Some odd solar system questions answered

The questions here were inspired by reading some of the 'letters from afar' submitted by the class. The answers illustrate the application of basic physical principles and in this spirit approximations are made so that simple physics can be applied. For example, asteroids are taken as spherical, though real ones aren't. Using a realistic shape would complicate the answer a lot and not change the gist of the result. Although most of the questions involve specific numbers, general conclusions can usually be drawn from the answers. The answers also show that 'common sense' isn't much of a guide when it comes to expectations away from Earth.

I should add that the answers to these questions aren't sitting ready-made in textbooks. You may need to research, on the web for instance, the appropriate physics formulae once you've thought through the principles that must be involved. You'll find the key data needed on the web too. I've spelt out the logic of going from the question to the answer. The numbers in the answers have not been checked so it's worth following the calculations yourself to see if they are right. Please report any errors spotted! I may regret saying this but if anyone on the course has any question you think could be answered in a like way, then e-mail it to me with your accompanying comments.

1 *Is it worth transporting hydrogen from Jupiter to Earth to use as a fuel*?

Answer: No!

At the visible surface of Jupiter the strength of gravity g = 25 m s^{-2} and the distance r of the surface from the planet's centre is 71×10^4 km. The work required to lift 1 kg of hydrogen against Jupiter's gravity so that it won't fall back again is just gr = 1800 MJ. [This is the same as the KE of 1 kg given the escape velocity at Jupiter of 60 km s^{-1}].

The energy available from burning hydrogen in oxygen is 143 MJ kg^{-1}. End of story. In burning the hydrogen you get back less than one tenth of the energy it takes to liberate the hydrogen from Jupiter's atmosphere. There are other energy factors involved such as the KE the hydrogen gains in falling the distance of Jupiter from the Sun to the distance of the Earth from the Sun and in falling to Earth from the upper atmosphere but even if these energies could be harvested they don't make up for the initial extraction effort.

If you want energy from burning hydrogen then much the best option is to generate the energy necessary to electrolyse water from a renewable resource and then separate water into its components of oxygen and hydrogen. In the process you generate the oxygen needed to burn the hydrogen and hence won't be depleting the world's stock of oxygen when the hydrogen is burnt to produce water again. Sustainability in action. Bringing hydrogen or methane from the outer solar system, even from places more favourable than Jupiter, won't be good for the Earth.

2 *Will a wind turbine generate useful energy for a Mars colony*?

Answer: No!

The density of the atmosphere at the surface of Mars is about 0.018 kg m^{-3}, compared with that of the Earth's atmosphere of just over 1.2 kg m^{-3}. [See the blue-panel section on the course web-page on 'planetary ballooning'].

The power, P, available from a wind turbine is P = $\frac{1}{2}\alpha\rho\pi r^2 v^3$, where α is an efficiency factor determined mainly by the design, ρ is the density of the atmosphere, the crucial factor here, r is the radius of the blades and v the velocity of the wind. [This can be deduced from first year mechanics but for a statement see e.g. WikipediA article 'Wind turbine'].

On Earth it takes a decent sized turbine to generate 1 kW of electricity, with a blade diameter of some 2 m in a wind speed of 10 m s^{-1}. For the same wind speed on Mars the turbine needs to have 10 times the radius (i.e. be gigantic), since the atmosphere is only about 1/100th as dense. It's true that gravity is only 38% of its value on Earth and that tall structures will be easier to make but against that the only natural resources are stone! Into the bargain, the wind on Mars isn't nearly as regular as we are accustomed to.

Conclusion: forget about wind turbines on Mars until terraforming has produced a breathable atmosphere.

3 *Could you cycle at 10 mph (4.4 m s^{-1}) on the surface of Venus?*

Answer: No!

The aerodynamic drag force F_d of an object moving through a fluid is given by $F_d = \frac{1}{2}\rho v^2 C_d A$, where ρ is the density of the fluid, v is the speed relative to the fluid, C_d is a dimensionless number called the drag factor, which depends on the shape of the object and its texture and A is the cross-sectional area of the object at right angles to the flow. [See, e.g. the WikipediA article 'Drag coefficient'].

For a person on a bike C_d is about 0.9; A $\approx$ 1 m^2; $\rho \approx$ 1.2 kg m^{-3} on Earth and hence for v = 4.4 m s^{-1} the drag force F_d is about 10 N. In short, when cycling at a modest pace on Earth you don't notice very much wind force against you.

On Venus, $\rho \approx$ 70 kg m^{-3} [See the blue-panel section on the course web-page on 'planetary ballooning']. Hence at the same speed the force against you is about 700 N. This is as big as many people's weight on Earth and larger than their weight on Venus (where gravity is 91% of Earth's gravity). There is no way you could power yourself to travel as fast as 4.4 m s^{-1}. Even at normal walking pace, the effort on Venus you would need to expend would be the same as walking straight into a near gale on Earth. Another comparison can be made by using the drag area figure (C_dA) for a typical car of 0.8 m^2. A drag of 700 N is generated on Earth by a car travelling at 38 m s^{-1}, equivalent to 137 km h^{-1} or 86 mph. In other words, you'd need pretty well all the power of an average car going near its top speed, burning oxygen that isn't readily available on Venus at a good rate, to reach a speed of 10 mph.

Conclusion: powered movement over the surface of Venus is going to be very slow. Another conclusion is that a wind of 10 mph, if it occurs, would lift a person clean off their feet. This conclusion is re-inforced when you remember that it is about 450 ºC on the surface and hence anyone 'out there' would be wearing a very cumbersome furnace resistant protection suit.

4 *Would wind on Mars blowing at the speed of a gale on Earth make it hard for an astronaut on Mars to walk?*

Answer: no.

On Earth it's difficult to walk into a gale, force 8 on the Beaufort scale where the wind speed is typically 70 km h^{-1} or 20 m s^{-1}. The drag force against you is given by $F_d = ½\rho v^2 C_d A$ (see the previous question). Taking ρ = 1.2 kg m^{-3}, v = 20 m s^{-1}, $C_d \approx 0.9$ and A = 1 m^2 gives a force of about 200 N. For an adult weighing 800 N (about 80 kg wt), this force is 25% of their weight. On Mars, ρ = 0.018 kg m^{-3} and even allowing that you will be wearing a space-suit and hence your surface area will be say half as large again (1.5 m^2) the drag force is only 5 N. This is very little. Gravity is only 38% on Mars and if you weighed 400 N in your space-suit then the drag is only 1.25% of your weight, scarcely noticeable.

Average wind-speed at surface level on Mars is light. A speed of 20 m s^{-1} is rare. As far as I know, the Mars rovers Spirit and Opportunity have not been affected by wind buffeting in over 4 years of operation. Winds up to 30 m s^{-1} have been recorded in dust devils and higher speeds inferred but these last for only minutes as the accompanying mini-tornado passes by. Mars' winds pick up dust but the atmosphere is so thin that the dust-grains most likely to be picked up are less than 0.1 mm in size, a lot less than a typical sand grain picked up in a desert dust-storm on Earth. However, once travelling at speed then a dust grain has just the same abrasive power and penetration capacity on Mars as it does travelling at the same speed on Earth. Hence on Mars, scratching and damage by wind-born dust is likely to be a bigger hazard than being knocked over by the force of wind.

5 *Will a car with its doors and windows sealed float on the surface of Venus?*

Answer: no, but a caravan would!

A Toyota Aygo is 3.4 m × 1.6 m × 1.5 m and has an unlaiden mass of 835 kg. If it were purely rectangular it would displace a volume of atmosphere of 3.4×1.6×1.5 m^3 = 8.16 m^3. However, it's not rectangular. There's appreciable clearance space below the body and the bonnet is below the windscreen, obviously. Say it displaces 5 m^3 of atmosphere and hence the upthrust on it will be equal to the weight of atmosphere displaced, namely ρgV = 70×8.9×5 = 3115 N. The weight of the car is mg = 835×8.9 = 7532 N. The weight is a bit more than twice the upthrust and hence a small car like this won't float, even though it is a light car.

What counts is clearly the mass in comparison with the atmospheric ρV, the mass of an equal volume of atmosphere. A VW Caravelle has a volume of about 18 m^3 and hence ρV of 1260 kg compared with its mass of 2310 kg. It won't float either.

A modest caravan would have a volume of 25 m^3 giving it a ρV of 1750 kg and a mass of 800 kg. Hence it will clearly float over the surface of Venus.

People won't float but what about a craft like the space shuttle? From NASA's specified dimensions, a rough estimate of the volume it displaces is 5.8×10^3 m^3 and its unlaiden mass is 75,000 kg. Hence its ρV factor is about 400,000 kg, over 5 times its mass. A craft like that has no chance of landing on the surface of Venus unless atmosphere is let into the craft as it descends. Lift-off becomes easy. Just pump out the native atmosphere within and it will float up.

In summary, objects designed to leave the Earth need to be as light as possible to reduce the need for fuel and hefty rockets yet objects designed to rest on Venus' surface need to be of average density greater than that of the Venusian atmosphere.

Conclusion: It will be very difficult to take large objects to the surface of Venus. Objects such as living quarters will need to be assembled, secured to the ground to prevent them floating away and then have the native atmosphere removed. They have to be strong enough not to collapse under an atmospheric pressure 90 times that on Earth (if their internal pressure is made similar to Earth's atmospheric pressure) and survive a standing temperature of 450 ºC. It's a challenge too great for mankind at present.

6 *If you can exert enough muscular effort in a space suit to launch yourself upwards at a speed of 1.5 m s^{-1} what is the smallest spherical stony asteroid you can stand on such that you will return to the ground again after such a leap?*

Answer: about 2 km diameter

On Earth, an initial velocity u of 1.5 m s^{-1} will result in your centre of mass rising a height given by $u^2/2g$ = 0.33 m, not much without a spacesuit but probably a challenge in one. The question boils down to how large an asteroid has an escape velocity of 1.5 m s^{-1}? If you are to return to the ground, the asteroid needs to be a little bit larger.

On the surface of a spherical body of radius r, the escape velocity v is when the kinetic energy $\frac{1}{2}mv^2$ equals the gravitational potential energy (measured from infinity) of mgr. g is the local strength of gravity. i.e. $v^2 = 2gr$.

The local value of g is the value such that $mg = \text{G}m\text{M}/r^2$, where M is the mass of the asteroid. The mass is the volume $4\pi r^3/3$ times the density ρ. Putting this together makes $g = 4\text{G}\pi r\rho/3$. Hence the escape velocity $v^2 = 8\text{G}\pi\rho r^2/3$. Writing this the other way around gives the radius r for a given escape velocity as $r = \sqrt{3/8\pi\rho G}v$.

Using G = 6.67×10^{-11} N m^2 kg^{-1} and choosing ρ = 3000 kg m^{-3}, with v = 1.5 m s^{-1} the numbers pan out as $r = 1.16\times10^3$ m, or 1.16 km. The mass M of such an asteroid is $4\pi r^3\rho/3 \approx 2\times10^{13}$ kg.

Conclusion: the figures are a stunning illustration of how weak a force gravity is. It takes the combined gravitational attraction of 20,000 million tonnes of stone to just prevent an astronaut leaping up and not disappearing off into space.

If you jumped up with a velocity of 1.5 m s^{-1} on an asteroid only a little bigger, you would travel many km into space before returning to the ground – pretty scary! I suspect it would be difficult to walk to a desired place on an asteroid just 2 km in diameter because the slightest upward velocity will cause you to leave the ground and travel a considerable distance.

7 *If the asteroid in the previous answer (radius 1.16 km) were rotating, what period of rotation would give an object just sitting on the equator enough speed to reach the escape velocity?*

Answer: about 1 h 20 min.

If the asteroid rotates in period T then it has a rotational velocity ω rad s^{-1} such that $T = 2\pi/\omega$. The speed of an object a distance r from the rotation axis is ωr. On the equator, r is the radius and the escape velocity v is 1.5 m s^{-1}. Hence $\omega = v/r = 1.5/1.16\times10^3 = 1.3\times10^{-3}$ rad s^{-1}. This gives a rotation period of 4.86×10^3 s or 1.35 h.

Conclusion: a modest rotation is enough to sweep rocks and boulders off the parts of the surface that are furthest from the rotation axis for a small asteroid.

8 *If you can lift a weight of 100 N in your spacesuit (≡ a mass of 10 kg on Earth), how big a mass can you lift while standing on the asteroid of 1.16 km radius of the previous questions?*

Answer: a boulder about 4 m in diameter

You can lift a mass mg = 100 N. Given $g = 4G\pi r\rho/3 = 9.7\times10^{-4}$ m s^{-2}, this gives a mass of 1×10^5 kg, or 100 tonnes. A spherical boulder of this mass will have a radius of $(3m/(4\pi\rho))^{1/3}$ = 2 m. i.e. you could lift a boulder about twice your height.

9 *If you are standing on a surface in the outer solar system where the temperature is -200ºC and the outer skin of your space suit has the same temperature, at what rate is energy leaking into space from your suit?*

Answer: less than 1 W

The energy loss E in J m^{-2} s^{-1} from a body due to radiation is $E = \alpha\sigma T^4$ where T is its absolute temperature, σ is Stefan's constant of 5.67×10^{-8} W m^{-2} K^{-4} and α is a dimensionless number that gives the 'emissivity' of the body, the fraction of blackbody radiation that it emits.

If the space suit at a temperature of 73 K (-200ºC) of say 3 m^2 area were surrounded by space at a temperature of 3 K then the radiation loss would be $\alpha\times3(73^4 - 3^4) = 4.8\alpha$ W. Since half of the surroundings are at the same temperature as the spacesuit, the loss rate is only half this or 2.4α W. If the emissivity of the spacesuit is a third or less, then the rate of emission of energy will be less than 1 W. The next question shows that spacesuit outer temperatures need to be much higher to radiate the heat produced by an astronaut.

10 *Estimating the metabolic activity of an astronaut working in space to be 200 W, what emissivity should the spacesuit of 3 m^2 surface area have if its outer surface is at a temperature of 20 ºC and it radiates at a rate that matches this activity?*

Answer: 0.16

Our astronaut working on a modest task might generate 200 W (about twice the basic metabolic rate of a fit person not yet middle-aged). If the emissivity of the spacesuit (in the infra-red where it emits its radiation) is α and its surface area is 3 m^2, then the energy emitted by the spacesuit at temperature 293 K (20 ºC) is such that $200 = 3\alpha\sigma 293^4$. Hence $\alpha = 200/(3\times5.67\times10^{-8}\times293^4) = 0.16$.

Conclusion: You might think that freezing to death is the hazard in the cold of space but overheating can be a serious problem. If the emissivity of the spacesuit is less than the figure above then for that rate of working it can't radiate away heat fast enough. If the outside of the suit cools down more, then the same applies or if the astronaut works harder there will be overheating within the suit. In reality, keeping the temperature inside the suit at a comfortable level is not an easy technological problem to solve.

11 *How large must solar panels be at the distances of the solar system planets and their moons to generate 1 KW of electricity when held perpendicular to the Sun's rays?*

Answer: there is a table at the end of the following calculation

Thinking of 'space' applications, we'll ignore atmospheric absorption for simplicity. We'll find the answer for the distance of the Earth from the Sun and use the inverse square law of radiation intensity to convert the area needed near the Earth to other distances. For distances closer than the Earth we'll take account of the reduced efficiency because of higher operating temperatures.

We need a figure for the efficiency of solar panels. Various web-sites quote numbers but it's not always clear what input spectrum is being assumed. We'll assume that 50% of the Sun's radiation is useful in activating the solar cell and that the solar panel is 15% efficient at converting this radiation to electricity. (You'll find web-sites discussing solar cells over 40% efficient but that is not the norm). There is also a decrease in efficiency with increasing temperature that will affect solar cells much nearer the Sun than the Earth. At the distance of Mercury, we'll take it that the cells are 50% less efficient. With these facts and a solar flux of radiation at the Earth of about 1300 W m^{-2} then we get a solar panel size at the Earth's distance of about 10 m^2. We'll take this as the baseline size.

Planet	**Dist (AU)**	**Area (m^2)**
Mercury	0.39	3
Venus	0.72	7.5
Earth	1.0	10
Mars	1.52	23
Jupiter	5.2	270
Saturn	9.6	920
Uranus	19.2	3700
Neptune	30.1	9000

For this calculation, planetary moons are at the same distance as planets. Pluto and the outer solar system are at 40 AU and beyond. In reality, solar panels degrade in efficiency in space due to bombardment by high energy particles so as time goes on the requirement gets bigger. A half-life of 30 years is not an unreasonable figure in the inner solar system.

Conclusion: enormous solar panels are needed in the outer solar system to generate significant power. Remember that the communications signal from a distant source decreases in strength with the square of the distance away of the source so more power is needed to communicate with the outer solar system. A better technology for the outer solar system may be to create enormous solar reflectors (much cheaper than enormous solar panels) to heat a central unit that generates electrical power by a standard turbine/alternator arrangement, or some variation of this. The technology of the moment is to put a nuclear-powered source in probes to the outer solar system.

12 *Could objects the size of the Earth in the Oort cloud be seen with the best telescopes?*

No!

Let's say that modern imaging can detect an object as faint as magnitude 30. We need a comparison object to gauge how bright an Earth-sized object would be. Let's choose Pluto. Take its brightness as m = 15 at a distance of 40 AU. Pluto is 0.2 times (1/5) the diameter of the Earth and hence an Earth-sized object with the same albedo as Pluto (0.15) will emit 5^2 = 25 times the light at 40 AU. This would give it a magnitude decrease x such that $2.512^x = 25$, making $x = \log(25)/\log(2.512) = 3.5$. At 40 AU an Earth-sized outer solar system object will therefore have a magnitude of 11.5.

Is such an object further away has a magnitude of 30 then the amount of light coming back will be $2.512^{(30-11.5)} = 2.512^{18.5}$ less. If it is z times as far away as Pluto then the amount of reflected light coming back with decrease as z^4. Therefore we can find how many times Pluto's distance such an Earth-sized object will be to have a magnitude m = 30 by setting $z^4 = 2.512^{18.5}$. Hence $z = 2.512^{(18.5/4)} = 71$. 71 times as far as 40 AU is 2840 AU.

2840 AU is a long way short of the Oort Cloud, which is considered to be well over 10,000 AU from the Sun. So, who knows what might be lurking in the Oort cloud! 2840 AU is, though, much further than the Kuiper belt so any objects as large as the Earth in the Kuiper belt should be spottable with modern telescopes. The problem is to distinguish them from the myriad faint stars of that magnitude and indeed from random 'noise' in the detector.

The Earth reflects about 200 W m^{-2} of light at a distance of 1 AU from the sun and hence an Earth-sized object of magnitude 30 and half the albedo will reflect about $100/2840^2 = 12$ μW m^{-2} of light, which is half the story of why it is so faint. The other half is because it is so far away.

You can do a different calculation starting from the observation that the Sun has a magnitude of -26.7 at 1 AU distance and making allowances for its size and luminosity deduce the magnitude of an Earth-sized body at 1 AU emitting 100 W m^{-2}. From this you can use the 4th power law to find how far away such a body needs to be to have a magnitude of 30. The answer is similar to the one above and the conclusion is the same.

13 *Venus's atmosphere is the first great impediment to terraforming the planet. Assuming the technology to do so, about how much energy would it take to exhaust the atmosphere into space so that terraforming could 'start again' by putting in place an atmosphere of appropriate composition and pressure?*

Answer: so much energy that it's beyond any current aspirations; see below for numbers.

First, how much atmosphere is there now? The surface atmospheric pressure 9.2 MPa (~ 90 times Earth's sea-level pressure); this means that the weight in a column of atmosphere of cross section 1 m^2 produces a force on the surface of 9.2×10^6 N. The local value of g = 8.87 m s^{-2}. Hence the mass m in the column is such that $mg = 9.2\times10^6$ N, giving $m = 1.04\times10^6$ kg. That's 1000 tonnes of atmosphere above every square metre of surface. Venus radius = 6052 km giving an effective surface area of $4\pi r^2 = 4.6\times10^{14}$ m^2. Hence the atmospheric mass M is 4.8×10^{20} kg. This is a lot, 0.01% of the mass of the planet. The escape velocity, v, from the surface of Venus is 10.4 km s^{-1}. To give that mass an escape velocity requires a kinetic energy of $\frac{1}{2}Mv^2 = 2.59\times10^{28}$ J.

This is an astronomical amount of energy by any measure. At current rates, it represents mankind's total energy use for 25 million years. Venus receives about 2 kW of solar energy per m^2 on its upper atmosphere (the majority of which is currently scattered away), which translates to 7.3×10^{24} J per year of energy. So the energy required equals the total solar irradiation of Venus in over 3500 years, and more of course because any technology to harness this energy will not be 100% efficient. Alternatively, getting the energy on the planet by converting mass into energy ($E = mc^2$) would require the conversion of 280 million tonnes of matter.

How did the Earth get rid of its CO_2? Mainly by co-opting biology to convert it into limestone over many hundreds of millions of years (though no conscious decision was made!). Terraforming Venus? Forget it for at least very many thousands of years.

14 *What is the best idea for personal transport on Mars?*

This is a suggestion for some lateral thought, not a solution. I got to wondering, as one does, about the best form of personal transport on Mars. It's not that I'm planning to go there but some people are and I've no doubt that some 'professionals' in the business have given this serious consideration. An averagely fit person on Earth on a normal bicycle will be doing well to sustain a speed of 30 km h^{-1} (18.8 mph) on the flat. The limit to a cyclist's speed is provided by air resistance. On Mars, air pressure is about 1/200th of that on Earth at Mars' datum and even less on the continent sized Tharsis Plateau that is well over 5 km in height above datum. Since a cyclist's limiting speed is determined by the inverse of the square root of the air density, other things being equal, does that mean a cyclist could maintain a speed of about $30\times\sqrt{200} \approx 400$ km h^{-1} on Mars? Well of course other things aren't equal so what are the issues?

Perhaps the first piece of physics to note is that your momentum on Mars at 400 km h^{-1} would be just the same as it is on Earth, so a crash at that speed on a bicycle would be life terminating, no doctor's verification necessary. Factors that aren't equal on Mars are that what atmosphere there is contains no oxygen, temperatures are normally well below zero and UV above safe limits so you will be travelling in a full space suit, assuming you will want to get off your transport to walk around. In addition, gravity is 0.376 that on Earth and the ground is strewn with rock, boulders and sand. Over time a very fine dust will threaten to get onto and into all exposed parts. So far, Mars rovers haven't really shown us 'typical Mars' since they have been sent to areas as free from obstacles as possible to maximise their chances of a safe landing. The weather and water on Earth that creates flat land has been absent on Mars for well over a billion years so a lot of Mars is not flat and nowhere is it tarmac road hard and smooth. Mars' average distance from the Sun is about 1.5 times that of the Earth so incident sunlight will be typically down by a factor of 2.3, sometimes more. However, though there is some atmospheric haze, the general absence of cloud means that sunlight falling on a well oriented solar panel normally receives several hundred watts per square metre, as good as at many places on Earth, and more reliable.

So this is the environment. Now design your personal transport. Make a list of the pros and cons of bicycle, tricycle or quad bike? What about a pogo stick, or walking on stilts? How much mechanical power can you deliver wearing a spacesuit? The reduced gravity is likely to weaken skeleton and muscles in the long run. Does carrying your oxygen set the limit on how long you can go for, or the need to carry food and water and the means to ingest them? Is your device stable following impact with a rock or leaving the ground at speed? Electrical power seems attractive but accessible indigenous raw materials are just stone, sand and carbon dioxide so it's likely that the whole device will need to be designed on Earth and sent out, at least in kit form. What are you going to order?

JSR