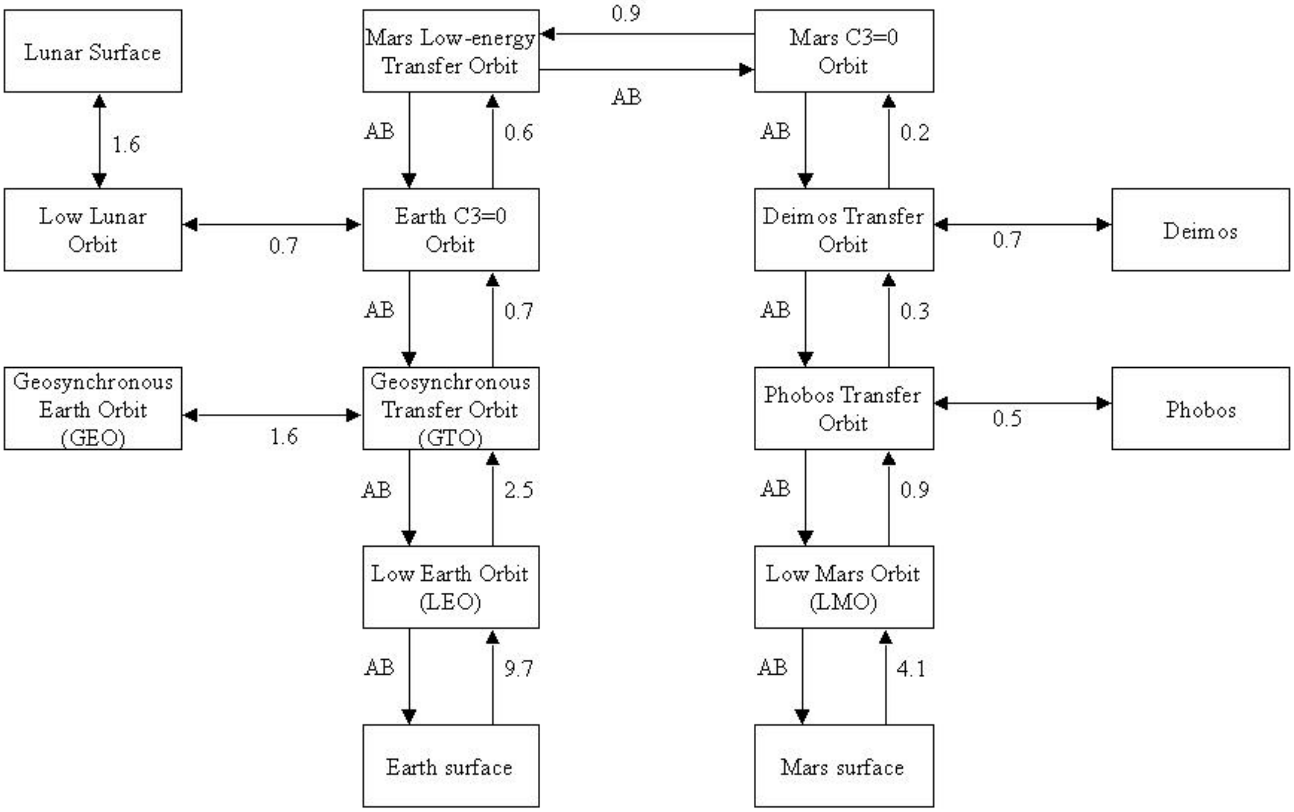
Rockets and Space Transportation

Delta-V in the Solar System

When a rocket flies from one planet to another, it typically fires a rocket engine to depart one planet, and perhaps fires another rocket engine to stop at the destination, but it can coast in between. Therefore, "miles," "kilometers," and other distance units are not appropriate for measuring the difficulty of space travel. The rocket's equivalent of the automobile's distance is the *Delta-V*, typically measured in meters per second (m/s) or kilometers per second (km/s). To get into Low Earth Orbit (LEO) from the ground requires a Delta-V of 9.7 km/s, meaning that if a rocket capable of launching into orbit is ignited in empty space, it will achieve a speed of 9.7 km/s when it runs out of fuel.

The Delta-V's separating various destinations can be calculated from orbital mechanics and are shown in the figure:



NOTE: "AB" implies that the atmosphere of a planet (Earth or Mars) can be used instead of a rocket to change the orbit.

Something should be said about each of these destinations. Low Earth Orbit (LEO) is where most space activity takes place; it has altitude approximately 250 miles (400 km). The Space Shuttle and Mir fly there, as will the International Space Station. Geosynchronous Earth Orbit (GEO) is an orbit at altitude 22,300 miles (36,000 km) above the equator, and is popular for communications satellites because the orbit period is 24 hours. Since the Earth's rotation period is also 24 hours, the satellite sits above one point on Earth's surface. Geosynchronous Transfer Orbit (GTO) has its low point at 250 miles altitude and its high point at 22,300 miles; as its name implies, it is used to transfer from LEO to GEO.

The highest-energy orbit around Earth is the C3=0 orbit, a parabolic orbit where the spacecraft has just enough energy to escape Earth's gravity. It is used to send spacecraft (e.g. the Lunar Prospector) to the Moon. Once the spacecraft reaches the Moon, it can enter lunar orbit or land on the lunar surface. If the spacecraft is given even more energy than it needs to reach C3=0, it can enter the Earth-Mars transfer orbit around the Sun.

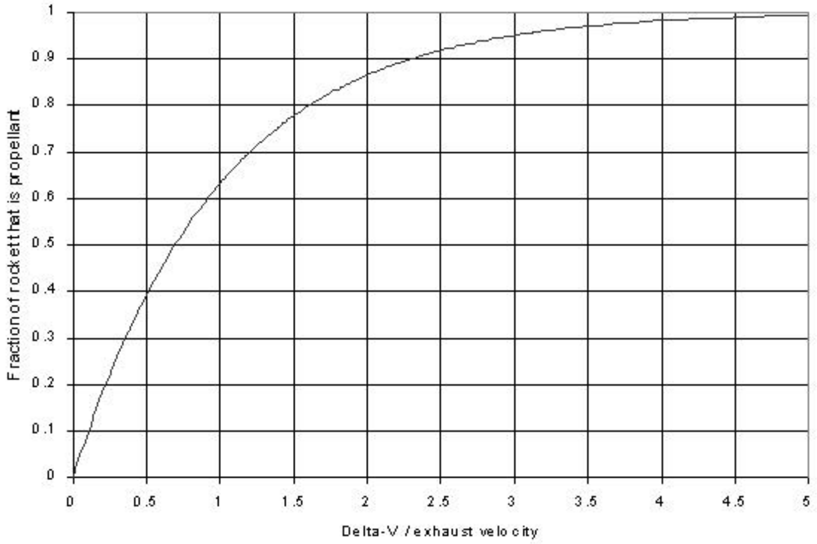
At Mars, the situation is very similar, except that Mars has two moons: Phobos and Deimos. Neither has a significant amount of gravity, so the Delta-V required to go from the surface of one of these objects into orbit around it or vice versa is negligible.

Rocket Performance

Having discussed the destinations in the Earth and Mars systems, and the Delta-V requirements for reaching them, we now examine the ability of rockets to move around in space. Just as the automobile's distance figures on maps are replaced with Delta-V figures on the chart above, so the automobile's "miles per gallon" figure is replaced by the rocket's "specific impulse." The specific impulse, or Isp, is measured in seconds and is given by the formula:

Isp (seconds) = 102 * [rocket exhaust velocity in km/s]

How "far" a rocket can go on the Delta-V chart is a function of its specific impulse and the fraction of the rocket that is propellant. For example, to achieve a Delta-V of 1.5 times the exhaust velocity, the rocket must be 78% propellant. Then the remaining 22% must be everything else - payload, fuel tanks, mechanical support structures, engines, fuel pumps, guidance computers, and anything else the rocket needs. Rather than give the formula for the fraction of the rocket that must be propellant to achieve a certain Delta-V, I will give a graph:



It is clear from the graph that if the Delta-V necessary is much larger than the exhaust velocity, the rocket needs to be almost all propellant. Therefore, high specific impulse (remember, specific impulse is proportional to exhaust velocity.) The question is, then, how high of a specific impulse can we realistically expect? The answer depends on the type of rocket we use. Below, I will discuss different types of rockets in existence (as well as some more futuristic ideas on how to get high Isp) and the specific impulses that can be achieved with them.

Rockets

Chemical Rockets

The oldest types of rockets are chemical rockets, in which two or more chemicals mix together, producing a chemical reaction. The reaction produces hot gases that are forced out a nozzle, pushing the rocket in the other direction. The specific impulse is:

Isp = 144 * SQRT [heat released (kJ/mol) / mass of products (g/mol)]

For example, the space shuttle main engine (SSME) uses hydrogen and oxygen propellants, with water produced as a product. Water has a mass of 18 g/mol, and its formation releases 242 kJ/mol of heat, so this reaction can produce an Isp of 528 seconds. In reality, the SSME can only produce

465 seconds, because it is not perfectly efficient. Some chemical rocket fuels that have been used or investigated are:

Propellant	**Exhaust**	**typical Isp (seconds)**
zinc/sulfur	zinc sulfide	240
aluminum/ammonium perchlorate	*	287 (Shuttle)
hydrazine/nitrogen tetroxide	*	313 (Shuttle)
ethanol/oxygen	water/carbon dioxide	330
methane/oxygen	water/carbon dioxide	370
hydrogen/oxygen	water	465 (Shuttle)

* Contains many chemicals in exhaust.

Thermal Rockets

A different approach to the problem is to eliminate the chemical reactions and supply energy to the rocket from a source other than the propellant. This increases the mass of the rocket, but it can make it more fuel efficient. In particular, note from the equation above that the lower the mass of the exhaust product, the higher the specific impulse. If hydrogen (the lightest gas) is used as propellant, and it is simply heated by solar or nuclear power, specific impulses of 800-1000 seconds are achievable. If the energy source is solar, the rocket is called a solar-thermal rocket (STR); if it is nuclear, the rocket is called a nuclear-thermal rocket (NTR).

During the Apollo program, NASA engineers built and tested several NTR rocket engines. Unfortunately, the NTR program was canceled in 1972, and it will be difficult to revive for many reasons. First, it is not absolutely needed to send humans to the Moon, Mars, Phobos, Deimos, or the asteroids (although it is the most efficient way to go there.) Second, the environmental aspects involved in any nuclear power program could delay any NTR-based program for years as pseudo-scientists and crazed "consumer advocates" declare "Thou shalt not split the atom" to be God's Eleventh Commandment. (See here for some perspective on nuclear energy and your health.) Third, nuclear power is politically unpopular, and attaching a space project to NTR could put the entire program at risk for cancellation.

In summary, thermal rockets hold great promise for space transportation because of their high potential specific impulses. It remains to be seen whether they will be selected for human flight to the planets, or if we will instead turn to another form of propulsion: the ion rocket.

Ion Rockets

The ion rocket does away with the hot, fiery blast of a conventional rocket engine. Instead, it uses a small electrostatic particle accelerator to accelerate ions to very high exhaust velocities. By doing so, it can achieve Isp of thousands of seconds. (The Deep Space 1 ion rocket, scheduled for launch in October 1998, has an Isp of 3000 seconds.) There are two catches, though: thrust and power.

Thrust: An ion rocket has very low thrust, meaning that it pushes a spacecraft very gently. On our Delta-V chart, therefore, its motion is analogous to that of a car that has a top speed of 5 mph, but can drive 200 miles on a single gallon of gasoline. Such a car is probably non-optimal in cities like Los Angeles (although the environmentalists would love it!) However, if that same car were supposed to travel from Los Angeles to New York, and there were no gas stations along the route, it would easily beat anything else on the highway. In this analogy, Los Angeles is like Earth, and New York is like Mars. Because of its low thrust, the ion rocket is unsuitable for lifting payloads off the surfaces of planets (e.g. driving in a major metropolitan area); however, the fuel consumption is so low that ion rocket can run for months or years on a single tank of propellant. In interplanetary space, it may be optimal.

Power: An electrostatic accelerator like that in the ion rocket requires a power supply. The power is very important: Deep Space 1's ion rocket uses 2300 watts of power, but only produces 0.02 pounds of thrust - and that is for a small robotic spacecraft! While such robotic spacecraft can travel around using solar-powered ion rockets, human spacecraft using ion rockets will need hundreds of thousands of watts for propulsion. In the inner solar system, the use of solar panels to accomplish this is difficult; after all, near Mars, a 25%-efficient solar cell array (about the best available) the size of a football field is required to produce 500,000 watts. In the outer solar system, solar-powered ion rockets are an utterly hopeless idea: that same solar array produces 50,000 watts near Jupiter; 12,000 watts near Saturn; 3,000 watts near Uranus; and 1,300 watts near Neptune. For outer solar system transportation purposes, ion rockets will need to be nuclear-powered.

Futuristic Rocket Propulsion Systems

High-Energy Chemical Propellants: One proposed way to increase the efficiency of rockets is to use higher-energy propellants. Some proposed systems (and specific impulses) are: hydrogen/fluorine (546 sec), hydrogen/ozone (580 sec), and beryllium/oxygen (710 sec). These all have problems; for example, the exhaust product of hydrogen/fluorine (hydrofluoric acid) is corrosive and eats rocket engines, liquid ozone is explosive, and beryllium is toxic.

Metastable Compounds: Another proposal has been to use metastable compounds or free radicals as propellants. These are usually self-destructing, and so it is difficult to use them as rocket propellants. Proposals have included atomic hydrogen, helium-based compounds, and several others; specific impulses could reach 2000 seconds.

Nuclear-pulse propulsion: This scheme was featured in the movie *Deep Impact*. It carries a set of nuclear warheads, which are detonated; the explosions push the spacecraft forward. It was briefly considered during the 1960s, but it became an international-treaty and environmental nightmare and was dropped. Specific impulse was projected at 5000 seconds.

Fluid-core nuclear rockets: In this idea, a magnetically confined cloud of uranium-ion gas (or large droplet of uranium liquid) undergoes nuclear reactions. It thereby heats hydrogen flowing by it to tens of thousands of degrees, ionizing it. The ionized hydrogen is then electromagnetically channeled through a nozzle. Specific impulse could reach 10000 seconds.

Fusion: Fusion has been the dream of many people for decades - the potential for a clean energy source. Unfortunately, it faces two major difficulties: first, the multi-million-degree temperatures at which it operates; and second, the relatively high price ($ millions per pound) of helium-3, the fusion fuel. Various schemes have been designed (but not carried out) for extracting helium-3 from the Moon, Mercury, or the giant planets. If these difficulties can be resolved, fusion rockets could reach Isp=2 million seconds.

Antimatter: Here we have the potential for rockets close to the maximum Isp allowed by Einstein's Special Theory of Relativity, 30,570,300 seconds (at which point the exhaust velocity is the speed of light.) Unfortunately, antimatter is currently expensive and dangerous.

Inertial propulsion, warp drives, wormholes, etc.: Science fiction always has a way around Einstein's special relativity and its universal speed limit of 299,792.458 km/s. Some of these ideas are standard in science fiction books and movies; most probably won't work, although we can't say that for sure. However, I don't want millions of my tax dollars spent on them given what we know now.