Rockets of the Future?

The gravity problem

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. 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 1/10th 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 $\mathrm{m\ s^{-2}}$ 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 $gR_E = 6.257\times10^7\ \mathrm{J\ kg^{-1}}$, or about 62.5 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 $\mathrm{km\ h^{-1}}$ - 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 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 $\mathrm{m\,s^{-2}}$. Ignoring air resistance, it would go from 0 to 100 $\mathrm{km\,h^{-1}}$ in 2.8 seconds and after 10 seconds would be travelling at 350 $\mathrm{km\,h^{-1}}$. Providing enough thrust to support the weight of a rocket is hugely energy expense 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 $(2m\times\mathrm{KE})^{\frac{1}{2}}$. 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 $\sqrt{2}$. 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 liquid rocket fuel is more usually kerosene and liquid oxygen.

So how much gas must be emitted to support a rocket of 1 tonne weight against Earth's gravity? The best of chemical rockets can emit exhaust at a speed of about 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 $m \approx 2.5\ \text{kg s}^{-1}$. Perhaps this doesn't sound much, though of course 1 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 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. 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.

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 it 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 2 men weighing less than 200 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.

Plan B is to 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.

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 and it's aiming for orbital capability. Physics, it seems, is having a very strong say in what rockets must be like. Virgin Galactic is aiming for sub-orbital flight with their 'SpaceShip One' and 'SpaceShip Two' designs. 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. 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 and a rocket higher up. 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, cruising and then return to ground. The ISS is at a height of about 350 km, about the lowest orbit one can have before air drag causes too quick 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 of the future 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. 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. It looks as if physics dictates that rockets will not follow this trend.

Addendum

What else can you do in space beside 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. Stellar radiation pressure is too small; the gravity of distant objects too weak to pull you away from local gravity. The energy required to escape from solar orbit when you start from 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 it’s 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 visit 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 tens of thousands of years. 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.

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