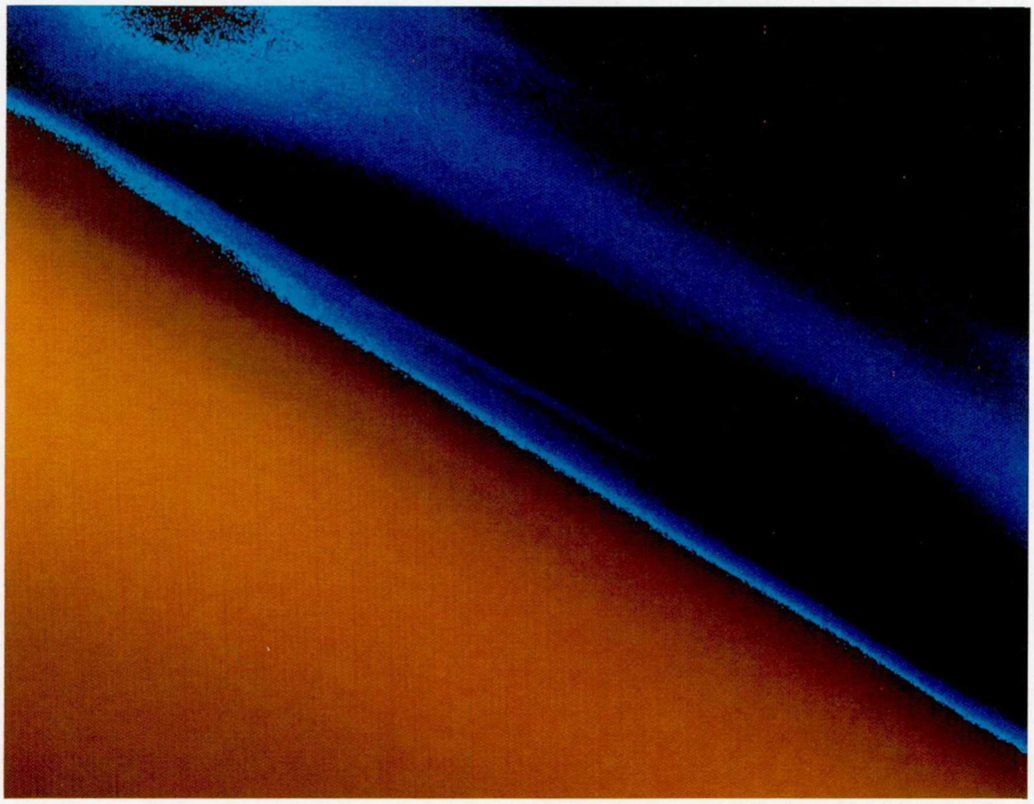
Jupiter's internal energy, although small by stellar standards, has important effects on the planet. About 10^{17} watts of power, comparable to that received by Jupiter from the Sun, reach the surface from the still-luminous interior. The central temperature is still thought to be about 30 000 K, sufficient to maintain the interior in a molten state. Scientists generally agree that Jupiter is an entirely fluid planet, with no solid core whatever.

Composition and Atmospheric Structure

Because of its great mass, Jupiter has been undiscriminating in its composition. All gases and solids available in the early solar nebula were attracted and held by its powerful gravity. Thus it is expected that Jupiter has the same basic composition as the Sun, with both bodies preserving a sample of the original cosmic material from which the solar system formed.

The primary constituents of Jupiter have long been suspected to be hydrogen and helium, the two simplest and lightest atoms. However, it has proved impossible to derive accurate measurements of the abundance of these two elements from astronomical observations. On

Here is an extract (Page 146) from NASA's 1981 Voyager post Saturn report NASA-SP-451. This illustrates the determination of some of Titan's chemistry, as such it really brings out the enormity of the knowledge derived and the quality of the post processed images.



This spectacular view of the edge of Titan was obtained by Voyager 1 from a distance of only 22 000 kilometers. Several tenuous high-altitude haze layers, which appear blue, are visible above the opaque red clouds. The highest of these haze layers is about 500 kilometers above the main cloud deck and 700 kilometers above the surface of Titan. (P-23107)

The Atmosphere

We can only speculate about the past history of Titan, but its atmosphere was subject to direct observation by Voyager. The ultraviolet spectrometer first detected a strong emission from nitrogen in the upper atmosphere, suggesting that this was the dominant gas and that its glow was excited primarily by the impact of electrons from the magnetosphere of Saturn. This emission extended to a height of about 1000 kilometers above the surface and was strongest on the side facing into the rapidly moving magnetospheric plasma. The power associated with this excitation is about a billion watts. Also visible at high altitudes is the ultraviolet glow of atomic hydrogen, which is a trace constituent of the upper atmosphere, having been produced by the action of sunlight on methane (CH_4). This hydrogen escapes from Titan at a rate of about 10^{27} atoms per second, spreading out around the orbit of the satellite to produce a huge torus of dilute hydrogen gas.

Our primary knowledge of atmospheric composition comes from the IRIS infrared spectra. The IRIS could not measure nitrogen, but it did detect methane (CH_4) and the more complex hydrocarbons ethane (C_2H_6), acetylene (C_2H_2), ethylene (C_2H_4), methylacetylene (C_3H_4), propane (C_3H_8), and diacetylene (C_4H_2). All of these

This extract (Page 18) from NASA's "To Uranus and Beyond" report NASA-EP-260. Gives shows the Uranian moons, the major interesting fact discovered about Uranus is that the magnetic poles are flat, so the planet effectively rolls around its orbital path like a ball and does not spin vertically in the sense of the others.

Voyager photographed each of the five large moons of Uranus known before the encounter: from the innermost out these are Miranda, Ariel, Umbriel, Titania, and Oberon. Ten additional moons were discovered by Voyager. The largest of the new moons is about 170 kilometers (110 miles) in diameter.

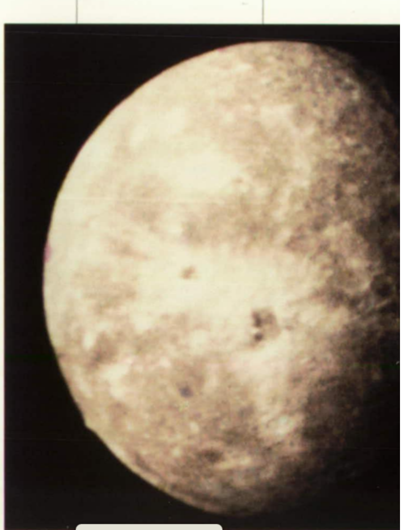
Titania is marked by huge fault systems and canyons that indicate some degree of geologic activity in its history. Ariel appears to have undergone a period of even more intense activity leading to many fault valleys and flows of melted methane ice.

Umbriel is ancient and dark, apparently having undergone little geologic activity. Large craters pockmark its surface, undisturbed since they were formed. The outermost of the pre-Voyager moons, Oberon, is also heavily cratered, with little evidence of internal activity other than some dark material covering the floors of several of the craters.

Titania is the largest of Uranus' moons and shows long, deep fault valleys across its surface.

ORIGINAL PAGE
COLOR PHOTOGRAPH

Umbriel's southern hemisphere displays heavy cratering. The face of this dark moon indicates a low



Oberon's icy surface displays several large impact craters. A large peak protrudes 20 kilometers (about

Information about the Neptune encounter seems hard to find. This website summarises the complete Voyager 2 mission https://solarsystem.nasa.gov/missions/voyager-2/in-depth/

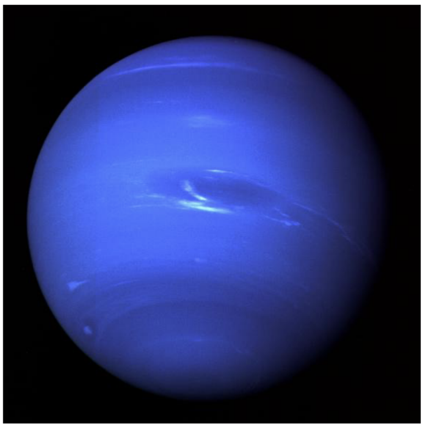
The image below is a sample from that website.

Neptune Accomplishments

Voyager 2 is the only human-made object to have flown by Neptune. In the closest approach of its entire tour, the spacecraft passed less than 3,100 miles (5,000 kilometers) above the planet's cloud tops.

It discovered five moons, four rings, and a "Great Dark Spot" that vanished by the time the Hubble Space Telescope imaged Neptune five years later.

Neptune's largest moon, Triton, was found to be the coldest known planetary body in the solar system, with a nitrogen ice "volcano" on its surface.



This picture of Neptune was produced from the last whole planet images taken through the green and orange filters on the Voyager 2 narrow angle camera. Image Credit: NASA/JPL

Interstellar Accomplishments

A gravity assist at Neptune shot Voyager 2 below the plane in which the planets orbit the Sun, on a course out of the solar system.

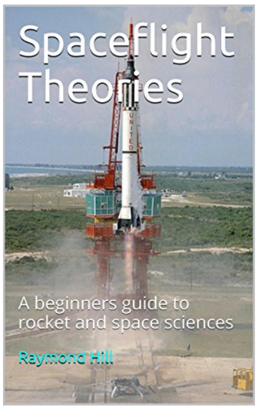
NASA announced in December 2018 that Voyager 2 had entered interstellar space, the second spacecraft to do so after sister ship Voyager 1.

As of July 2019, Voyager 2 continued to return data from five instruments as it travels through interstellar space.

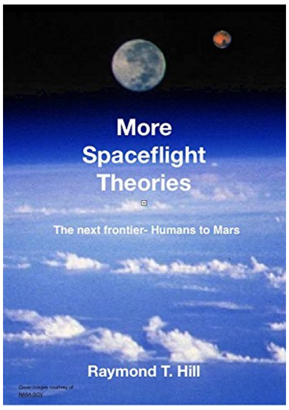
Eventually, there will not be enough electricity to power even one instrument. Then, Voyager 2 will silently continue its eternal journey among the stars.

Appendix 1 Further reading

I hope you have found this brief work of interest. There is far more information to be found on NASA and JPLs websites, some links are below in Appendix 2. If you want to know more about the fundamentals of space technology, which is of a moderate scientific and mathematical nature then I do have some e-books, details follow, which are available on Amazon. Please click on the required image, if you do wish to purchase any of these, you will need to navigate from this national site to your own national Amazon site, they are free to Amazon Prime subscribers.

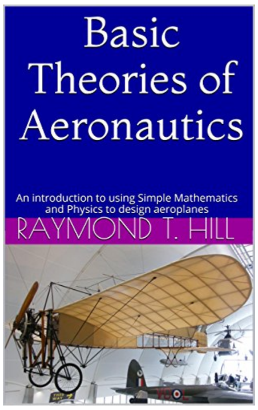


Spaceflight Theories



More Spaceflight Theories

Motorsport Theories



Basic Theories of Aeronautics

Appendix 2 NASA download links)

Jupiter Study (1966) https://ntrs.nasa.gov/citations/19660011615

Voyager Technical Design Report (1966) https://ntrs.nasa.gov/citations/19660011783

Orbit Planning NASA-SP-35 (1969) https://ntrs.nasa.gov/citations/19690024112

Mission contractor report (1977) https://ntrs.nasa.gov/citations/19770026289

Voyage to Jupiter ans Saturn (1977) https://ntrs.nasa.gov/citations/19770022102

Post Jupiter Overview (1980) https://ntrs.nasa.gov/citations/19810002402

Post Saturn review (1982) https://ntrs.nasa.gov/citations/19820018276

Neptune Travel Guide (1989) https://ntrs.nasa.gov/citations/19900004096

Pioneer mission overview (1990) https://ntrs.nasa.gov/citations/19900009039