On balloons, etc: basic science applied to planetary atmospheres

Gravity is less anywhere else in the solar system where we can set foot on than it is on Earth. Would we just float, then, on the Moon or on Mars, for example? Floating involves being buoyed up by your surroundings so on places like the Moon or on asteroids where there is no atmosphere, floating as such is impossible. What about Mars then, which has a lot less gravity than on Earth, or Venus that has an overabundance of atmosphere? The first thing to notice is that floating is achieved if your density is less than that of your surroundings. Your density doesn't change when you go to Mars or Venus, since density is just mass per unit volume and neither of these changes. What changes is the density of your surrounding atmosphere. Even on Venus, the atmosphere isn't as dense as you or I so a more realistic question is "How easy is it to make a balloon that floats in alien surroundings, where gravity is different from that on Earth and so is the composition of the atmosphere and the temperature of the atmosphere?"

That sounds a complex question but in fact it's one that you can answer using basic science that you already know. The numbers on the next page are numbers that you yourself can deduce. This note shows you how.

Local atmospheric density is the key issue in determining how much mass a balloon can lift, but not the only issue since the gas you are going to fill your balloon with is also influenced by local conditions. Atmospheric density also relates to the impact loading of a given wind speed, the effectiveness of a hovercraft and other issues related to being on a different planet (or moon with an atmosphere) but we'll not go into those here.

Ideas you will need are:

- the definition of density
- pressure as force per unit area
- the relation between weight and mass
- the ideal gas law relating pressure, volume and temperature in a gas

Assumptions:

- Constant atmospheric temperature (in K);
- constant gravity g over the height of atmosphere;
- constant composition (i.e. mixing of atmospheric ingredients);
- ideal gas law.

Deductions:

From the basic definition of pressure,

Pressure at surface, $P(0) = M_c\, g$ where M_c is the total column mass per unit cross-section ($1\ m^2$), i.e. the mass of atmosphere that is above a square metre of the surface.

For the same column mass but lower gravity (g) you get less surface pressure. The surface gravity is therefore a key variable when it comes to pressure. This is just what the basic physics equation 'weight = mg' is saying. From the above, M_c can be calculated if the surface pressure and strength of gravity are known.

Start with the ideal gas law "PV = nRT" (n is the number of moles in the volume V) and the definition of density ρ = mass/volume = nM/V, with M as the molecular wt (the molecular weight in kg is a "kilomole", abbreviated kmol). Using these two relationships you can see that the density and pressure are related by

Density at surface, ρ(0) = P(0)M/RT (R in J K^{-1} $kmol^{-1}$ to get density in kg m^{-3})

The line above shows that density depends not only on surface pressure (and hence g) but on atmospheric composition and temperature. Larger temperatures reduce density, just as you would expect from everyday experience.

The pressure and density decrease with height exponentially with factor $e^{-h/H}$, where the scale height H is given by RT/Mg. You can deduce this from the facts above, along the lines suggested in the meteorology lectures, for those who take these too. H is the height at which the atmosphere decreases in pressure (or density) by a factor of 1/e. Since H = P(0)/(ρ(0)g) = M_c/ρ(0) then you can also visualise H as the height the atmosphere would be if all the gas in it were at the same density as it is at the surface. For the Earth this is 8 km.

[We shan't use the following two facts but you might like to notice in passing that surface gravity $g = GM_{pl}/r_{pl}^2$ where M_{pl} is the mass of the planet (or moon) and r_{pl} its radius. The total amount of gas in the atmosphere of a planet is $4\pi M_c r_{pl}^2$].

Some data:

R = 8.314×10^3 J K^{-1} $kmol^{-1}$; M for CO_2 = 44 (taken as atmosphere for Venus and Mars); M for N_2 = 28 (taken as value for Titan); M for Earth (~78% N_2 and 21% O_2 and 1% Ar) = 29 (ignoring details of isotopic abundance, minor constituents and variation of water content).

Results:

The first 5 columns below are given data, the final 3 are deduced from the formulae above.

The temperature figures are most approximate, because the temperature does change a bit with atmospheric height. Temperatures a little lower than average surface temperatures have been used.

Body	**T** K	**M**	**P(0)** Pa	***g*** ms^{-2}	**M_c** kg m^{-2}	**ρ(0)** kg m^{-3}	**H** km
Earth	270	29	1.0×10^5	9.81	1.02×10^4	1.28	7.98
Venus	700	44	9.3×10^6	9.04	1.03×10^6	69.48	14.81
Mars	230	44	800	3.69	2.17×10^2	0.0182	11.92
Titan	80	28	1.5×10^5	1.35	1.11×10^5	6.24	17.81

Points:

Venus has 100 times the column mass of the Earth's atmosphere on this calculation and Mars only about one fiftieth. However, the density on the surface is 'only' 54 times as great on Venus (largely because of the higher temperature) and on Mars it is $1/70^{th}$ as large. On Titan, the atmospheric surface density is almost 5 times as large as the Earth's and this moon has a much more extended atmosphere than the Earth's, due to its greater column mass and lower gravity.

On balloons:

An empty plastic bottle floats easily on water because it's filled with a gas that's very much less dense than the water. A balloon skin must be filled with something of less density than its surroundings to achieve any lift. If the balloon skin can't hold a shape except by virtue of the pressure within then the internal gas will be at least at the pressure of the external atmosphere. The obvious choice for the filling of an extra-terrestrial balloon is hydrogen (H_2), since it's the gas with the least molecular weight and extra-terrestrial atmospheres don't have oxygen in them to make hydrogen a fire hazard. Also, hydrogen can be made by electrolytic decomposition of local water. The filling of hydrogen gas will experience the same temperature, pressure and gravity as the local atmosphere and hence the mass that can be lifted by a hydrogen filled balloon will be $(\rho(0) - \rho_{H_2})V = \rho(0)V \times (M - 2)/M$.

Thus on Venus and Mars, hydrogen is an even more effective filler than on Earth because it is replacing a gas (CO_2) of greater molecular weight than that of the Earth's atmosphere.

Venus and Titan are obvious candidates for balloons, since the surface density of their atmospheres is appreciably greater than on Earth. The gain on Venus is a factor of 84 (according to the figures in the table above) but on Venus, though, it's so hot that finding a suitable balloon material won't be easy. On Titan, the gain is a factor of 7.6, though it's so cold that finding a material that won't crack will also not be easy. Perhaps foam expanded with H_2 can do it.

Mars is unfavourable since the density of the atmosphere on Mars is pretty low. For a balloon to float whose total mass is just 10 kg, we need $10 = 0.0182 \times (42/44) \times V$ and hence a volume V of 575 m^3. That is a sphere of diameter 10.3 m which will have a surface area of some 500 m^2. If the material it is made of has density of 1000 kg m^{-3} (a ball-park figure) then a thickness of 0.01 mm (i.e.10 microns) will give the skin alone a mass of 5 kg. If the thickness is only 20 microns then the balloon won't be able to lift anything else except itself on Mars and in reality it would soon leak a bit and sink to the ground. Doubling the diameter will multiply the volume by 8 and the surface area by a factor of only 4 and hence a 20 micron skin balloon will begin to have some lift over and above its own weight. However, that's a pretty big balloon for a pretty small lift.

JSR