SPACE-IN-BYTES

Science Fiction – Science Fact

LESSON NOTES

> *"There's no real objection to escapism, in the right places... We all want to escape occasionally. But science fiction is often very far from escapism, in fact you might say that science fiction is escape into reality... It's a fiction which does concern itself with real issues: the origin of man; our future. In fact I can't think of any form of literature which is more concerned with real issues, reality."*
> - Arthur C. Clarke

Science fiction has had to come up with solutions to living in space for prolonged periods of time. For many years, authors such as Jules Verne and Arthur C. Clarke have constructed visions of how we, as humans, can deal with zero gravity or the need for food and oxygen. There's also the issue of getting from place to place – could we really do a Star Trek and zoom off at "warp" speed or be teleported from one place to another?

Constants referred to in this document:

Universal gravitational field constant, $G = 6.7 \times 10^{-11}\ \text{m}^3\ \text{kg}^{-1}\ \text{s}^{-2}$

Mass of the Earth, $M = 6.0 \times 10^{24}$ kg

Radius of the Earth, $R_E = 6.4 \times 10^6$ m

Speed of light, $c = 3.0 \times 10^8\ \text{ms}^{-1}$

Acceleration due to gravity at the Earth's surface, $g = 9.8\ \text{ms}^{-2}$

1. Geostationary orbits: where are you now?

This is possibly an odd question to open with, but think about it for a moment. You are probably reading this at a computer and have downloaded the page via the internet. Furthermore, you might have travelled to an internet café, made a long distance telephone call, watched television or used public transport today. At some point in the past 24 hours, you have more than likely used, either directly or indirectly, some form of communication satellite system (e.g. a satellite television receiver).

These rely on satellites in geostationary orbits. In other words, each satellite's position in the sky is fixed relative to the ground. Can you imagine the chaos if this wasn't the case? How would you know where to point your receiver or transmitter dish?

Let's now consider this orbit – scientists need to be able to calculate the geostationary altitude if they are to launch a communications satellite. What about satellites of different mass? Would these have different orbit altitudes?

To find the geostationary orbit, we need to consider a satellite orbit period of one Earth day, i.e. $T = 24 \times (60 \times 60s) = 8.64 \times 10^4$ seconds.

We can equate the gravitational force between two masses (namely the Earth and the satellite) with the centripetal force required to keep the satellite in orbit. In other words, gravity provides this centripetal force.

The gravitational force between two masses M and m, separated by a distance r is given by $F = -\frac{GMm}{r^2}$.

where G is the universal gravitational field constant. The negative sign appears in the equation as this is an attractive force acting in the opposite direction to the distance measurement. In this case, however, we are only interested in the magnitude of the force, so from now on, we can ignore the sign.

According to Newton's Second Law, a force is given by $F = ma$. If we assume circular motion for the orbiting satellite of mass *m* and substitute $a = \omega^2 r$ for the centripetal acceleration (where ω is angular velocity and *r* is the radius of the circular path), then we have that the centripetal force is

$$F = m\omega^2 r = m\left(\frac{2\pi}{T}\right)^2 r.$$

Where T is the time needed to complete an orbit (period). Equating, we get

$$\frac{GMm}{r^2} = m\left(\frac{2\pi}{T}\right)^2 r$$

$$\frac{GM}{r^2} = \frac{4\pi^2 r}{T^2}$$

$$r^3 = \frac{GMT^2}{4\pi^2}$$

$$r = \sqrt[3]{\frac{GMT^2}{4\pi^2}}$$

Note that this is independent of the mass of the satellite, which means we can calculate the geostationary orbit for any satellite, using *T*= 8.64×10^4 s.

$$r = \sqrt[3]{\frac{GMT^2}{4\pi^2}}$$

$$r = \sqrt[3]{\frac{6.7\times10^{-11}\times6.0\times10^{24}\times(8.64\times10^4)^2}{4\pi^2}}m$$

$$r = 4.2\times10^7 m$$

This is the distance from the centre of the Earth. Subtracting the radius of the Earth gives an equatorial orbit altitude of approximately 35600km. This is also known as the Clarke orbit, after Arthur C. Clarke, who proposed the idea of a geostationary orbit on a wide scale in the mid 1940's, before going on to write a number of science fiction novels.

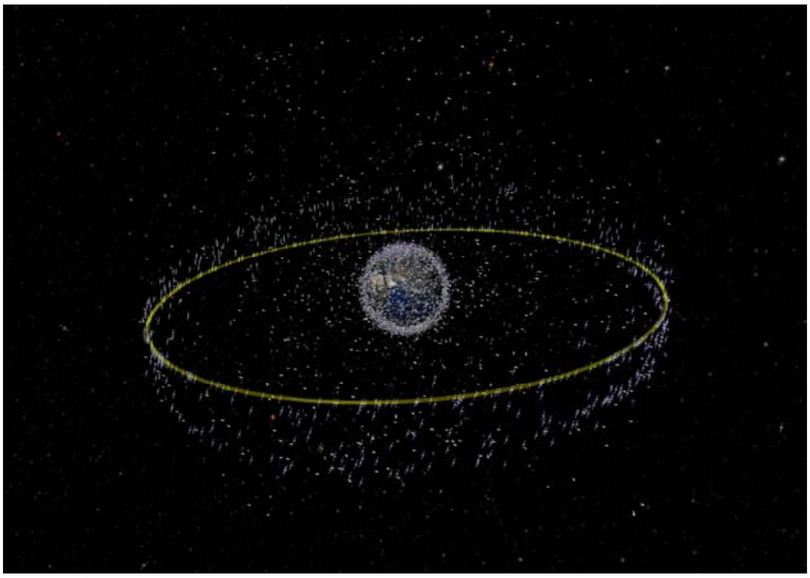


Fig. 1 *The geostationary ring, at an altitude of about 36,000 km. This orbit is heavily used by telecommunication satellites and the ESA Meteosat Second Generation (MSG) meteorology satellites.*

2. Jules Verne's Moonship

One of the things that many authors have to tackle is how to get humans into space in the first place. In 1865, Jules Verne wrote *De la Terre à la Lune (From the Earth to the Moon),* a humorous account of three men who plot to launch themselves in a "moon ship" from a cannon (the Columbiad). For this to succeed, the projectile (in this case, the moon ship), would need to reach a speed high enough to allow it to climb out of the Earth's gravitational potential well, thus escaping from Earth's gravitational attraction.

The depth of this well is equal to the potential energy per kilogram required to take a mass from the Earth's surface to a point in space where the gravitational potential becomes negligibly small, namely to infinity. At the surface of the Earth, the gravitational potential energy, E_{grav} for a mass m is given by:

$$E_{grav} = -\frac{GMm}{R_E}$$

and the gravitational potential is hence

$$V_{grav} = -\frac{GM}{R_E}$$

$$\left|V_{grav}\right| = \frac{6.7\times10^{-11}\times6.0\times10^{24}}{6.4\times10^{6}}\,Jkg^{-1}$$

$$\left|V_{grav}\right| = 6.3\times10^{7}\,Jkg^{-1}$$

We are interested in the magnitude of this potential, indicated by the modulus symbol $|V_{grav}|$, and so, once again, we can ignore the negative sign.

If you consider a mass of 1 kg, the corresponding amount of energy enormous. Given that this needed to be transferred to the projectile carrying the people in Verne's story, you can already see that the energies start to get very large. There is a bit of a problem here. This energy is needed to ensure that the total energy (kinetic, E_k, plus gravitational potential, $E_{grav}=mV_{grav}$) of the projectile is greater than zero. But what sort of speed would be required?

The escape condition is $E_k + mV_{grav} \geq 0$. Kinetic energy is given by $E_k = \frac{1}{2}mv^2$ and we can use this to calculate the escape velocity:

$$\tfrac{1}{2}mv^2 + mV_{grav} \geq 0$$

$$\tfrac{1}{2}v^2 + V_{grav} \geq 0$$

$$v^2 \geq 2\times 6.3\times 10^7\, m^2 s^{-2}$$

$$v \geq 11 kms^{-1}$$

Now, if we were to launch passengers from stationary, using a cannon of 10m in length, then the acceleration can be found from the expression $v^2 = v_0{}^2 + 2as$ (where v is the escape velocity, v_0 is the initial velocity and s is the displacement). Re-arranged (and considering v_0=0), this gives

$$a = \frac{v^2 - v_0{}^2}{2s}$$

$$a = \frac{(11\times 10^3)^2}{2\times 10}\, ms^{-2}$$

$$a = 6.1\times 10^6\, ms^{-2}$$

Those poor passengers! The acceleration to achieve this speed from a cannon would be catastrophic (almost 1 million times the gravity acceleration g!), unless the muzzle was extremely long.

There can sometimes be a misconception that any craft needs to reach 11kms^{-1} in space to escape the Earth's gravitational potential well. In fact, this is the speed at the surface of the Earth. Of course, this does not take into consideration the effects of frictional forces from the air which at this speed, would cause the craft to burn up during take-off. Again, this would be bad news for the passengers.

It therefore follows that if you start further away from the Earth, then the escape velocity would be lower due to the reduced gravitational potential well. Less velocity and, hence energy to accelerate, would be needed to achieve this. The ISS could be one possible starting location.

3. The ISS – an Interplanetary Stepping-Stone?

As we have shown above, starting at the International Space Station would make it easier for a spacecraft to escape the Earth's gravitational field. As we improve our observing techniques, it is only natural that we should want to explore further into space.

If the ISS is in orbit at 350km, then the gravitational potential at this altitude is

$$E_{grav} = -\frac{GMm}{R_E + r}$$

$$E_{grav} = -\frac{6.7\times 10^{-11}\times 6.0\times 10^{24}}{6.4\times 10^6 + 350\times 10^3}\, Jkg^{-1}$$

$$E_{grav} = -6.0\times 10^7\, Jkg^{-1}$$

This results in an Earth escape velocity of just under 11kms^{-1}. However, to travel even further into space, there is still the gravitational pull of the Sun; any spacecraft will need to climb the Sun's gravitational potential well. There is no getting away from the fact that in order to travel further, you need more energy.

In his story "The Lady Who Sailed the Soul", Cordwainer Smith made reference to the use of solar sails on interplanetary spacecraft. He wrote how the first interstellar ships might be propelled by light (radiation) sails. Solar sails have appeared in numerous films such as Star Wars and Star Trek too. This idea makes use of the pressure due to the momentum imparted on a surface by photons emitted from the Sun. (N.B. It should not be confused with the smaller pressure exerted by the solar wind.)

You can vividly see the effects of solar radiation pressure whenever a comet approaches the Sun. The comet develops an ion tail which is deflected by the pressure of sunlight and hence this tail always “points” away from the Sun.

Fig. 2 *Comet Halley, showing the distinctive tail*

The energy *E* and linear momentum *p* of an electromagnetic wave are related via $E = pc$ (where *c* is the speed of light). We can calculate the associated radiation pressure (the force F per unit area A) for a wave of intensity S arriving at a surface at right angles as follows:

$$P_{radiation} = \frac{F}{A} = \frac{S}{c}$$

So what sorts of forces are we talking about? How useful are they? We’ll start by considering the force on a large square solar panel on Earth, of side 10m. The intensity of solar radiation just outside the Earth’s atmosphere is 1.4 kW m^{-2}. It follows that the average force exerted on the panel is

$$F = \frac{SA}{c}$$

$$F = \frac{1.4 \times 10^3 \times 10^2}{3 \times 10^8} N$$

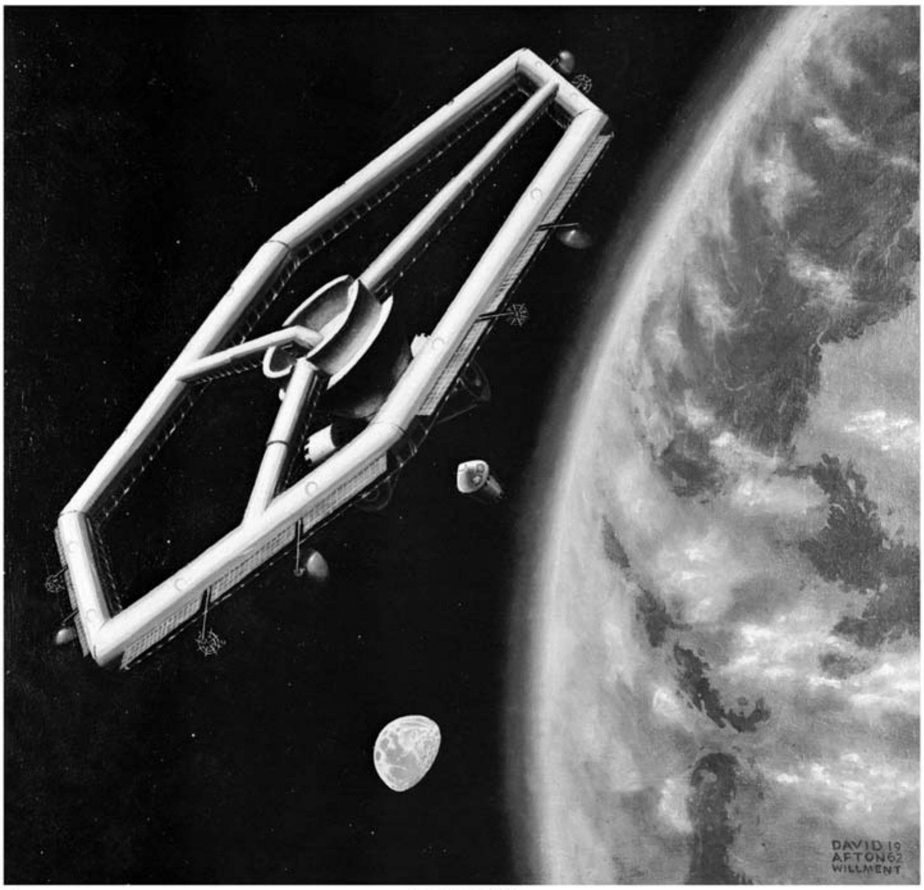
$$F = 4.7 \times 10^{-4} N$$

Despite this seemingly tiny value, the force from radiation pressure can be very useful in space, particularly over long periods of time. Naturally, a larger sail area would result in a greater imparted force. The spacecraft itself wouldn’t need to carry as much fuel and hence the reduced mass would make it easier to accelerate wherever there was a source of photons to capture.

4. Artificial gravity

Living in a microgravity environment, such as in outer space, poses practical difficulties (e.g. eating and drinking), not to mention adverse effects on the human body (e.g. muscular atrophy). Therefore, scientists are considering ways of simulating gravity for prolonged stays on board the ISS.

One of the ideas put forward in the movie *2001 A Space Odyssey* is a rotating space station. This would employ the same principles as a fast rotating fairground ride. Instead of keeping passengers in their seats, it would simulate gravity and keep astronauts on the "floor" of the space station module.



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Langley Research Center
Hampton, Virginia 23681-0001

Fig. 3 *An artist's impression of a rotating space station. (Image courtesy of NASA)*

This force experienced on such rides is commonly termed centrifugal force. This force does not actually exist as such. On a fairground ride, it feels like you are being thrown out as your body is trying to continue along a straight line. What you actually feel is the sides of the ride continually pushing you, and hence accelerating you, towards the centre of the circle.

Newton's First Law states that a body continues to maintain its state of rest or of uniform motion unless acted upon by an external unbalanced force. In circular motion, acceleration is perpendicular to the instantaneous velocity of the body. Thus, at any moment in time, the passenger on the fairground ride will be travelling at an instantaneous velocity tangential to the circular motion path.

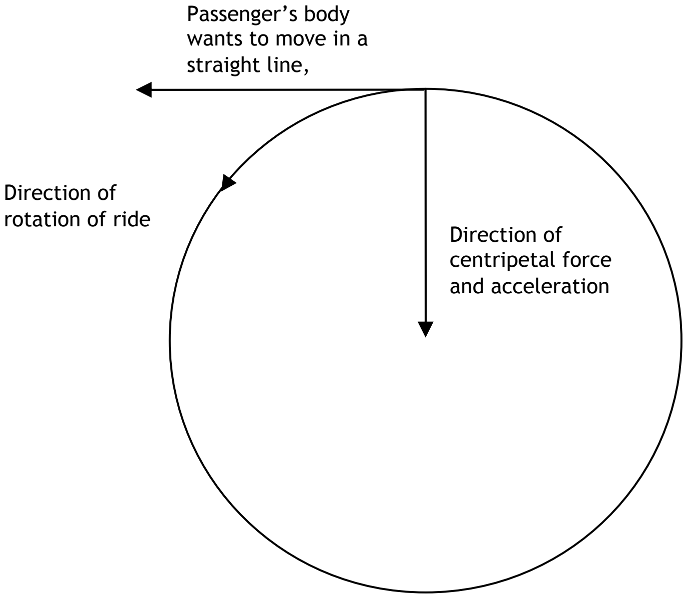

Fig. 4 *An instantaneous snapshot of a passenger on a fairground ride shows the direction of motion and acceleration at right angles to each other.*

Worked example:

What is the minimum rotational frequency that is needed to keep a passenger in their seat when a circular motion fairground ride seat is upside-down? We'll assume the typical diameter of such a ride is *2r*=25m.

For uniform circular motion, the centripetal acceleration is given by $a = \frac{v^2}{r}$ and the angular frequency $f = \frac{\omega}{2\pi}$ where $v = \omega r$ and *ω* is the angular velocity.

Substituting for *v* and rearranging, we get:

$$a = \frac{v^2}{r} = \omega^2 r$$

$$f = \frac{\omega}{2\pi}$$

$$f = \frac{1}{2\pi}\sqrt{\frac{a}{r}}$$

We are looking for the case where gravity provides this centripetal force, meaning that *a* > 9.8 ms^{-2}

$$f > \sqrt{\frac{9.8}{12.5}}\frac{1}{2\pi}s^{-1}$$

$$f > 0.14s^{-1}$$

This corresponds to one revolution every seven seconds. You should be able to see from the above that the larger the radius, the lower the spin rate required. This has practical implications. How would the artificial gravity on your head compare to that experienced by your feet?

From the above equations, a rotating module of time period of 6.3 seconds would give an acceleration of 1*g* at a radius of 10 metres. An average person standing in this module would have their head approximately 1.7m closer to the centre of rotation than their feet. The acceleration on the person's head at a radius of 8.3 metres would be

$$a = \left(\frac{2\pi}{T}\right)^2 r$$

$$a = \frac{4\pi^2}{6.3^2} \times 8.3ms^{-2}$$

$$a = 8.3ms^{-2}$$

which is 15% less than at their feet. If this person bent down to tie their shoe laces, they would feel the effects of the change in centripetal acceleration on their upper body parts. As they bend they would feel as if they were being pushed sideways slightly. This is known as the Coriolis effect and if too perceptible, could lead to motion sickness.

5. "Mr Sulu, proceed to Warp Drive 2"…Could this be a reality?

The term "warp drive" was coined in the Star Trek series and films. It refers to travelling through space at speeds greater than the speed of light. We'd need to think very carefully about the accelerations involved, in order to protect any crew and equipment on board. Furthermore, we would need to take into account several aspects of relativistic physics. Einstein's theory of special relativity states that the speed of light is constant in all inertial frames, which contributes to suggest that the speed of light cannot be exceeded. One additional important consideration would be the amount of energy required. According to special relativity, as the velocity of an object increases, so does its momentum and energy without bound. This means that an object with mass travelling at the speed of light would have infinite energy!

But suppose, just for one moment, that this were possible. For the purposes of this calculation, we will ignore relativistic physics.

If the maximum acceleration was limited to *a=3g*, similar to that experienced in a Space Shuttle launch), then the time to reach the warp drive threshold from the orbit speed of the ISS (8 kms^{-1}) would be

$$t = \frac{c-u}{a}$$

$$t = \frac{3\times10^8 - 8\times10^3}{3\times9.8} s$$

$$t = \frac{3\times10^8}{29} s$$

$$t = 1.0\times10^7 s$$

which is nearly 116 days. That's a long time for the human body to be subjected to 3*g* continuously. You'd also need a similar amount of time to decelerate. Of course, with present understanding and technology, this is not realistic, but it does illustrate some of the more practical issues associated with accelerating to such high speeds, even if it were physically possible.

6. Science-Fiction or Science-Fact?

We have seen that some of the ideas first put forward by science fiction authors, several of whom were actually space scientists, are now a reality. Indeed, a lot of space scientists today also write science fiction, so who knows what lies in the future out there? There's no point shouting about it though, because "*in space, no-one can hear you scream*" (Alien, 1979).

Fig. 5 *Internal view of a fictional space station colony (image courtesy Don Davis/NASA)*