Rockets of the Future?

The gravity problem

Rockets were designed and built for centuries to project things horizontally over a greater range than could be achieved mechanically. Often it was gunpowder that was delivered; sometimes things like a crew rescue line to a boat swept onto shoreline rocks. Even the German V1 and V2 rockets of WWII were horizontal projection technology. All that changed after WWII and now rockets are first and foremost associated with space exploration and travel. Military rockets with their implied intentional destruction are usually called ‘missiles’.

Rockets built for space launches are huge constructions. Stand near to one and it towers skyward as high as a 15 story tower block. ESA’s ‘Ariane 5’ is 50 m high and weighs over 750 tonnes; the Russian ‘Proton’ satellite launcher is a comparable height and a little lighter at 690 tonnes; the Soyuz-FG used for taking astronauts to the ISS (International Space Station) is also about 50 m but ‘only’ about 300 tonnes, having less height to reach; the USA’s Atlas V rocket is 58 m tall and weighs in at 330 tonnes; the Indian space agency’s own rocket that has put a satellite in geostationary orbit is 50 m tall and has a mass of 435 tonnes. You get the picture. Think of the biggest lorry you’ve seen on public roads, fully laden. It’s got a pretty big engine just to pull it along. Imagine the engine that would be required to lift the whole thing into the air and keep lifting it upwards, kilometre after kilometre. Whatever engine you’ve imagined isn’t nearly enough for a satellite launch vehicle, for the lorry is less than $1/10^{th}$ of the weight of the larger rockets just mentioned.

Are today’s rockets bulky, heavy, the first steps in launching technology, the steam engines of the vertical transport world, or is the rocket scientist indeed an advanced thinker? The rocket is a solution to a problem. The problem that besets rocketry is weight. Not mass, but weight. A rocket of mass 20 tonnes sitting on a small asteroid has very little weight, so little that you could lift the rocket by hand if you were standing beside it in your space suit. That’s true. Launching 20 tonnes off a small asteroid a few km long would not be a difficult problem. On Earth 20 tonnes of mass behaves differently, as we all know. Gravity causes weight. Gravity is the rocket’s enemy.

Gravity brings two problems to rocketry. First it gives everything in its influence potential energy, in such a way that energy must be supplied to raise a body against gravity. Secondly, the thrust of the rocket must support its weight and then have something left over to accelerate it. Let’s look at potential energy first.

Sometimes gravitational potential energy is very useful. For example the potential energy in a lake behind a dam is partly used to make electricity when water from the lake runs downhill from the dam through pipes and turns a turbine generator. This is clearly gravitational potential energy working in our favour. The lower an object, the less its gravitational potential energy. In running downhill the water is losing some of its potential energy, which appears as kinetic energy of motion. In rocketry, the rocket is going uphill and its engine has to do work to give the rocket the increased gravitational potential energy its increased height demands. How much energy is that? The zero of gravitational energy is usually measured when the two objects involved (e.g. Earth and the rocket) are very far apart. With that zero, the gravitational potential energy of a rocket of mass m on the surface of the Earth (radius R_E = 6378 km) is $-mgR_E$. g is the usual gravitational constant on the surface, namely about 9.81 m s^{-2} on Earth. Put it another way, to get a rocket a very long way from the Earth, it needs to be given a total amount of energy of gR_E for every kg of its mass.

That's a lot of energy, because $g\mathrm{R_E} = 6.257\times10^7$ J kg^{-1}, or about 62.6 MJ for every kg of mass. A kilogram is the mass of a small bag of sugar. The energy required is about the same as the kinetic energy of a large diesel locomotive of mass almost 200 tonnes travelling at 100 km h^{-1} - all to get a measly 1 kg into 'outer space'. That energy given all at once to the bag of sugar would get its speed up to over 11 km per second. That's 11 km per second, not per hour, the kind of speed Superman is credited with when traversing Metropolis. "Is it a bird? Is it a plane?" 'No, it's a bag of sugar heading for space'. The energy needed is real, not fantasy. 1 kg is next to nothing in the serious rocket business. The Apollo spacecraft (lunar module, service module and command module) clocked up almost 100 tonnes, over and above the prodigious Saturn V (Roman 5) launcher. There's no getting around having to supply this amount of energy whatever technology is used, for it's fundamental physics. Not all rockets end up by going into distant space, though. We'll come back to that.

The second problem with gravity is that a rocket destined for space starts by sitting vertically and, initially at least, the thrust of its motors must support its weight. In contrast, cars for example sit on their wheels and the propulsion system doesn't have to support the weight; aircraft support their weight in flight using the lift generated by the atmosphere as they travel forward. Travelling on level ground, the biggest effect of air is to provide drag that limits our speed, whether we are going by bicycle, car, coach or train. Going uphill, gravity provides a backwards force aiding the air drag in slowing us down and it takes only a very modest hill for the effect of gravity to exceed that of air drag. With a rocket that's climbing more steeply than any terrestrial transport, gravity is the main force that the rocket's thrust must overcome.

To put a figure on the problem, if a car were to provide a thrust equal to its own weight, it would achieve an acceleration of g, or 9.81 m s^{-2}. Ignoring air resistance, it would go from 0 to 100 km h^{-1} in 2.8 seconds and after 10 seconds would be travelling at 350 km h^{-1}. Providing enough thrust to support the weight of a rocket is hugely energy expensive but doesn't get the rocket moving anywhere. It just stops it crashing to the ground. A rocket must provide **more** thrust than its own weight if it is to get off the launch pad.

(Rockets do get some lift from the atmosphere on Earth once they get going, for you'll see from pictures that they climb diagonally. There's an interesting balance of forces here. Rockets are heavy, they haven't got big wings (to reduce weight and drag) but conventional rockets do get faster with increasing height (because they are losing the weight of burnt fuel). However, the atmosphere gets thinner with height approximately exponentially, so what air lift they do get lower down peters out. Of course launching from a location with no air means that a rocket there gets no help at all from this effect.)

Rocket workings

Rockets work by ejecting material out of the back. This produces forward thrust in two ways. First, Newton's second law says that there is a thrust given by the rate of change of momentum of the rocket material, which boils down to the rate of flow of mass out of the back multiplied by the ejection speed. Secondly there is a force given by the excess pressure of the exhaust over the surrounding air, multiplied by the cross-sectional area of the exhaust. This second term improves at higher altitudes when the outside air pressure falls away. "Plan A" then, the method used in conventional rockets, is to load the rocket with chemically active fuel that when burnt produces high temperature gases that emerge under pressure, travelling rapidly.

Does it make a difference what gases emerge? Yes, it does, for a given exhaust temperature. The temperature dictates the kinetic energy of the exhaust gas molecules, given by KE = $\frac{1}{2}mv^2$. The momentum of a gas molecule is just mv which is $(2m\times\text{KE})^{1/2}$. So for a given temperature of exhaust gas, the lighter gas molecules are travelling faster but there is more momentum in heavier molecules. Doubling the temperature doubles the kinetic energy of the molecules but that only increases the speed of the molecules by a factor of √2. Hence for twice the input energy one has less than twice the thrust so in energy terms the engine is less efficient. However, to achieve twice the thrust for twice the energy one needs instead to burn twice the mass of fuel at the same temperature, and increased fuel mass usually means less payload mass. 'Rocket science' turns out to be a complicated balancing act of the many design factors involved.

Liquid oxygen and hydrogen burnt together to produce water vapour exhaust are more effective than most other fuels and have the advantage for off-world rockets that they can be obtained, in principle, by solar-powered electrolysis of local water and subsequent (solar powered) refrigeration. However, to make and store liquid hydrogen requires serious cryogenic technology and large tanks, so liquid rocket fuel is more usually kerosene and liquid oxygen. If you'd like a few figures for commonly used rocket fuel then liquid oxygen and hydrogen provide exhaust velocities of about 4400 m s^{-1}; liquid oxygen and kerosene, about 3500 m s^{-1}; nitrogen tetroxide and hydrazine (N_2O_4 & N_2H_4), both liquids at room temperature but highly toxic, about 3400 m s^{-1}; solid propellants about 2500 m s^{-1}.

So how much gas must be emitted to support a rocket of 1 tonne weight against Earth's gravity? Suppose we can manage an exhaust speed of 4000 m s^{-1}. To support a 1 tonne rocket (weight = 1000 × 9.81 = 9810 N on Earth) requires a thrust equal to its weight and if this is mainly provided by the rate of change of momentum then the momentum per second of the exhaust must equal 9810 N. i.e. the mass m of the exhaust emitted per second is given by $m \times 4000 = 9810$, or $m \approx 2.5$ kg s^{-1}. Perhaps this doesn't sound much, though of course one tonne is little by space rocket standards. It's a very rough figure. One tonne is the weight of a small car, whose tank holds about 40 kg of fuel. Burnt at the rate of 2.5 kg s^{-1} (using oxygen from the air if that were possible), a tank of fuel would last about 16 seconds, which highlights that rockets are monster gobblers of fuel. The power required can be estimated. 40 litres of petrol (which is less energetic than rocket fuel) contains about 0.4 MW h of energy. Expending this in 16 seconds represents a power usage of 90 MW. A lot of the energy of the fuel is wasted as heat. Remember that this fuel merely supports the rocket against gravity; much more fuel is needed to get the rocket rising steadily to overcome the large negative gravitational potential energy that the rocket starts out with on Earth.

Science fiction stories sometimes have rockets squirting out light instead of gas – the photon drive. Will that work? Photons travel at the speed of light, obviously, which is $c = 3\times10^8$ m s^{-1}, much faster than 4000 m s^{-1}. So far so good. However, photons are very light, no pun intended, with an effective mass E/c^2, where E is their energy. This gives them a momentum of E/c. Their high speed c actually counts against them. A 10 kW laser, for example, the largest now commercially available, generates a beam of photons with momentum $10^4/3\times10^8 = 3.3\times10^{-5}$ kg m s^{-1} every second. Squirted out the back of a rocket this would provide a thrust of 3.3×10^{-5} N, a pittance. A 10 MW laser, 1000 times the power, if it didn't fry its own optics would still give next to no thrust. A 10 MW gamma ray source would be just the same (but emit fewer photons). 300 MW per Newton is the photon energy you need for your thrust and a 100 tonne rocket needs around a million Newtons just to stop it crashing to the ground once released from its launch tower. Don't put your faith in photon drives, at least not for Earth launches. Fine jingo, no substance.

To return to reality, one final point to set the scene is to mention that rocket engines may be simple in principle but are complex in practice and quite weighty. They have to supply fuel at a controlled rate, burn it at temperatures exceeding that in almost all furnaces (around 3000 K for high efficiency) in carefully designed chambers that provide burn stability, and eject the exhaust through a refractory nozzle that will support the huge stresses involved and optimally shape the exhaust plume. An important figure of merit of an engine is its thrust to weight ratio. If this is say, 20 (a respectable figure) then it can't lift a total load including all the fuel of more than 19 times its weight. This figure sets a limit on fuel and payload.

While on the subject of basic physics, I'll add a paragraph or two on 're-entry'. Have you wondered why the space shuttle needed to be covered in fantastically heat-resistant tiles, or the Apollo re-entry craft came down backwards so that some of its back surface could be ablated by the immense heat generated during re-entry? None of this was necessary for leaving the Earth so why was it necessary in returning? The answer is again simple physics with some numbers added. The downside to this is that since the issue is governed by basic physics, we're going to be hard pressed to do much better or do it much differently in future. On the way up there are three forces acting on the rocket, the thrust of the engines, the downward pull of gravity and the aerobraking force. The first two almost balance, with the edge going to the thrust so that the rocket rises. At first it rises very slowly but even when it's gained speed it doesn't travel faster than a jet plane when it's in the lower atmosphere so it needs no more than standard technology to keep the heat from destroying it.

The difference between going up and coming down is that for most of the coming down there is no rocket to counteract gravity's pull. In a sub-orbital flight, the kind being targeted for space tourists, the rocket goes up, along and comes down. A moderate speed (in rocket terms) along in the upper atmosphere won't produce excessive heating. The potential energy of a mass 100 km high is about 10^6 J kg^{-1}, which in the absence of an atmosphere would give the rocket a speed of 1 km s^{-1} as it hit the ground. The atmosphere must dissipate this energy and if that is done over a distance of 1000 km then the atmosphere has only to absorb 1 J m^{-1} on average. In a descent from orbit the rocket, or starting capsule, has the speed needed for orbit as well as its gravitational potential energy. The ISS, for example, at about 400 km altitude is orbiting at a speed of 7.7 km s^{-1} and it has 4 times the gravitational potential energy of a sub-orbital rocket. In reality, 7.7 km s^{-1} is fast. The astronaut Chris Hadley said that looking out from the ISS *your speed is so high it's like nothing you've ever experienced in your life. You go around the world in 92 minutes.* If you jumped out of a sub-orbital flight, you would eventually hit the ground. If you jumped off the ISS, you'd just continue in orbit at a similar height. A capsule returning from the ISS has to get rid of kinetic energy equivalent to over 10 km s^{-1}. That's a hundred times the energy of a sub-orbital flight, since energy depends on v^2. Some braking is done by rocket motors but to make the coming down the reverse of going up would need engines as big as those needed for launch. It can't be done in the gravity of Earth. Aerobraking has to be used. This is why the re-entry module experiences temperatures of thousands of degrees and without some form of well-conceived protection the occupants will be toast, or worse.

Can rockets be different?

If you look at pictures of one of the Saturn V rockets that took men to the Moon in the early 1970s (or are lucky enough to see some of the hardware still on display in the States) you'll see that the Saturn V was gigantic: 110 m tall, weighing almost 3000 tonnes. The 5 kerosene and liquid oxygen F-1 engines of the first stage developed 180 million horsepower, over 3000 tonnes of thrust (obviously) and consumed over 2 million kg of fuel in two-and-a-half minutes, all to get 3 men weighing less than 300 kg and some hardware on the first stage of their journey to the Moon. I'm simplifying it a bit but will serious space travel in future need to reproduce comparable rocketry?

You'll have seen by now that rocket design is quite strictly circumscribed by fundamental physics. The fuel load is the biggest issue with rockets. The payload one wants to get up is typically only a few percent of the weight of the whole rocket. If automobiles were like that, a car weighing 1 tonne would not be able to transport more than say 20-30 kg, about the weight of a case and a half of wine; no drivers heavier than an average 7 year old, please, and no passengers or luggage.

When the Apollo launch vehicles were being developed in the 1960s (Saturn I, Saturn IB and Saturn V), plan A2 was not only on the drawing board but was being prototyped and tested. This was to ditch the chemical fuel used to create the high-temperature, high-speed rocket exhaust and use hydrogen alone, heated by on-board nuclear reactor. A uranium powered nuclear reactor can easily reach the highest temperature of a hydrogen-oxygen burn. In fact a nuclear reactor can easily reach a temperature at which the materials it is made from just melt. That is the problem. The hydrogen is used as a 'coolant', heating up in the process to some 2500 K before being blasted out at the rear. Much hotter and the reactor melts so the concept needs very careful choice of materials and reactor control. Several prototypes were made and tested on the ground. They worked and could have powered a serious launch but the thrust-to weight ratio was a lot less than achieved by a liquid fuel rocket (basically the reactor was too heavy). Also the sight of conventional rocket launches failing was a common sight in the 60s. The prospect of nuclear reactors crashing in flames and in pieces to the ground was not appealing. At least one nuclear rocket engine was deliberately blown up on its test-bed 'to see what happens'. Some of the Nevada desert is still littered with radioactive debris – obvious really.

This takes us to Plan B, which also dispenses with the chemical fuel. Carry liquefied gas on the rocket and heat it to say 2000 K by absorbing energy from a microwave beam directed from the ground. The hot gas is then expelled as rocket exhaust. This isn't 'photon drive', for the energy of the microwave (photon) beam is being used, not its momentum. The 'heat exchanger rocket' is under development but I don't see much future for it on any sizeable scale. For a modest rocket, the microwave beam needs to be many megawatts in power. Diffraction from the transmitting aerial necessarily spreads the beam out so that more and more will miss the target as the rocket gets higher and higher. The rocket still carries the gas ejected so why not make use of the chemical energy of a suitable mixture of gases?

Plan C is not to carry all the mass that you need to put out at the back in exhaust but to suck air in at the front. In addition, no fuel is on-board. Instead a large reflector at the rear focuses a directed high power laser beam from the ground with enough energy to turn the air into a superheated ball of high-pressure, fast expanding gas that, acting against the reflector, propels the craft forward. One version of this concept is called 'Lightcraft'. Of course it can't get anyone into space since there is no air there to suck in. Again one needs megawatts, this time of laser power. A laser pointer that can deliver a near blinding amount of light has a power of a few mW; a 1 watt laser is a serious potential health hazard; 10 kW lasers for welding are about the largest on the market so it would take a thousand of these to potentially get a modestly sized Lightcraft into the stratosphere. The concept might be useful for lifting small craft into the lower atmosphere but it's not going to provide space-launch capability.

Plan D is in some way already with us. *Ion engines* highlight a feasible way of separating the energy requirement from the need to create mechanical movement. The energy comes from electricity (typically generated by solar panels or a nuclear power source); the motion is created by heavy ions, often the rare gas xenon (atomic weight about 130 times that of a hydrogen atom), that carry more momentum for a given speed than the products of chemical combustion. In principle a xenon ion can be accelerated by a version of a particle accelerator to very high speeds. A 1 Gev xenon ion has a speed of over 0.1 times the speed of light. It all sounds promising until you realise that to lift a 100-tonne rocket from the Earth's surface at a very modest 10 m s^{-1} takes 10 megawatts of power over and above the thrust needed to support the rocket's weight. On-board electricity can't supply that kind of power for the time required. Where is the electricity to come from? Other difficulties soon appear. Ions at that energy will destroy any material they come in contact with, so that must be avoided. One can't keep pumping out positive ions without doing something with the negative electrons that have been stripped off. The aim is to add them back to the ions in the exhaust so that neutral gas is left behind. All that said, the ion engine concept does work but current technology is more likely to be 10 kW, not 10 MW, and provides less than 1 Newton of thrust. This, sustained over days is useful for manoeuvring craft once in space but useless for launches.

Plan E, relevant if you're thinking of taking a large payload a very long way, has two ingredients. As the Irishman said when asked directions to Dublin, "It's better if you don't start from here". First, don't start from Earth. It's obvious that almost all of an Earth-based rocket is used to get the rocket away from the Earth without making much inroad into the total journey. The Moon has only one sixth of the Earth's gravity; asteroids, a lot less. These are clearly better places to start from. Secondly, to reduce the mass of the fuel needed, an exit velocity equivalent to a temperature of perhaps 10^7 degrees is going to be a lot better than a temperature of 10^3 degrees. An increase in temperature by a factor 10^4 increases the thrust by a factor of 100, from what was said earlier. This is the kind of temperature one finds in a fusion reactor or, to be more precise at this time, in test rigs aiming to develop a fusion reactor. The very high temperature plasmas involved are held in place by powerful magnetic fields. This idea could in principle be used for advanced rocketry, with the magnetic fields directing the plasma out of the rear once the fusion reaction has done its business in heating the plasma. There is another gain potentially available from such a process because the energy released from fusion of a given mass of deuterium/tritium (isotopes of hydrogen) is more than a million times greater than from burning hydrogen, though not all is 'available energy'. I know that most of this century has still to come as I write but I really wouldn't expect such rockets until the 22nd century at the earliest.

Plan F taps into the 'hidden energy' that is contained in all mass. Einstein pointed out that a mass m has an intrinsic 'rest energy' of mc^2. You may remember that 62.6 MJ kg^{-1} is needed to get objects away from the Earth into space. I mentioned earlier that the Saturn V rocket had a mass of some 3000 tonnes in order to get a few hundred kg of mankind to the Moon. How much mass do you actually need if its hidden energy were to put 1 kg into space? We just have to set $mc^2 = 62.6\times10^6$ J. Since $c^2 = 9\times10^{16}$ m^2s^{-2}, the answer comes out as $m = 7\times10^{-10}$ kg, less than one nanogram. Good grief! In principle the hidden energy in 1 milligram of mass would have got the Apollo astronauts and their various modules all the way there. In principle.

In one sense the energy needed for space launches is present in matter but there is no recipe for simply extracting it. Fusion is about the best that can be done and it works on the principle that the mass of the fusion products is less than the mass of the starting ingredients and this mass loss is converted to energy. The mass loss is typically a bit less than 1%. That still leaves 1 gram of fuel as having enough energy to get three astronauts to the Moon. However, some ‘stuff’ still has to be squirted out the back, a lot more than 1 gram and it’s this that will make up most of the ‘fuel’ of a fusion rocket. To take an example, suppose one could squirt out hydrogen at a speed of 5×10^5 m s^{-1}, then 30 g s^{-1} would provide a thrust of 1.5 tonnes wt. Near the ground that would support the weight of a rocket of mass 1 tonne and leave 0.5 tonnes to give the rocket an acceleration of 0.5g (4.9 m s^{-2}). Ignoring some initial velocity the rocket would have been given by the spinning Earth, if it maintained this acceleration it would reach the escape speed of just over 11 km s^{-1} in about 40 minutes after squirting out some 72 kg. Where’s all this going? It highlights that in centuries to come, providing the energy for rocket propulsion may be a problem solved but a significant amount of mass still has to be squirted out to achieve usable speeds. There would seem to be no alternative. If such ideas do become reality, then rockets of the future will finally be different from the rockets of today.

Today’s private sector

So what is the growing private sector in the space world doing? They haven’t had to follow the historical development of NASA, Russia or ESA. The front runner, SpaceX has the Falcon 9 rocket, about 50 m tall with mass just over 300 tonnes……… Yes, superficially it’s not much different from its predecessors with orbital capability. Physics, it seems, is having a very strong say in what rockets must be like. Amazon’s Jeff Bezos is concentrating on re-usable rocket technology of comparable size, with his company Blue Origin. Richard Branson’s Virgin Galactic is aiming for sub-orbital flight with their ‘SpaceShip Two’ design that’s developing the X-prize winning ‘SpaceShip One’. They have gone for a rocket plane, lifted by a large ‘mother plane’, using the aerodynamics of plane technology to support the weight of the suborbital flier. It’s a variant of the Space Shuttle approach. It still, undoubtedly, is taking billions of dollars to develop. All these aspirations are taking years longer and much more money than the promoters hoped for. XCOR Aerospace have also gone for a rocket plane aiming for sub-orbital flight, initially powered by a kerosene/liquid oxygen engine but they are planning, as I write, to develop a lighter liquid hydrogen/liquid oxygen engine. The British company Reaction Engines Ltd. are developing *Skylon*, a re-usable ‘spaceplane’ (84 m long) for satellite launches that will be powered by a proprietary engine that acts like a jet engine in the lower atmosphere (using atmospheric oxygen and liquid hydrogen fuel) and a rocket higher up (drawing on its own liquid oxygen). That’s the plan, at least, and so far development is said to be going well. Look for a viable craft around the year 2020 if progress continues.

Sub-orbital flight is typically flight up to about 100 km altitude, cruising for a few minutes and then returning to ground. The ISS is at a height of around 400 km, about the lowest orbit one can have before air drag causes too fast a loss of altitude. 100 km is not very far in terms of distance to ‘outer space’, to where the Earth’s gravitational potential energy is near zero. One doesn’t need to give sub-orbital vehicles nearly as much energy as orbital satellites or space probes, so less fuel is needed. The weight of an object decreases as its distance from the centre of the Earth. 100 km above the Earth's surface isn't all that much further from the centre than the surface itself. A craft 100 km in altitude has lost only 3.1% of its weight, actually a bit less because it's also lost the upward buoyancy that the air gave it at ground level because of Archimedes' Principle. Of course a rocket or rocket plane reaching this height has actually lost a lot more weight because of the ejected spent fuel. The good news is that to reach 100 km in altitude one only has to overcome 1.5% of the gravitational potential energy and not the entire 62.5 MJ per kg needed to get into outer space. The bad news for private space hopefuls is that getting into sub-orbital flight is actually a long way from the capability of being able to launch space probes, even though one is effectively 'in space' at 100 km above the Earth's surface.

Conclusion

I haven't said anything about rockets powered by nuclear explosions, a technology that is feasible but, at least near Earth, unacceptable. I haven't said anything about hoisting items up a space cable tethered to a synchronous satellite. That technology doesn't circumvent the energy issues involved. We're stuck with the fact that the weight of an object on Earth is greater than it is on any other solid surface in the solar system where one can stand: planet, moon, asteroid or comet. It seems that rockets in our lifetimes capable of launching payloads of tonnes into space from Earth are going to be remain large, expensive items, not hugely different from existing launch practice, though no doubt containing a lot of new materials and new control technology. In short, getting into space is hard. The Apollo program and other rocket developments of the 1960s did pretty well. We've got so used to shrinking phones, radios, TVs and other everyday items that it's easy to draw the wrong conclusion that in future all the old ways of doing things are going to be replaced by newer, smaller, slicker, neater technology that does more. It looks as if physics dictates that rockets will not follow this trend, at least for a time probably measured in centuries.

Appendix on the Tsiolkovsky rocket equation

Konstantin Tsiolkovsky was a Russian space visionary, born in 1857, who had a life-long passion about mankind escaping the confines of Earth. He also thought through the basic science of how it could be done. He talked a lot about 'escaping Earth's gravity' but since Earth's gravity clearly goes out to the orbiting Moon and far beyond he was really referring to the 'weightlessness' that astronauts would experience. He saw rockets as the key technology, artificial satellites as the first step and manned spaceflight as the sequel. He may not have been the first to derive the equation associated with him but he certainly was the first to present it in a context that would become the thrust of 20th century space exploration.

Tsiolkovsky was 25 years older than Robert H. Goddard, America's pioneering rocket enthusiast, and older still than Hermann Oberth, the German rocket pioneer, born in 1894 in what is now Romania, who had a seminal influence on rocketry in Western Europe. All three pioneers born in the 19th century began their fascination with rocketry and space as personal interests but Goddard and Oberth went on to become rocket engineers whereas Tsiolkovsky, who had wide-ranging interests besides rocketry, remained a schoolteacher until he retired in 1921. Both Tsiolkovsky and Oberth have museums to mark their work while Goddard has the Goddard Space Flight Center in Maryland, a large NASA research and development facility with a visitor centre.

There are plenty of derivations of the *Tsiolkovsky rocket equation* on the web, though the result can appear differently depending on the use to which it is put. What the equation does is determine the change in speed of a rocket due to the momentum transferred to the exhaust, in the absence of all other effects. 'Other effects' may include atmospheric drag that slows a rocket (in environments that have an atmosphere), the force created by the difference in pressure between the rear of a rocket (where the exhaust is) and the front of a rocket, and the effect of gravity. The equation can be used to estimate how much fuel is needed to produce a given change of speed or, for a given mass of fuel, what change in speed can be accomplished for a rocket of given mass. There is still an implicit effect of any atmosphere around the rocket because the speed of the exhaust relative to the rocket depends on whether the exhaust is emitted against atmospheric pressure or emitted into a (near) vacuum.

The rocket equation is based on Newton's 2nd law of motion. It therefore can't be circumvented. You may meet the phrase 'the tyranny of the rocket equation', for one implication is that if you want to get to a speed of km s^{-1}, which you need to launch satellites or travel well away from the Earth, then you have to carry a lot of fuel. It's the rocket equation that dictates that rockets leaving Earth will be big, very big.

Call v_e the speed of the exhaust relative to the rocket, m_i the mass of rocket including the fuel before it is burnt, m_f the mass of rocket after the fuel burn. The change in the speed of the rocket is usually called *delta-v* and is given by the symbol ΔV. *Tsiolkovsky's rocket equation* relates these quantities: $\Delta V = v_e \ln(m_i/m_f)$. As with all equations, it is the implications that count. A variant form is $m_i/m_f = e^{\Delta V/v_e}$. It is the exponential that creates difficulty in rocketry.

Consider a rocket (such as ESA's Ariane 5) designed to launch 10 tonnes of satellites, a mass of 10,000 kg. To achieve low Earth orbit (LEO), a satellite needs to be given a speed of about 7.5 km s^{-1}. In addition, it needs to be hoisted up about 1000 km above the Earth's surface against gravity and against low altitude air resistance. This makes the effective ΔV about 9.4 km s^{-1}. If the rocket exhaust is a decent 3 km s^{1}, then $e^{\Delta V/v_e} = 23$. This means that at least 23 times the mass to be lifted into orbit is needed in the fuelled rocket on the ground. The lift must not only include the satellites but the rocket engine, outer casing and fuel tanks, control systems and all the workings of the rocket. The mass to be lifted is a lot more than the satellites. You can see why satellite launch rockets come in at hundreds of tonnes. The factor of 23 is rather bad news, for I mentioned earlier that a rocket engine that could lift 20 times its own mass was doing rather well.

But wait a minute - surely after say half the fuel is burnt there is no point in further lifting empty sections of fuel tanks? Exactly. The simple Tsiolkovsky rocket equation applies to a rocket that loses mass by expending its fuel. The equation shows that it's better to eject used parts of the rocket and not accelerate them to higher speed, in other words multistage rockets are intrinsically more efficient than single stage rockets. They are, however, technically more complicated. Many a satellite launch has failed because a second stage has failed to ignite and take over properly. In practice the mass saving is not quite as large as you might at first think. If you look at pictures of Ariane 5 and some other designs you will see they have 'booster rockets' strapped to the side that are jettisoned early, effectively an additional low altitude stage.

For low Earth orbit, most of the *delta-v* is needed to achieve orbital speed. For geostationary orbit, the satellite is likely to be placed in low Earth orbit first and then, using a smaller rocket, transferred to geostationary orbit. The orbital speed for geostationary orbit is only about 3.1 km s^{-1} (Kepler's 3rd law applies, relating how the further the orbit is from the centre of attraction the slower is the orbital speed). Although the speed of the higher orbit is lower, because of the energy used to gain the large amount of extra height the equivalent of an additional ΔV = 4.3 km s^{-1} is needed. The rocket equation tells us that we need 4 times the mass in LEO than will be taken up to geostationary orbit. No wonder the Ariane 5 is huge.

All the above applies not only to rockets of the present but to rockets of the future. There is no escape from the Tsiolkovsky rocket equation in one form or another for a chemically fuelled rocket. Rockets launched from Earth for a payload to be put in orbit will be massive, mainly because of the fuel needed.

Addendum

What else can you do in deep space to get somewhere besides use a rocket? Nothing, if you want to get any reasonable distance in a reasonable time. There's nothing there to pull or push yourself along by. In the solar system you can get a bit of help from the 'gravity assist' of orbiting planets and other bodies but not a lot. Stellar radiation pressure is too small; the gravity of distant objects too weak to pull you away from local gravity. We now have a more comprehensive view of what's in the Universe than our ancestors ever had and we've found no natural phenomenon that accelerates substantial masses to high speeds in a short space of time. The energy required to escape from solar orbit when you start at the distance of the Earth from the Sun is more than 14 times that necessary to escape from Earth orbit. There's another problem with space exploration. Suppose you did manage to set your craft towards another star of similar mass to the Sun (many are). The gravity of that star will exert its pull on you whether you like it or not and by the time you get to the inner reaches of its planetary system you will be travelling at around 40 km s^{-1} due to this pull, seriously fast. None of the moons or planets you might wish to explore will be going this fast in their orbits. If you want to stop and explore you have to get rid of most of your speed. A body can't absorb its own kinetic energy any more than a falling stone can slow up of its own accord, it needs an external force to slow it. For the spacecraft, rocket technology is needed not only to speed up but to slow down.

We're heading into the realms of science fiction here in talking of interstellar travel but the more you think about it the more it's not surprising that aliens haven't visited us. The energy costs of space travel are enormous and at travel speeds that might be achieved by reasonable energy expenditure the time taken to travel interstellar distances works out at millennia. Science fiction writers have sometimes taken another line and imagined tunnelling through an otherwise hidden dimension (hyperspace or some such word) to your distant destination. That idea may well be as divorced from reality as Narnia, the Never-Never land or a world through the looking glass. Rockets are here to stay.

JSR