Surface Gravity and Interstellar Settlement
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Abstract. *Gravity determines the scale of many physical phenomena on and above a world's surface. Assuming that tool-using intelligences come from, and would settle, worlds with solid surfaces and gravities equal or less than that of their origin, we note that such worlds in the Solar System have surface gravities significantly lower than that of Earth. The distribution of these surface gravities clumps around factors of about 2.5 and favors worlds with about one-sixth Earth gravity, conventionally considered too small to retain atmospheres. Titan, however, shows that low surface gravity does not, in itself, preclude the presence a substantial atmosphere. Where small worlds have low exobase temperatures,and protection from stellar winds, substantial atmospheres may be retained.*

Significantly lower surface gravity affects a number of physical phenomena that affect environment and technological evolution--most significantly, heavier than air flight is easier and races evolved under such conditions should reach space at an earlier level of development. It is proposed that low gravity worlds in other planetary systems could be the sites of native or transplanted interstellar settlement, and, perhaps, be the majority of such sites.

1. Introduction

The possibility that life-sustaining worlds may be found around other stars has intrigued people ever since the true natures of stars and planets were ascertained. Speculation concerning such worlds has conservatively centered around Earth-type worlds with Earthlike distances from sunlike stars and Earthlike surface conditions. (Dole, 1970; Breuer 1982; Baugher, 1985). This seems reasonably safe, but may be overly restrictive.

An important feature of any world is its "surface gravity," the downward force per unit mass that anything experiences at the surface in question. A look at the other solid bodies of the solar system shows that on all of them have surface gravities less than Earth, and only Venus comes close. A given mass, be it a mountain, a parcel of air, or a living being weighs less on these worlds than here, and this paper shall explore some of the physical consequences of that difference.

The discovery that Saturn's moon, Titan, has an atmospheric pressure that is greater than Earth's, that tidal heating of Jupiter's inner satellites melts the ice of Europa and drives volcanoes on Io, and that Mars in the past has had rain and floods serves notice that worlds that are significantly less massive than Earth and have significantly less surface gravity can still have the deep atmospheres and liquid water temperatures needed to sustain life.

2. Surface Gravity Basics

Mass is, roughly, a measure of the amount of substance. Weight is the force by which that substance is attracted to another mass. This force is directly proportional to the product of both masses and inversely proportional to the square of the distance between them. A spherically symmetric planet can be treated as if all the mass were at the center, so the relevant distance is the radius from the center to the object.

While the force of gravity varies with the mass of an object, the force per unit mass does not. By Newton's law, force divided by mass gives acceleration and, indeed, if nothing resists gravity, objects fall, gaining velocity at a rate that is called "the acceleration due to gravity, or "g." On Earth, g is 9.81 m/s^2.

This acceleration varies slightly according to altitude and the centrifugal force of a spinning world, but these variations are usually very small on the surface of a solid world, and thus aren't important for the purposes of this paper (an exception to this will be discussed briefly later).

Meters per second squared are the units of acceleration in the "System Internationale," the version of the metric system which physical scientists and engineers, world wide, have agreed to use. In many older astrophysical texts, surface gravity is given in centimeters per second squared. In astronomy references, surface gravity is often given in terms of Earth's surface gravity. Finally, in older references, and some popular one can still find surface gravity in feet per second squared. In doing calculations, of course, it is important to use the same units for all numbers.

Table 1. Earth's surface gravity in various units .

System/Units	Value
System Internationale (S.I., mks)	
meters per second squared (m/s^2)	9.81
Centimeter-gram-second (cgs)	
cm per second squared (cm/s^2) (gal)	981
Astronomical, Earth-normalized ($\oplus$)	
Earth's gravitational acceleration, $g_\oplus$	1.0
English, foot-pound-second (fps)	
feet per second squared (ft/s^2)	32.17

For bodies of uniform density exposed to vacuum (much like the moon), gravitational force is at a maximum at the solid surface. Above the surface, it decreases as the square of radius from the world's center (not altitude). The layers of mass above a given surface don't count in the calculation of surface gravity at

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Note: This is an interdisciplinary paper geared toward authors, anthropologists and nonphysical science professionals, so an effort has been made to increase accessibility at the cost the compact but unfamiliar terminology and notation that would shorten the paper. Some simple equations, have been included for those interested in making calculations. But this is mainly a survey paper, and with the exception of some of the material on surface gravity distribution, data are from representative secondary and tertiary sources--in some cases being read from graphs--so readers with a need for high precision are advised to check references.

that surface because the pull of the closer mass just above is exactly balanced by the pull of all the mass of rest of the shell on the other side. A spherical shell of uniform density exerts no gravitational pull on anything within it.

A concept closely related to surface gravity is escape velocity, "v e ". An object leaving Earth at escape velocity will coast away from Earth indefinitely, slowing to a halt at infinite time and distance (In the real universe, of course, it will coast into some other object's sphere of influence well short of infinity).

Note in Table 2 that, like gravitational acceleration, escape velocity is a function of the body's mass and radius, but in this case it decreases proportionally as the square root of distance from the center and is thus less sensitive to altitude.

Circular orbit velocity, v c, is the minimum velocity a space vehicle must obtain to stay at a given radius from the center of the body. This is less than escape velocity by a factor of the square root of two. It is the minimum velocity any planet-bound culture must achieve to get into space.

If one exceeds escape velocity, there would be some velocity left over after one reaches an infinite distance, or, more practically, where the gravity of some other body equals that of the body one left. This residual velocity is called "hyperbolic excess velocity" (since the path of the escaping body is a hyperbola, and denoted by "v_∞ " or "v_{inf} " for velocity at infinity.

v_∞ is typically much larger than the velocity "Δv" one adds to escape velocity, because kinetic energy goes up as the square of velocity, and Δv represents the addition of kinetic energy to an already moving body [$(v_e + \Delta v)^2$ is larger than $v_e^2 + \Delta v^2$].

Table 2. Gravity-related quantities for representative bodies (1)

Quantity	Symbol/Equation	Venus	Mars	Titan
Mass (10^{24}kg)	M	4.869	0.642	0.1346
Radius (km)	R, r	6,051	3,397	2,575
Surface g(m/s^2)	$g = M \cdot G/R^2$	8.87	3.71	1.35
Exobase g(m/s^2)	$g_x = M \cdot G/r^2$ (2)	7.81	2.97	1.01
Circ. orbit vel.	$v_c = \sqrt{(M \cdot G/r)}$	7.096	3.358	1.74
Escape vel.	$v_e = \sqrt{(2 \cdot M \cdot G/r)}$	10.036	4.750	2.457
Hyperbolic vel.	$v_\infty = \sqrt{((v_e+\Delta v)^2 - v_e^2)}$ (for Δv = 1 km/s)	4.590	3.240	2.431

(1) Data from Lang 1982, G is the universal gravity constant (6.672 E-11, in S.I. units), and Δv is the amount by which an object's velocity exceeds v_e at r.

(2) The exobase and circular orbit altitude are assumed to be at 400 km altitude, i.e., $r = R + 400$ km

3. The Distribution of Surface Gravities Among Worlds

One of the benefits of the Voyager program is that we now have reasonably good masses and diameters for the Planets and the larger moons in our solar system. Table 3 lists these bodies in order of surface gravity.

One thing that becomes immediately apparent is that the surface gravities fall into groups, the central value each differing from that of the next group by a factor of about 2.5. Also, the groups alternate in size: many, two, many, two, many, one. The equation for expressing the central values of these groups is:

$$g \approx 0.66 \times 2.47^n$$

where n is an integer ranging from -1 to 4.

Twenty-four bodies fall within 25% of the values predicted by this equation, and the remaining three, all small, heavily bombarded moons lie within 40%.

It is interesting, and perhaps somewhat surprising, to note that the surface gravity of the sun (taken at its zero-age radius), the theoretical zero-age main sequence (ZAMS) seems to fit the relationship as well. From there on, stellar data uncertainty make it difficult to see any periodic structure. It could be that at the high mass end as well as the low end, the periodicity of surface gravity broadens into a continuum.

One way of illustrating that something occurs in regular intervals is to create a window with a width equal to the suspected interval and plot the number of data points that fall in each part of the window. This is the "power spectrum" of the phenomena at hand–a term borrowed from communications relating to the distribution of power across a range of wavelengths.

Table 3. Surface Gravities Observed vs. Predicted

Name	Mass(1)	Radius	Surface Gravity Observ.	Surface Gravity Predict.	Deviation
	(kg)	(m)	(m/s^2)	(m/s^2)	%
Sun(0-age)	1.99 E30	606903	360.3	370.2	-3
Jupiter	1.90 E27	71400	24.87	24.57	1.2
Neptune	1.02 E26	24764	11.1	9.946	11.6
Saturn	5.69 E26	60330	10.43	9.946	4.9
Earth	5.98 E24	6378	9.81	9.946	-1
Uranus	8.68 E25	25559	8.87	9.946	-11
Venus	4.87 E24	6052	8.87	9.946	-11
Mars	6.42 E23	3398	3.71	4.027	- 8
Mercury	3.30 E23	2439	3.70	4.027	- 8
Io	8.89 E22	1820	1.79	1.63	9.8
Luna	7.35 E22	1738	1.62	1.63	- 1
Ganymede	1.48 E23	2640	1.42	1.63	-13
Titan	1.35 E23	2575	1.36	1.63	-17
Europa	4.79 E22	1565	1.31	1.63	-20
Callisto	1.08 E23	2420	1.23	1.63	-25
Triton	2.14 E22	1350	0.783	0.66	18.7
Pluto	1.29 E22	1150	0.651	0.66	- 1
Titania	3.48 E21	790	0.372	0.2672	39.2
Oberon	3.03 E21	760	0.35	0.2672	31
Charon	1.77 E21	595	0.334	0.2672	24.8
Rhea	2.49 E21	765	0.284	0.2672	6.2
Umbriel	1.33 E21	585	0.259	0.2672	- 3
Ceres(2)	7.99 E20	457	0.255	0.2672	- 4
Ariel	1.26 E21	580	0.250	0.2672	- 6
Iapetus	1.88 E21	730	0.235	0.2672	-12
Dione	1.05 E21	560	0.223	0.2672	-16
Tethys	7.50 E20	530	0.178	0.2672	-33

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(1) Mass and Radius values (except for Ceres) mainly from Lang (1992), (2) There is no directly measured mass for Ceres. It's density estimated at 2,000 kg/m^3 based on comparison with Phobos and Deimos, which have similar surface composition and densities of 2.1 and 1.9 Mg/m^3 respectively (Hartmann 1993).

Figure 1. shows how often (analogous to power) one finds objects in a given range of deviation from "periods" of 2.47.

Actually, instead of g itself, the graph uses the natural logarithm of g--that way part of an interval of a few meters per second up around Earth's surface gravity is as wide as an interval of a few tenths of a meter per second squared down by Pluto. This is fair--it's the proportion that counts.

Another interesting thing to do is to look at an intervals of 2.47 squared, just twice as wide, logarithmically as the first interval. Now we can see two distinct peaks-- the smaller (hatched) one is Jupiter, Mars, Mercury, Pluto, and Triton--all at even powers of "n" with the larger population of objects at odd powers.

Unfortunately, this rule of 2.5 hasn't appeared in literature searches to date, and the author has no explanations of his own at this time. One does, however, note the presence of resonances in many complex, chaotic processes and suspects that once the mechanics of planetary accretion are much better understood, an explanation will emerge.

Whatever the reason for it, if this rule is replicated in other solar systems, then there may be some increased hope of finding bodies with surface gravities like that of Earth, Mars, and the Moon, and less expectation of finding bodies that have two thirds or one and a half times Earth's surface gravity.

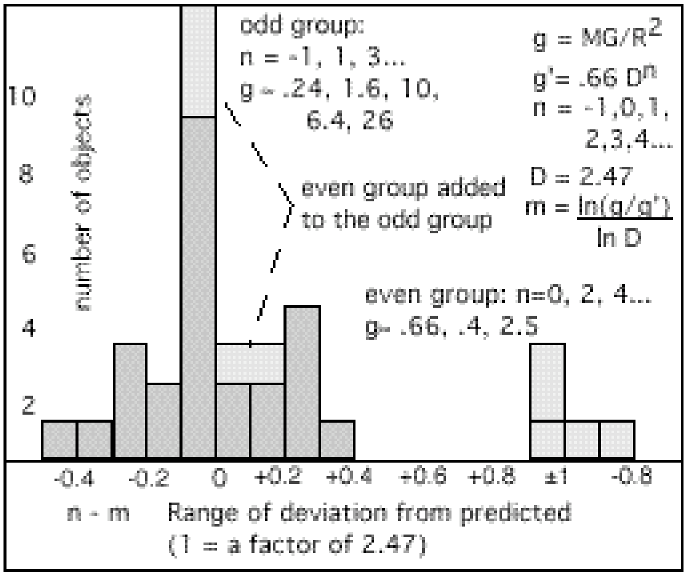


Figure 1. Number of objects versus predicted surface gravity

The bulk of such worlds appear to be the satellites of gas giant planets. Recent discoveries have shown that gas giant planets can exist much closer to their primary stars than Jupiter is to the sun. (Marcy, 1997). We don't know the precise mass of such worlds because they are detected by the line of sight velocity variations they give to their primary star, we don't know the angle at which their orbital planes are tipped away from edge-on; we can only get a minimum mass (the case where all the velocity difference is along our line-of-sight).

Three planets apparently circle Upsilon Andromeda, with minimum masses of 0.71, 2.11, and 4.71 Jupiters (Butler et al. 1999). If the inclination of this system were 50 degrees (view angle 40 deg from edge-on) their masses would be .93, 2.75, and 6.15 Jupiter. For theoretical reasons, all objects from about half a Jupiter mass to a hundred Jupiter masses (red dwarf size) should have about the same radius, their surface gravities would then be in reasonably good agreement with the rule of 2.5.

47 Ursae Majoris apparently has a planet at least 2.3 times the mass of Jupiter in a circular orbit about 2.1 AU from this near twin to the sun. Giant planets of that size should have not problem holding on to Titan-sized moons even as close as 2 AU to a sunlike star.

4. Surface Gravity and the Planetary Environment

The environment near the surface of a moon or planet is described by reference to various layers. Figure 2 gives the names of some of the layers found near the surfaces of worlds. For bodies that don't have a well-defined solid surface, such as Jupiter, some other surface must be specified--such as the radius at which the atmospheric pressure equals that of Earth. Note that the use of the names of these layers is still evolving may vary somewhat from text to text.

Surface gravity affects the vertical scale of processes in these layers by determining how much mass is needed to generate a given amount of pressure.

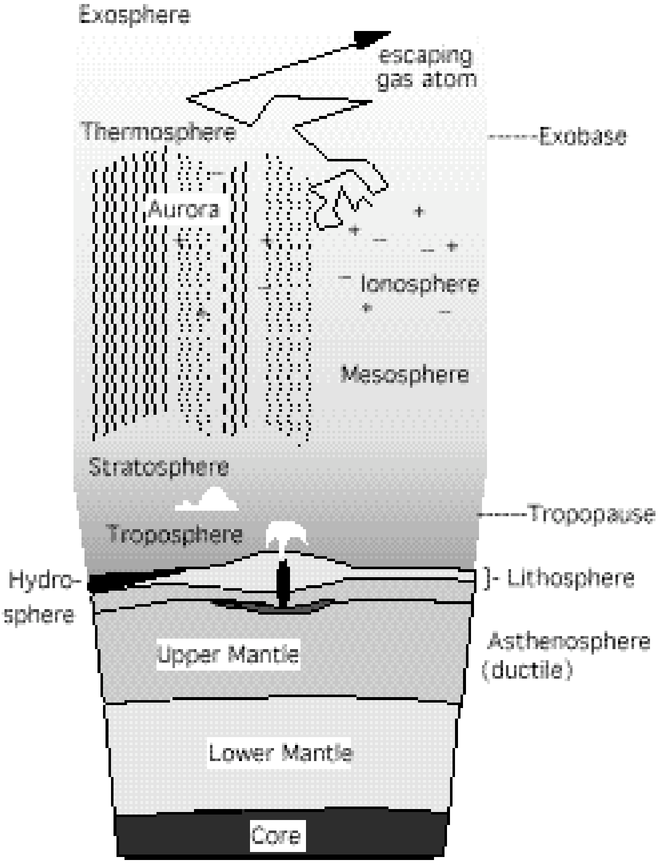


Figure 2. Overview of world layers

4.1 Exosphere and Atmosphere Retention

The most important thing a habitable planet has to do is to retain a biologically compatible atmosphere. A planet on which life evolves to intelligence must retain its atmosphere for billions of years. A planet which has been terraformed may only need to retain an atmosphere for a few thousand years (it can, of course, be replenished), a much less stringent condition.

There are two main ways that an atmosphere leaks away from a planet. They are thermal evaporation and "pick-up" by the solar wind. Gravity is important in the former mechanism and not so much in the latter. In thermal evaporation, atoms that exceed escape velocity at the top of the atmosphere can generally be considered to have escaped (Titan, as we shall see, is a little different). In solar wind pick-up, magnetic fields generated by passing solar wind ions accelerate atmosphere ions to escape.

Language can be problem here--we are using words that imply sharp distinctions and boundaries for phenomena that are fuzzy and are better described by distribution curves and statistics than categories. For instance, an atmosphere doesn't have a sharp top–it just gets thinner and thinner as you go higher and higher. Eventually, one notices that gas molecules can travel for many kilometers before hitting other gas molecules. Now the gas molecules can start to sort themselves out, with the lighter ones rising to the top--causing the average mass per molecule to decrease. Table 4 shows what happens on Earth.

Table 4: Earth's Atmosphere
(Source: Handbook of Chemistry and Physics, CRC Press, 1986)

Altitude (km)	g (m/s^2)	Pressure (bar)	Ave. Mass (amu)	Mean Free Path (m)	Temp. (K)	Ave. Speed (m/s)	Escape Vel. (m/s)
0	9.81	1.001	28.96	66 E-9	288	459	111
25	9.73	25.5E-3	28.96	2 E-6	222	402	111
50	9.65	0.80E-3	28.96	79 E-6	271	445	111
100	9.51	0.32E-6	28.40	0.142	195	381	110
200(1)	9.22	0.85E-9	21.30	240	854	922	110
400(2)	8.68	1.4E-11	15.98	16 km	996	1149	108
600	8.19	8.2E-13	5.54	1400 km	(3)	1954	105
1000	7.32	7.5E-14	3.94	3100 km	(3)	2318	104

(1) orbits possible, but with high drag (2) typical orbital altitude for telescopes and space stations (3) Earth's exosphere temperature is highly dependent on solar activity, often exceeding 1500K

There are various was of defining the "top" of the atmosphere, depending on one's concerns. By 60 km (about 200,000 ft), one has a pretty good vacuum for most purposes, and this is the top of the aviator's and the meteorologist's atmosphere. The last thin layer of "noctiluminescent" clouds lies just below.

One can get a pair of astronaut wings (in the US) by going to 80 kilometers. But the gasses there are still reasonably well mixed and a satellite or meteor traveling at interplanetary velocities would be heated to incandescence by going through air that thick. Air molecules, on average, can't travel a tenth of a millimeter before running into another one. Ultraviolet light and charged particles are knocking molecules apart, and light atoms are becoming more common.

One needs about 200 km for temporary orbits; this is the top of the atmosphere for spacecraft. Molecules bouncing off a space shuttle can go a quarter of a kilometer before hitting anything else; shock waves are large, diffuse, and very low pressure. Dissociation of molecules by UV light, becomes more and more common, as evidenced by the lower average molecular weight. But this is still definitely part of the atmosphere, home of ionosphere phenomena such as auroras, and while the average density is low, sometimes the solar wind can boil more gas up from below and dramatically increase the density of this layer. Skylab came down early, not so much because its orbit came down-but because the atmosphere rose up more than expected to engulf it.

At 400 kilometers, you can count on staying in orbit for years. Molecules travel sixteen kilometers before they hit one another. With so much empty space between molecules, the assumptions of gas thermodynamics begin to falter for small volumes, and one has to keep track of which molecules are moving how fast to model things. Ions, currents, magnetic fields and so on are more important than the ideal gas laws. This is the top of the thermodynamicist's atmosphere.

600 km is a good number for the Earth's exobase. By this altitude, even most astrophysicists will concede you are in space. The mean free path of atmosphere particles has increased to 280 km. A particle headed upward will probably not encounter another one before being pulled back by gravity. The atmosphere has differentiated so that it is mostly hydrogen and helium, with an occasional heavy atom to raise the mass average. Table 5 compares four solar system exobases.

The average particle speed at Earth's exobase is well short of escape velocity--however, this average contains much atomic hydrogen. Atomic hydrogen, torn from water and methane by the sun, has one tenth the mass and about 3 times the average velocity as nitrogen for the same average particle energy--even at 1000 K, only about forty percent of escape velocity.

"Average" here means the middle of a distribution curve--and a significant number of particles may be moving three to four times average velocity--and thus exceed escape velocity.

Earth is losing hydrogen, this way but slowly. A low thermal minimum in the atmosphere freezes out hydrogen-containing compounds and reduces the rate that they reach altitudes where they are rapidly broken up by ultraviolet light with little chance to recombine. (Earth also gains hydrogen from the impact of neutral atoms in the solar wind, and the impact of meteors containing hydrocarbons and ice). At the exobase, pressure and temperature are very different things than they are down at the bottom of the atmosphere. An ordinary thermometer shaded from both the Sun and Earth at 600 km would likely measure a temperature of a few tens of kelvins or so--it would lose heat by radiation much faster than it would gain heat from the occasional fast moving molecule. Some sources don't bother with exosphere temperature above 1000K.

Table 5. Exobase Temperatures and Velocities

Body	Venus	Earth	Mars	Tita
Surface g (m/s^2)	8.87	9.81	3.8	1.
Press.(bars)	90	1	0.008	1.
Surface temp (K)	700+	270	218	96
.001 mb level temp	180	190	150	≈150
Exobase temp	≈300(1)	≈1200	≈210(2)	175
Exobase Alt.(km)	≈135	≈600	≈175(2)	≈1500
O_1 velocity (m/s)	394	790	558	322
H_1 velocity (m/s)	1579	3159	2234	1290
Escape vel.(km/s)	10000	10850	4750	2457

(1) Day side, 130 K night side. (2) may be low.

Nonetheless, calculations of this sort give a rough way to compare the temperatures of space around the various planets. Generally, if thermal velocities are less than around 20% or so of escape velocity, the atmosphere will have a lifetime of billions of years, but if they are within a factor of two or so, the lifetime will be on the order of only thousands of years. On Titan and Earth, large reservoirs (such as lakes or oceans) apparently replenish the gasses that are leaking away.

Mars and Venus are exposed to the solar wind, and while they have low exobase temperatures, they lose much hydrogen by solar wind "pick-up." The solar wind contains charged particles, and like all moving charges, they generate a magnetic field. Ions in a planet's upper atmosphere that are created by incident solar wind particles and ultraviolet light can be accelerated by these magnetic fields and carried off.

The same thing can happen to matter on the surface of satellites of rapidly rotating planets with off-axis magnetic fields . Jupiter's field lines whip by Io at some 57 km/s, for instance, and the tilt gives this relative velocity a component normal to the field lines, resulting in a strong electric field that accelerates ions--mostly from the satellite's vigorous outgassing (figure 3). This energy shows up in Jupiter's very energetic radiation belts helps heat its exosphere temperature to some 1500 K .

Saturn's magnetic field, however, is nearly axially symmetric and therefore does not wobble and generate a high electric field gradient and so does not accelerate ions to really high energies.

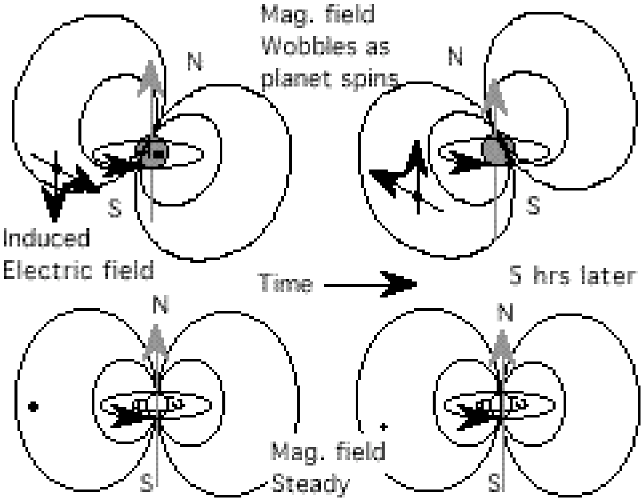


Figure 3. Magnetic field acceleration of ions in the exosphere.

> Physics note: Consider a flat circular loop of wire carrying a current and spinning around an axis perpendicular to the loop at a constant rate. The spin helps determine how fast the charge carriers inside the loop move. But there's no change in the magnetic field they generate to accelerate a test charge. Now tilt the loop. The spin makes it wobble and the change in field accelerates ions.

Also, Saturn's rings tend to take particles out of the magnetosphere, unlike Jupiter's moon Io, which contributes heavy ions that act as the stirrers, spalators, and heaters in Jupiter's exosphere. High energy particle counts around Saturn are typically two orders of magnitude less than around Jupiter. But Saturn's field is just extensive enough to protect Titan from solar wind.

The net result is still that the exospheric environment near Saturn is only about 400 kelvins, decreasing to around 200 K at Titan's distance. This plays a significant role in Titan's ability to retain an atmosphere, despite the low escape velocity at Titan's exobase. Prior to Cassini, Titan was estimated to lose mass at a rate of about 1E25 Nitrogen atoms per second (≈7400 tonnes/year) by non-thermal processes (Strobel et al. 1992 p.525). At this rate, it would take about 100 billion years E9) for a tenth of Titan's ten thousand billion tons (1 E19 kg) of atmosphere to escape.

One more note on Titan; to completely escape Titan, gas must escape Saturn as well, and the escape velocity from Saturn at Titan's orbital distance is still a healthy 7.9 km/s--gas molecules just barely escaping Titan go into orbit around Saturn, and, likely as not, run into Titan again!

In fact, Titan's orbit is surrounded by a thin torus of neutral hydrogen (figure 5) and nitrogen, reminiscent of the much denser "smoke ring" in Larry Niven's novel The Integral Trees . Saturn's torus is gas that has escaped from Titan, but not from Saturn.

So, despite its low surface gravity and distended upper atmosphere and its low surface gravity, Titan still can retain hydrogen-containing molecules such as methane and ethane.

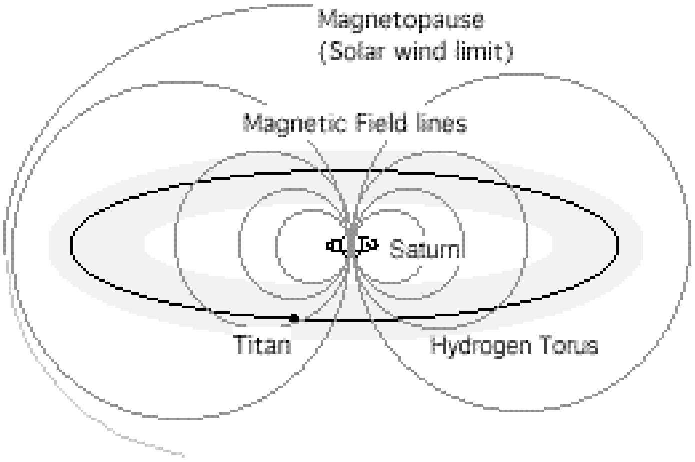


Figure 4. Hydrogen Torus in Titan's Orbit

<u>4.2 The Depth of the Mesosphere</u> .

Between the Exosphere and the lower atmosphere lies a region which, for most of its depth, lies at a constant temperature. While this part of the atmosphere is very tenuous, it is dense enough to drag orbiting objects into denser layers. It is also the home of the ionosphere, with its aurora, and of meteors. At the bottom of the mesosphere are those layers where ions and radicals form from compounds brought up from below. Figure 4. The neutral hydrogen torus around Titan's orbit.

Mesospheres are highly variable--they are sensitive to solar winds, planetary magnetic fields, night and day, and even, as we saw on Jupiter, comet impacts. They are easily polluted, and the pollution (whether artificial or natural) can have an influence far out of proportion to the tiny masses involved. The mesospheres of most planets are roughly isothermal, i.e. at constant temperature; Earth and, apparently, Titan (Strobel, et al. 1992) are exceptions in having a sharp secondary temperature minimum above their tropopause. If this didn't exist, Titan and Earth's atmospheres would have similar temperatures at the 1 μb level, where ozone is formed and the atmosphere starts to differentiate ; this layer is called the "homopause."

Note: Density scale height H is inversely proportional to surface gravity and directly proportional to temperature, so that (Hartmann 1992, 409):

$$s' = s \exp(-\square/H), \text{where } H = k\,T/(m\,g)$$

where s is density, □ is change in altitude, m is average molecular mass, k is a gas constant, 1.380662 E-23 J/K.

The local change in density with altitude is well represented by something called "scale height." This is generally the change in altitude needed to change density by a factor of "e," the base of natural logarithms (2.718...), though sometimes other factors such as 10 or 2 are used. For a given temperature, the lower the gravity, the greater the scale height.

Columns of nitrogen with the same pressure have seven times as much mass on Titan as on Earth (actually somewhat more--as one goes higher; Titan's gravitational acceleration decreases significantly). This means any incoming meteors or cosmic rays must plow through seven times as much mass on Titan as Earth to reach the same pressure layer. On Earth, one significantly increases one's exposure to cosmic radiation at high altitude, on Titan, one would be much better shielded.

4.3 Tropospheres and Surface Gravity

Assuming a planet or moon retains a dense atmosphere, will it be warm enough at the surface to support life? While the upper atmosphere temperatures that determine whether a planet will retain an atmosphere are affected by things besides solar input, the lower atmosphere's temperature is largely determined by the balance of energy input and radiation at the tropopause. Between, as one can see from table 5, atmospheres tend to have similar upper stratosphere temperatures.

This minimum temperature of the atmosphere generally lies just above the tropopause. Frequently, there is a haze layer here, and a "cold trap" where rising volatile compounds may condense and fall back instead of rising high enough being destroyed by UV. This reduces the loss of light atoms.

The higher the surface gravity, the more pressure it takes to support a given mass of air, and for a given gas density, the more rapidly pressure and temperature increase with depth. The rate that temperature changes with altitude is called the "lapse rate."

Imagine a small mass of neutrally buoyant air being carried deeper into an atmosphere by a convection current. The pressure on this mass of air increases because it is compressed by the weight of the column of air above it and the pressure of the parcels of air on either side (which are also supporting the columns of air above them). This compression increases the temperature of our parcel of air--but the air around it is at essentially the same temperature, so there is no easy way for our parcel to lose its heat so both temperature increase and volume decrease contribute to the higher pressure needed.

In dry air, this compression is called "adiabatic," which means "at constant heat." The laws of thermodynamics allow one to calculate the "adiabatic lapse rate" for a given set of conditions. Troposphere lapse rates tend to be roughly linear--each kilometer one descends increases temperature a given amount.

A difference between dry and measured lapse rates indicates energy gain or loss due to non-ideal gas behavior such as rain or evaporation. Condensation, for instance, releases heat The lapse rate of a wet troposphere is often less than the adiabatic rate. Such "subadiabatic" behavior would be expected near the surface of a world with oceans, for instance.

One can measure the temperature of different layers in the atmosphere by looking at different parts of the electromagnetic spectrum, and thus get an idea of the temperature profile of an atmosphere from a great distance. But there are many complications--some amounts derived for the Jovian atmosphere appear to have been off by a factor of two compared to first look Galileo probe readings (NASA, 1996). Nonetheless, these measurements can go a long way toward telling whether a world may have an atmosphere suitable for living organisms. Raindrops probably form on Titan and all of the giant planets as well as Earth--though different liquids are involved. Drops should fall more slowly in low surface gravity, and may grow large more easily due to lower terminal velocity. Terminal velocity is when a falling object's weight is just balanced by the resistance of the wind of its passage. Since the object's weight is determined by surface gravity, terminal velocity will be less where things weigh less. The drops will fall more slowly in low gravity, and the altitude bands in which drops can form will be deeper.

Table 6. Lower Atmospheres

Body	Surface (1)			Composition			Lapse Rates(3)	
	Gravity (m/s^2)	Pres. (bar)	Temp (K)	Chem. 1st.-%	2nd-%	Mass(2) (amu)	Calc(4) (K/km)	Data (K/km)
Venus	8.87	90	345	CO2-96	N2-04	44	-10.76	-8.
Mars	3.71	8E-2	218	CO2-95	N2-03	44	-4.42	-5
Earth	9.81	1	270	N2-78	O2-21	29	-9.2	-7.
Titan	1.35	1.6	95	N2-95?	Ar-05?	28	-1.3	-0.
Triton	0.78	2E-5	38	N2-95?	Ar-05?	28	-0.76	NA
Jupiter	24.8	1	165	H2-92	He-08	2.3	-2.2	-1.9
Saturn	10.5	1	140	H2-92	He-07	2.3	-1.2	NA
Uranus	8.61	1	75	H2-83	He-15	2.58	-7.97	NA
Neptune	10.84	1	80	H2-74	He-25	2.64	-8.00	NA

(1) Low density atmospheres (Mars and Triton) are highly variable. A giant planet "surface" is defined as the mean 1 bar level. (2) Average molecular mass (3) Temperature Lapse rate is the change in temperature per change in altitude: dT/dh. Negative means decreasing with altitude (4) Calculated from:

$$T/T' = (P/P')^{(\gamma - 1)/\gamma} \quad \text{(Crawford 1963, 137) and}$$

$$T' = T + dT; \quad P' = P + dP = P + g\,\sigma\,dh$$

where σ is density; $\gamma \approx 1.4$ for N2 and H2 and 1.3 for CO2 (Crawford 1963, 150); T is temperature, P is pressure and dh, dT and dP are small changes in altitude, and g is gravity.
(5) 1 bar (-107 C) to 2 bar (-67 C, -21 km) (NASA, 1996)

The lapse rate and change of pressure with altitude help determine the slope of warm and cold fronts moving through the atmosphere, and thus the width of bands of rainfall. Vertical circulation may be more ponderous in a low gravity atmosphere, involving more mass and thus greater thermal energies for a given horizontal scale, but rising and falling more slowly.

As one gets into upper atmospheric "wave" phenomena, surface gravity becomes important in determining the wavelength and propagation speed of such waves (Friedson, 1994). Since the densities of worlds vary significantly, the total surface area of a world is only loosely coupled to its surface gravity. Titan, for instance has a larger surface area than Mercury, despite having a little more than a third the surface gravity. The absolute size of the surface area limits the absolute size and energy of large-scale currents in the oceans and the atmosphere.

Smaller worlds close to stars or large planets will tend to be tidelocked and have lower rotation rates and less Coriolis force. With the sinkings and risings having greater vertical scale, there may be a tendency for the scale of related phenomena to be larger. Thus the fluid dynamics of small, low gravity worlds, may have more stringent boundary conditions as the increasing scale due to lower gravity collides with the decreasing room available with the smaller radius. Earth and Venus, for instance, have room for only a few "belts" in their atmospheres, while Jupiter has room for many sharply defined belts.

4.4 The Case of Titan

The adiabatic lapse rate varies inversely with scale height, which means it varies directly with local gravity. For a given kind of atmosphere, the higher the gravity, the faster things get warmer as you go deeper into the atmosphere. Compare Jupiter and Saturn, or Earth and Titan.

This creates the interesting situation wherein, if there is any internal or external source of energy at all, and the atmosphere is deep enough, one will eventually reach a temperature at which liquid water can exist--almost regardless of how cold the top is.

What if Titan's atmosphere extended further down? If it went down another eighty kilometers, the solid surface would have a radius of 2495 kilometers. (If the mass remained the same, its mean density would have to increase slightly, the surface gravity would be somewhat higher surface gravity the scale height less, but we'll ignore that for now.) An adiabatic curve would lead to a new surface temperature of about 300 kelvins–room temperature, but at a pressure of some 87 atmospheres.

This is about the same that a diver would experience at some eight hundred meters–well beyond the limit of what divers can do with even the most risky gas mixtures. The level of illumination would be very low, of course--perhaps a tenth of one percent of of what we get on a sunny day. But that is still much brighter than a full moon at night--unlike in our ocean depths, one would have no problem reading. It is noteworthy that Jupiter's atmosphere reaches liquid water temperatures at a tolerable seven atmospheres (NASA 1996).

Another interesting fact is that the total mass of Titan's atmosphere is larger than that of Earth's; Titan's surface area is only about one sixth of Earth's, but the mass of a column of air needed for its surface pressure is about ten times as great.

Suppose Titan were trapped in a gravitational resonance such as that which gives Io its volcanoes and keeps the surface of Europa liquid below a thin (astronomically speaking) layer of ice. The surface might then have Earthlike temperature and pressure. The atmosphere would be forced a little higher by the expanded troposphere, but the minimum temperature and exosphere temperature would be very similar.

The surface gravity of the Moon is higher than that of Titan, the Moon is outside Earth's scalding magnetosphere and further from the sun than Venus. So why doesn't the Moon have an atmosphere, at least one of heavy gasses?

While they have similar surface gravities, Titan's mass is almost twice that of the Moon, and Titan's escape velocity is about one and a half times as great--even at the top of its extended atmosphere. And beyond that, it has help from Saturn. The top of a hypothetical lunar exosphere would have a solar wind-driven magnetosphere and an exosphere temperature much like that of Venus or Mars, averaging around 250 kelvins, but peaking probably around 500 kelvins during the day.

The Moon, if given an atmosphere, should thus dry out rapidly from hydrogen loss, then loose nitrogen, oxygen, and carbon dioxide more slowly. Even argon would have an average thermal velocity greater than a quarter of escape velocity, and the atmosphere would evaporate in a few thousand years.

Could an atmosphere be put on the Moon? Given the massive capacity of a robotic economy limited only by solar energy and materials, the answer is probably yes. Exobase temperature might be brought down to about 200 kelvins by adding molecules that are very efficient radiators to the mesosphere. There might even be a way to give the Moon its own magnetic field in a configuration that would protect it from the solar wind and channel its ions into some kind of trap before they hit its atmosphere.

But even without such extreme efforts an artificial lunar atmosphere might last for thousands of years (Vondrak, 1974) Resupply of hydrogen would be probably necessary over the long run, but for the civilization that put the atmosphere there in the first place, this might be literally child's play.

This discussion so far neglects the chemical evolution of atmospheres as affected by surface gravity. There are many processes involved, some, like the mass of vertical fluid movements, would be increased by lower gravity; others like plate tectonics, probably inhibited. One suspects that since the atmosphere could carry more dust, erosion might be faster. Surface-atmosphere interactions are important in determining what atmospheric composition can originate and how well it can be maintained on low gravity worlds.

5. Surface Conditions and Under different Surface Gravities

We are living on the planet with the highest surface gravity in the solar system that still has a distinct surface–a wide but relatively thin layer of water and a solid (with apologies to residents of Hawaii, Japan, and California) surface of light silicates floating in a thin skim of somewhat heavier basalt over a world-ocean of hot dense plastic rock that flows like liquid on a geologic time scale. These continents are analogous to icebergs, and show many of the same behaviors, occasionally calving (India, Australia), bumping into each other, and throwing up pressure ridges (the Himalayas, the Alps).

Continents, icebergs, and mountain ranges are held up by buoyant pressure from below in a phenomenon called isostatic balance--like icebergs, their deep roots displace enough of the heavier liquid below to equal their own weight. Now this "liquid" can be very dense and viscous and in the short term, it might seem solid, or at least plastic. But over geologic time, and under pressure, mantle rocks will flow around continental masses like water around the hull of a ship.

5.1 Surface Gravity and Mountains

Static buoyancy is independent of gravity because gravity affects the mass displaced and the displacing mass equally. An ice cube, or a mountain, will have just as much below the fluid line on Mars or the moon as on Earth. A buoyant feature that is neither trying to rise or fall is said to be in "isostatic equilibrium" or be part of a "isostatically compensated" surface.

Nevertheless, surface gravity determines how tall the mountains can be; it does so by limiting the depth of their roots. The depth at which rock begins to behave like a liquid depends on the weight, not the mass, of the rock above. Indeed, one can make a rough estimate of how deep rocks liquefy in a body by looking at its surface gravity and the height of its mountains (or, in the case of Europa, its ice ridges).

Melting depth isn't solely a function of pressure--internal temperature matters as well--but the additional depth needed to cause melting is small with respect to the overall scale. Rock begins to flow at a pressure of a billion atmospheres or so. On Earth this means a column of heavy basalt some 90 km tall, or a column of lighter silicates 100 km tall; the difference is the height of our tallest mountains.

On Mars, the columns are roughly two and a half times as deep, because one needs to go that far down to get melting, and its elevation features scale up accordingly. Olympus Mons rises some 2.5 times the height of comparable terrestrial volcanoes. The isostatic equilibrium argument may be only approximate for Venus; the major uplifted regions are slightly more massive than their surroundings, indicating that some force other than buoyancy is playing a part in keeping them above the mean elevation. These features probably lie on top of rising "plumes" of magma from its mantle.

Table 7. A comparison of maximum surface elevations.

Body	g(m/s^2)	mountain	r-R*	height**
Earth	9.8	Mona Loa	7	9
Mars	3.8	Olympus M.	27	24
Venus	8.8	Maxwell M.	11	17

* Absolute radius minus mean planetary radius

**Height above local isostatic plane

The roots of Io's volcanic mountains melt 50-100 km below its surface for reasons other than hydrostatic pressure-- changes in tidal stress due to its slightly eccentric resonant orbit heat the mantle so it melts at a lower pressure. It's difficult to measure the height of Io's volcanoes, but they appear only intermediate in height between Earth and Mars, despite a surface gravity of less than a fifth of ours.

Though lower surface gravity can sustain higher loads per unit area, the slopes of mountains, volcanic or otherwise, do not seem to change much with surface gravity. Olympus Mons, Mona Loa, and Io's volcanoes have similar profiles. Why, one asks? Shouldn't lower gravity mean steeper mountains?

But what keeps a mountain from slumping into a puddle of sand and rock? It's sides are pressed outward by the pressure of the mass of rock above, but are held back by the friction that keeps things from sliding over each other. The pressure is proportional to the weight of the mountain; lower the surface gravity and you lower the pressure. But the friction that keeps the rocks from sliding is also proportional to that weight. The two effects cancel, and piles of rock, or dust, maintained primarily by friction look pretty much the same, despite changes in surface gravity (except, of course, where the pressure gets high enough to change the coefficient of friction).

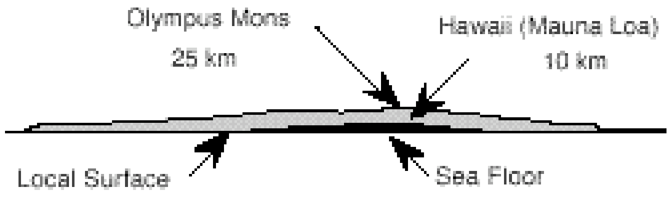


Fig. 5 Slopes and Elevation of Olympus Mons and Hawaii

On the Moon, one has to go so deep that the decrease in the force of gravity with depth is important, and according to most sources, one doesn't encounter ductile rock in this era until almost a thousand kilometers down. Because the horizontal scale of uplifted areas increases in proportion to the vertical scale, rather than an individual mountain one would look for a large area to be uplifted. Thick crusted Moon-sized bodies would run out of room. The far side of the moon bulges some, but its "column" is decidedly conical and lateral compressive strength in the mantel is significant. In fact, the much denser Maria on the near side of the moon are "out of compensation," or too massive for their altitude as evidenced by the mass concentrations that affect the orbits of (artificial) lunar satellites.

The extreme thickness of the lunar crust means a lack of the usual mountain--building mechanisms and lack of a lunar atmosphere also means that the surface has been significantly eroded by meteors. Its highest feature, in fact, turns out to be the rim of a crater on the far side, and is not much higher than anything on earth.

Of the other moon-sized bodies, Ganymede, Callisto and Europa appear completely glaciated, perhaps to a depth of hundreds of kilometers, and ice flows under pressure much more easily than rock, so ice tectonic features reminiscent of rock tectonic feature on Earth may be seen on these worlds.

Europa's ice crust appears particularly thin, and many have speculated that an actual ocean lies beneath it. Clearly, liquid water temperatures lie close to the surface, and if it had an atmosphere, it might very well be an ocean world. Atmospheres of any consequence, however, do not exist in Jupiter's extreme magnetosphere. Europa's silicate mantle may be liquid at a reasonable depth due to tidal heating. There may be volcanoes that reach high above the ocean floor and possibly some form of plate tectonics beneath the ocean.

Where significant atmospheric erosion is involved, one suspects that low gravity will yield some spectacular sights. Structures which are impressive on Earth could be scaled up by the factor of decrease in surface gravity. We get a hint of this in the Noctis Labyrinthus area of Mars. If there are any solid rock areas under Titan's atmosphere, there could be some spectacular precipices there as well.

Another factor affecting the evolution of surfaces goes back to fluid dynamics--the separation of rock into the light minerals that make up continents from the heavier minerals of the upper mantle. The ascent velocity of lighter material is directly proportional to local gravity (Hunten 1981, 750). This would give magmas more time to cool on low gravity worlds.

One possible problem for small worlds as a site for the evolution of life is the probable absence of plate tectonics to recycle the carbon dioxide that gets locked up in ocean sediment. As surface gravity goes down, the crust must get thicker and thicker to create the pressure and temperature conditions needed to make rocks flow. Eventually, the crust must get too thick for subduction to occur.

But plate tectonics may not be the only way to recycle crust. When Olympus Mons started life, its initial flows spilled over the Martian crust in the area of the volcano. Those layers have been pressed deeper and deeper into the planet as the mass of lava builds over it--there is evidence of this subsidence in the depressed boundary of the aureole around the mountain.

Since the total height of the mountain is limited by isostatic compensation, as lava comes out on the top, rock must melt away at the bottom--eventually some of the material covered eons ago will be taken up through the vents.

Even a thick crust may weaken and crack under tidal stress, or as a result of a major impact. The comet impact on Jupiter remind us that while these are much less frequent than in the first billion years of the solar system, they still occur. Impacts on sediment would vaporize large volumes of trapped gasses.

Gravity plays a role in this; things that fall from great distances hit with at least escape velocity. For a given mass, impact energy increases with the square of impact velocity. Crater size depends on impact energy, and the slopes of the debris walls (friction over weight) are similar, so craters on the moon look like the little one near Winslow, Arizona, or on Phobos.

Pieces blasted loose from impacts often fall on the impacted body and create secondary craters. Low gravity bodies lose more of this debris and get less secondary cratering. For the debris retained, at a given energy of ejection, the higher the surface gravity, the faster gravity brings them back and the closer the secondary craters are to the original.

Those that escape may reach other planets--we have found rocks from Mars in the antarctic ice cap. Meteors torn from a low-gravity life-bearing planet may seed another planet with spores or microbes. Some sources indicate that jet velocities at the moment of impact can, for large events can approach the escape velocity of even Earth (Curran, 1977, Vickery 1993). Whether spores or microbes inside porous rocks, or anything solid at all, could be carried off Earth in such jets is an open question. But Earth is the worst case known.

While, on Venus and Mars at least, we see the highest elevations scaling with surface gravity, we don't see the same with depths. The deepest parts of Earth are due to plate tectonics, overlain by a transparent "crust" of liquid water. The deepest parts of the Moon and Mercury are crater bottoms, the largest of which apparently manage to rebound by fracturing. Potentially, something similar to Earth's trenches could exist on Beneath Titan's clouds, or beneath the ice of Europa.

5.2. Surface Gravity and Oceans

Since neutral buoyancy is not affected by surface gravity, near neutrally buoyant phenomena should be only slightly affected by differences in surface gravity. Masses of water only slightly warmer or colder than their surroundings should behave much as they do on Earth. But to the degree that something departs from the buoyant condition, surface gravity may be important. On a low gravity world, dense objects would sink more slowly and lighter objects would rise less rapidly. A diver in an Europan ocean would have to carry five times as much mass to stay on the bottom with a given force as one on Earth.

Table 8. 5.0 sec. Deep-Water Waves at Various Gravities

Surface gravity g (m/s^2)	Wave(1) velocity c, (m/s)	Wavelength l, (m)	Crest(2) Height a, (m)
25	19.89	99.47	0.40
10	7.96	39.79	1.00
4	0.318	15.92	2.51
1.6	0.127	6.36	6.27(3)

(1) based on $c^2 = (gl/2p + 2 pg /rl) \tanh(2ph/l)$ where g is surface tension and h ocean depth (2) based on a single crest potential energy of $E = g\rho\lambda a^2/8 = 1$ kJ (3) actually, these equations become inaccurate as wavelength approaches amplitude.

Vertical currents wouldn't be as vigorous per unit volume on a low gravity world, so thermal barriers may be more effective and stratification more important. Dense objects would have lower terminal velocities. Waves will be higher and propagate more slowly in lower gravity because a given impulse will push a wave higher, and it takes more time for things to rise and fall.

Near the surface of a world, pressure in an incompressible fluid increases in direct proportion to depth and surface gravity. In Earth's oceans, pressure increases by about one atmosphere for every ten meters of depth. In a hypothetical Martian ocean, one would have to go twenty five meters deep to get a one atmosphere increase in pressure, but only four meters would do it in a Jovian sea. So, for anything that is limited by some absolute value of pressure, low gravity oceans offer more room than high.

Human breathing is one such thing. We use a partial pressure of 0.2 bars of oxygen, and we can do quite nicely in a two-bar atmosphere of almost pure oxygen (but be careful about fire). We can also do quite nicely in an atmosphere of ten bars, if two percent is oxygen and the rest is something that doesn't bother us. This turns out to be helium, or, surprisingly, hydrogen. At these pressures, the oxygen concentration needed for breathing becomes too low for explosion to be a problem.

However, as one goes deeper, problems occur. Blood can only transport so much gas, even under great pressure, so to make sure there's enough oxygen, the mixing ratio has to increase. But oxygen at high pressure is extremely reactive--toxic. The difference between too little and too much gets narrower as one goes deeper, until, at about twenty atmospheres, the curves cross and one can't go any deeper.

For human beings at ambient pressure, Earth's ocean is about two hundred meters deep. We won't, for instance, be able to make a shirtsleeve environment on Titan by simply adding air until the lapse rate takes care of temperature for us, and we won't be able to explore Venus by simply cooling it down.

But on the Moon, one could have an ocean over a kilometer deep and be able to explore it all in SCUBA gear. However, one would need to take an artificial light; light will be extinguished with depth just as well on a low gravity world as on Earth.

These considerations would, of course, be more limiting for worlds on which life evolves than on worlds that might be subsequently settled by spacefaring intelligences. But the logic of that is to increase the proportion of all settled worlds of low-gravity worlds with (engineered) biologically compatible atmospheres. The important point is that it is physically possible to equip worlds such as the Moon, Europa, Mars, and perhaps (with more work) Ganymede and Callisto with more or less permanent biospheres by controlling exobase temperature and providing a deep enough atmosphere. What engineers can do, nature may also have done, here and there, through the coincidence of a number of happy accidents.

6. Structural issues in different gravities.

The traditional way of looking at lower gravity worlds is to imaging their inhabitants lengthened and those of high gravity planets, squat. But this deserves some critical examination. Structurally, there is some good reason to think that while the height of life forms may vary with surface gravity, their proportions, like those of mountains and canyons, may not.

This reason is again the cube-square law. Consider a dinosaur thigh bone, or a tree trunk, with a cross -sectional area of 100 square centimeters (roughly the area of your hand). On Earth, this structure might support compressively a weight of ten tons, or 0.1 ton per square centimeter. On Mars, it could support a vertical mass two and a half times as great--which gives you the long, thin scenario. However, compressive vertical loads are not the only thing to consider--and the greater mass and leverage of a taller object implies proportionally larger stresses too.

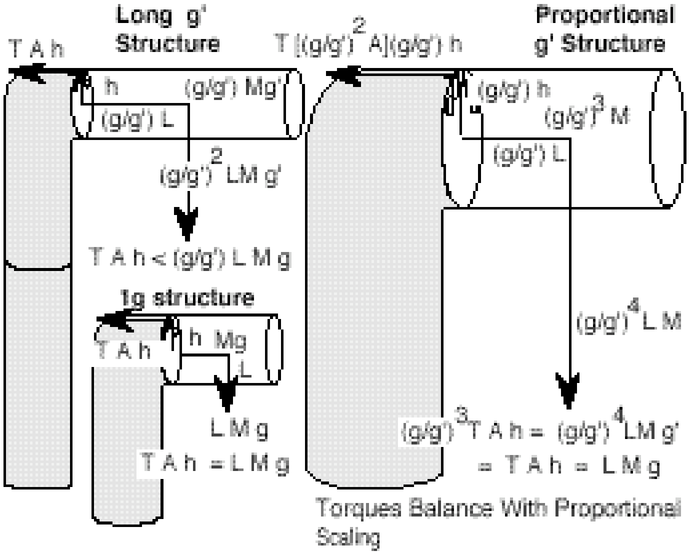
It turns out that if the cross sectional area of the bone grows in proportion to the height, the resulting structure achieves the same stress to mass and pressure ratio as on Earth.

Somewhat more surprising is that the thickness of projecting limbs should increase in proportion to surface gravity as well. The reason is that the tensile force acting against the gravitational torque on the projecting limb is proportional to the cross sectional area of the materials, and the torque is proportional to the length of the lever arm to which that tensile strength is applied (figure 6).

If the length of the limb increases in proportion to the gravity reduction, and the thickness does not increase, the torque generated by the limb increases (even though the weight of the limb does not, due to the reduction in gravity). Increasing the thickness of the limb restores the balance, even though its mass and weight increase proportionally. Since animal limb bones generally need to support themselves in any radial direction, their cross section is roughly circular.

Since plant limbs generally don't have to rotate, they could, in principle, increase in thickness and not in depth--and indeed, the branch roots of many trees are elliptical rather than circular in cross section. If low gravity biospheres need to have thicker atmospheres as well, with correspondingly lower wind velocities, the need for lateral strength may be reduced too. With the same structural materials available, this could lead horizontal boughs and branches of plants evolved in lower than Earth gravity to be more elliptical in cross section than those of plants on Earth.

If the 100-ton Titanosaur, Argentinosaurus huinculensis, is an example of something that grew to the physical limits of its supporting bone structure, then the dimensions of a Martian Titanosaur might be simply two and a half times as great, all over! The volume and mass of the Titanosaur would increase by a factor of 2.5 cubed to a mass of some 1563 tons. The cross sectional area of its bones would increase by 2.5 squared, to 625 square centimeters, and the weight of the Martian Titanosaur under Martian gravity, per unit area of bone, would be exactly the same.



L is the length of a horizontal structure, M is its mass, and A is the cross sectional area. g' is some gravity different than g--on the scale of the figure, g' is about g/2. T is the maximum torque on the horizontal structure sustained over area A.

Figure 6. Scaling of Strength-limited Structures

If we assume that the chemistry available for constructing bones, shells, cellulose, and so on is universal, and that evolutionary pressures will lead to some animals approaching the their structural limits, then the scale of the largest life forms may prove to be inversely proportional to the surface gravity.

A word of caution, however. There may be an absolute limit to the size of vertebrates that has nothing to do with gravity and structural limits. Whales (and marine reptiles, earlier) live in an environment that has no gravity, but the largest of these seems to have topped out at about 150 tons, like the Titanosaur. One of the limiting factors may be another artifact of the square-cube law. The amount of heat generated by muscle activity increases as the cube of linear dimensions, but the surface area of its lungs and skin, through which this heat must pass, goes up only as the square of linear dimensions. Getting rid of this heat is an important issue for a large animal.

As an aside, the Titanosaur was a pretty incredible animal--we probably wouldn't believe it was possible if we hadn't found its bones. Perhaps the most astounding way of illustrating its size is not to scale it up to astronomical proportions with low Martian gravity, but to scale it down to the proportions demanded by Jovian gravity. The Jovian version would still be ten feet tall at the shoulder, bigger than most elephants! On Earth, an eight-ton Jovian Titanosaur would have to carry something like twelve tons just to feel at home--an impressive draft animal.

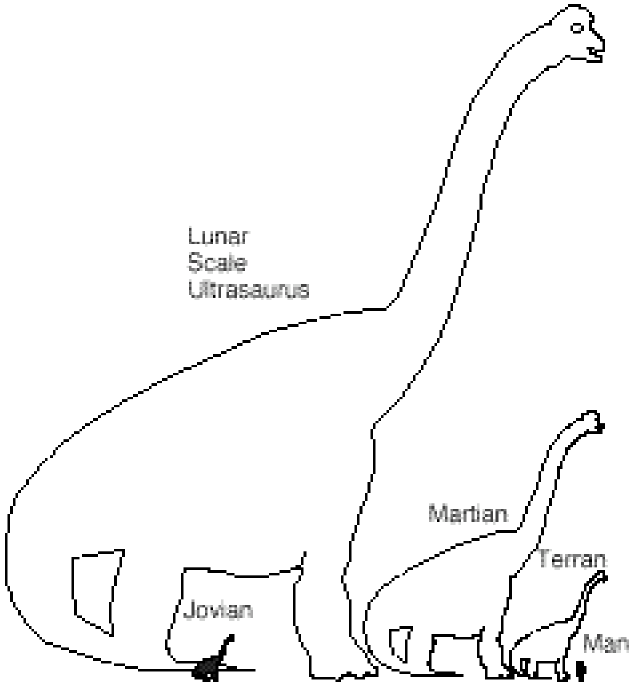


Figure 7. 100-ton dinosaur scaled to various surface gravities. ("Ultrasaurus" proved to be an error, but a 100-ton Titanosaur has been found. A new illustration is in work).

Another animal we would not believe (and some of us still won't) if we hadn't found its bones is the giant pterosaur, quetzelcoatlus (Bakker, 1990). There are some casts of its wing bones in museums around the country, and if you ever get a chance to do so, see them. The living model had a wingspan of some fifteen meters--as large as some fighters or small passenger aircraft. The wings were very large in proportion to its body, like a modern glider. And, like a modern glider, what body it had was likely to be of surprisingly light construction. Still, the body was probably human sized, and it might have been able to lift about its own weight of whatever food it required.

Assuming an optimal construction, whether an animal can sustain flight depends primarily on the ratio of the surface area of its wings to its mass, and secondarily on whether it can sustain, on average, enough flapping energy to overcome drag. A tertiary problem is whether, for short periods of time, it can generate enough power to get off the ground. This can, of course, be done anaerobically, and is an issue of strength and muscle mass to weight--not lung capacity.

In the Mesozoic era there were dragonflies a foot long which probably weighed several ounces. The same structure in Titan gravity could support a body seven times that size and over three hundred times that mass--heavy enough for a sophisticated central nervous system.

A human being, not evolved for flight at all, can just barely fly in our gravity with a suitable amount of lightweight equipment. Evolution, given a lower gravity world, with a denser atmosphere, should have no problem with winged intelligent species--and one can easily see how having the natural power of flight might go a long way toward developing an interest in space, the stars, and what other intelligences might be out there. As we contemplate the strength of a Jovian Titanosaur, we gain some perspective on how a low gravity civilization might look on us, as individuals. Seeing so much strength in such a small package might make them nervous.

7 Homesteading Lite--Settlement of Low Gravity Worlds.

The previous sections addressed the physical aspects of how surface gravity affects the environment of a world. Table 9 offers a brief qualitative summary of issues related to gravity and physical layers. The following will attempt to address how these factors affect the settlement of worlds by humans and possibly others.

Culture is tool using (Hawkes, 1963) (include language and writing as tools, of course). Tool technology evolves. Science evolves because tool makers that use it displace tool makers that don't. In less than a century, we will be able to make robot slaves, about as smart as insects, that can go forth into our planetary system and, using rock and sunlight, reproduce geometrically and make what we want as a side effect.

Suppose we can make a set of devices that, in a year's time, reproduce themselves and make a 1000 MW solar power satellite. Once they start, in about half a century they should be able provide us with all the solar energy we need to go to the stars and do planetary scale engineering ourselves. A dark pessimists in the software industry might say two centuries--but no matter; on the scale of planetary history, this will happen almost overnight. Let's say 500 years from the first electricity to a robotic economy: that's one ten millionth the age of the Earth.

Races that explore and colonize displace those that don't. Those that go out and colonize stars will inhabit many times the number of star systems than those who stay at home. While the absolute number of intelligent species in the galaxy is very problematical, if it is large enough--say ten or so--that simple bad luck has not prevented the invention of spaceflight, then, by several orders of magnitude, the populated star systems in the galaxy will be colonized star systems--not worlds where life has evolved.

That will certainly be true of human civilization in a few millennia. Whether in the twenty-first century or the twenty third, we will have gone from pyramids to starships in the blink of a cosmic eye--and there is no reason to think that at least some other races evolving technology under the same physical laws will not have done likewise. It will only take one other such species to completely dominate inhabited star system statistics.

Table 9: A qualitative summary of Surface-Layer Topics

World Surface	Gravity Related	Habitability Factors
Exobase	Escape velocity Molecule and Isotopic content	Atmosphere Retention
Mesosphere	Scale Height	Radiation Protection
Stratosphere	Depth, density	UV protection Gravity waves Weather-horizontal. scale
Tropopause	Altitude Min. temp.	Visible/IR Absorption H20 retention
Troposphere illumination	Depth Lapse rate	Weather-vert. scale Surface Temp.,
Hydrosphere	Gravity waves	Tidal area, wetlands
Lithosphere	Depth Tectonics	Atmosphere recycling Crust stability
Aethenosphere	Depth/temperature Vertical scale	Atmosphere chemistry Volcanism
Mantle	Depth Composition	Plumes, tectonics Volcanism
Core	Mass, Temp	Chemical Differentiation Magnetic Field

What does this have to do with surface gravity? Let us take a not too great a leap of faith and surmise that, since aliens will probably have evolved on a solid world with an atmosphere, they are likely to enjoy the feeling of an open sky and earth beneath their feet. If we look at the solar system, of the number of bodies with solid surfaces, two have Earthlike surface gravity, two have Mars like, six have Moon-like surface gravities. Their are two with Pluto-like surface gravity and a host with forty percent of that.

However, when we get down to seven and three percent of Earth normal gravity, the feeling of ground beneath one's feet becomes perhaps a little unconvincing. Granted that engineers will be able to put an atmosphere wherever they want one, my suspicion is that the Oberons of the universe will not be prime real estate.

But if one doesn't like to go too far down, one definitely doesn't like to go up in surface gravity. The predominance of Moon-like worlds and a more or less equal distribution of Mars-like and Earthlike worlds lead this author to speculate that races that evolve on worlds with significantly lower surface gravity will predominate, and such races will be unlikely to consider places like Earth and Venus prime real estate.

7.1. Human Performance at different gravities

Let us consider how changes in surface gravity would affect some normal human activities as a guide to where we might like to settle. We'll consider athletic performance because that tends to set the limit on what a well conditioned human might be able to do. But lest anyone think what people can do with their muscles is strictly a elite athletics consideration, consider the effect of surface gravity on ballet, on normal activities like climbing stairs, playing with children, or on people with certain medical problems. Also, if physical abilities tend to evolve to some fraction of the mechanical strength that hydrocarbon based bone and tissue can achieve, similar numbers might apply to any aliens we meet.

But athletics themselves may be more important to our future than we might think at first. By the time we are out in the galaxy, machines will take care of most of our material needs and our reasons for doing things will be mainly to entertain ourselves. Games and exploration are both part of that. Since the robot economy is probably necessary for star flight, other spacefaring races will probably have it, too. Therefore we should not be surprised to find entertainment prominent in their motivation as well--whatever form they may take. Will aliens have sports statistics? Consider that some quantitative ability will be necessary for culture and technology, and that playful tests of strength, speed and skill are quite common in the animal world.

Table 10 covers some athletic doings. The first columns consider "hang time," the time a jumper's center of mass spends on an unsupported trajectory. The height, h, of course, applies to the athlete's center of mass, which we will take to be 1 meter off the surface when the tips of the jumper's toes leave the earth and when they return. A good long jumper, of course, will go a little farther by pulling his or her legs up.

Table 10. Estimated human athletic performance

Surface	Hang	High Jump (1)		Long Jump(2)		Baseball 40 m/s			
gravity (m/s^2)	time (sec.)	h(3) (m)	Vac(4) (m)(5)	1 bar (m)	2 bar (m)	Auth (m)	Vac (m)	1 bar (m)	2bar (m)
24.5	0.47	1.27	3.51	3.39	3.27	0.76	63	46	38
9.8	1.22	2.38	9.76	8.81	8.07	3	160	87	63
3.7	3.07	5.09	26.2	20.3	16.9	8.23	392	139	92
1.6	6.46	9.67	60.6	37	27.7	17.5	978	198	122

(1) The world record at 1 g is 2.4m.
(2) The world record at 1 g is 8.9 m.
(3) at 1 bar pressure. Drag is modeled as proportional to the air density and square of velocity--four newtons at 2 m/s, sixteen at 4 m/s, etc. The standard atmosphere drag coefficient is assumed to be -.02/m for jumpers, -.01 for baseballs. The model was normalized to world-class Earth performance. For more precision, a more complex analysis of drag coefficients and body shapes is needed. Mathematically, $dv/dt = - k v 2$ □ at 1 bar./m, where k .01A m^{-1} .
(4) Vac is for performance in vacuum. 1 bar and 2 bar refer to performance in those pressures at 300 K. The "Auth" column is, for comparison, what the middle aged author of this paper might do--the 3 m jump was measured in his backyard.

What determines how high an athlete jumps? What a jumper does is to run fast and then try to convert horizontal to vertical velocity by using his legs as elastic springs, and adding as much force as they can. To lift their centers of gravity to about two meters, good terrestrial athletes need to leave the ground with a vertical velocity of 3 m/s. To achieve this velocity, jumpers must accelerate their mass upward against gravity with a force, F.

In the process of jumping, the center of gravity, located approximately at the hips, travels upward from the compressed crouch position by about 40 centimeters to full extension as the toes leave the ground. The force exerted over this distance first increases slightly as the legs return to a more optimum pushing position, then falls back to zero as the toes loose contact.

The exact curve of force versus distance is, of course, different for everyone, but the distance, Δh, over which the force acts is fairly constant for people of similar size and the velocity achieved is fairly constant for top athletes. This lets us calculate an "average" acceleration for limiting jumps in one gravity. The upward acceleration represents the difference between average muscular force, F and weight, m g. For first order estimates, we'll set aside concerns like traction or the role of the jumper's weight in compressing their "springs" and assume this acceleration represents the difference between the strength to weight ratio of their legs and surface gravity. Finally, the author estimated that the average acceleration was about two thirds of its maximum value, reflecting an expectation that the force-distance curve is roughly bell shaped where one can jump at all–i.e. where leg strength exceeds body weight. A few personal experiments were consistent with this result.

The accuracy of these estimates is most in question at higher gravities; a person who can leg-lift two and a half times his or her own body weight would have a maximum vertical acceleration of 25 m/s^2 in negligible gravity and reach a velocity of 3.6 m/s,versus 2.46 in one gravity. So, takeoff velocity is not extremely sensitive to surface gravity on the low end, though how high you go after takeoff with that given velocity is.

The long jump is essentially a high jump with greater horizontal velocity and no acrobatics over the bar. The optimum range takeoff angle in vacuum would be near forty-five degrees, but at a running speed of nearly ten meters per second, that would be impossible to achieve with a physiologically limited maximum vertical velocity of about 4.5 m/s.

For the baseball, we'll assume the ball is caught at the same altitude it leaves the thrower's arm. The baseball's coefficient of drag is less than a persons, but time and velocity make the effect more pronounced.

Readers who remember Le Petit Prince fondly may wonder just how small a planet has to be before one can just jump off of it. "Jump off" we take to mean reaching escape velocity with muscle power alone--let's say a velocity of 8 m/s. If we assume a typical rocky density of three for our planetoids, it turns out to be about 12.3 kilometers in diameter. This is roughly the size of the Martian moon Demos; it's surface gravity is about half a centimeter per second squared. To get an idea of how little gravity this is, hold a pencil out in front of yourself, count "one-thousand one" and imagine it taking that long to fall its own width.

To colonize such a body, one would have to put a bubble around it to hold the air in. But then you wouldn't be able to simply jump off of it. Such a sad, cruel, universe! But there is a way around this, which we shall visit a little later. Meanwhile, the idea of building a transparent envelope completely around a planet to hold air in that would otherwise leak away is an idea that should be taken seriously–it is well within the production capabilities of the robotic economy needed for star flight in the first place. One should keep in mind that in the normal course of their business, a mature spacefaring civilization will develop a physical infrastructure that will be as impressive and amazing to us as our airports and interstate highway system would seem to Moses.

A continuous envelope around an otherwise airless world could be held up by gas pressure and be tethered to the surface here and there to keep it centered. There would have to be locks to let spacecraft in and out, perhaps as part of orbital towers kept aloft by centrifugal force. This probably wouldn't be necessary for many Moon-type bodies, but for Pluto or Ceres sized bodies, gravity will need some help. Such a would could retain a life-supporting atmosphere for geological time spans if its exobase temperature is made low enough.

As Robert Heinlein envisioned in a story titled "The Menace from Earth," lunar gravity combined with an atmosphere would allow people to strap wings to their arms and fly like birds--a much different experience than pedaling a propeller chain drive to the point of exhaustion.

Some of the penalties for being overweight would be less on low gravity planets, and one suspects that obesity might become more frequent and less of a problem for human colonists of low gravity worlds than it is here. Members of any high gravity land species moving to a low gravity world could do new and wondrous things, and probably enjoy it immensely.

Going the other way, however, would be a bit of a burden. Two and a half gravities would not be catastrophic to a human being in good physical shape. There are people who walk around and function more or less normally with two and half times their normal body weight--though to be sure, their muscles and bones have adapted to some extent to the extra weight. Some football players and sumo wrestlers even perform strenuous physical tasks under this burden.

But the best person for going to Jupiter would not be a sumo wrestler, but a well conditioned small person with a maximum of muscle and a minimum of excess weight, such as some of our Olympic gymnasts. Likewise, aliens from Mars gravity worlds might be able to visit Earth, but those that do would probably be unusually well-conditioned aliens.

One would think aliens from lunar gravity worlds would be unlikely come here. Human pilots can, if properly supported, function under six and a quarter of our gravities for a limited time.

But there is an advantage, among many disadvantages, of higher gravity--things generally happen faster in high gravity. High gravity sophants will have to move and perhaps think faster than low gravity sophants. Dr. Robert L. Forward took this idea to an extreme in Dragon's Egg, a novel about life on the surface of a neutron star, composed of very dense" degenerate" matter. Surface gravity is in the millions, and the inhabitants live and think proportionally faster.

7.2 Adaptation to worlds with different gravity.

There has been an assumption in some science fiction that humans living on low gravity worlds would grow into long, stringy, weak things and so be permanently exiled from Earth. But this idea deserves some critical examination. It would take generations of selective breeding, or artificial intervention, to change human genes, and unless and until something like that occurs, our lunar descendants will be, in principle and with proper conditioning, capable of doing everything we can.

Can a low gravity environment affect their shape that much? Bedridden people and people who work in water several hours a day don't tend to grow into skinny giants. It seems doubtful that that would happen to low gravity immigrants either.

Of course, if all they do with their bodies is walk around in lunar gravity, they may get significantly out of shape. Also, they could have lower bone mass than we do, because bone area and strength increase with stress. However, these tend to respond to peak stress. World class weight lifters doesn’t lift twenty-four hours a day--in fact, like most other people, they spend several hours a day on their backs with essentially no stress at all. It may take only an hour or two a day or so of lifting weights, or even working one set of muscles against another, to bring your strength and bone mass up to their genetic potential. One can do this on the Moon just as easily as on Earth.

Well, maybe not just as easily. On Earth, it takes a force of 980 newtons to lift 100 kilograms. To get the same weight on the Moon, one would need to lift about 600 kilograms--which means six times as much inertia to push around. A lunar weight lifter would actually be working harder than one on Earth lifting the same weight.

One can envision other kinds of physical games that could help Earth people living in low gravity maintain enough bone and muscle to visit their native planet--games which require leaping as high as one-sixth g allows, carrying heavy things, and in general working up to their genetic potential. Calcium loss in low gravity is a concern, but one that can probably be addressed by training and, in the not too distant future, by medical advances.

Adapting to significantly higher gravity is more problematical. Depending on whose numbers one uses, the surface gravity of Neptune at its poles may be as much as 1.3 times Earth normal. While the gaseous north pole of Neptune is an unlikely colonization site, the gravity alone shouldn't be too much of a problem for someone in normal health. But if we go up to the next step, the two and a half gees of Jupiter presents unknown territory. For well conditioned people, visiting such conditions shouldn't be too much of a problem, but living there continuously raises questions about bone development, stress on the circulatory system, wear and tear on joints, and other issues.

No doubt boredom, if nothing else, will prompt some people, some day, to try living on Jupiter for a while, presumably in the gondolas of giant hot hydrogen dirigibles. These Jovian colonists might adopt an amphibious lifestyle, spending a significant part of their days in a buoyancy tank. We'll note here that childbirth can, and has, been done under water.

While going up a step in gravity is possible, if there is strong motivation, it is more reasonable that colonization efforts will stay at similar gravity levels, or go down a step or two using technology to handle any atmosphere or physiological adaptation problems. One should note here that hydrosphere ecological systems are much less sensitive to differences in gravity, and can provide food and air recycling no matter what strange things might happen to land life. The lives of fish and seaweed would be pretty much the same at one sixth or six gravities.

If terrestrial land species are let loose on a low gravity world long enough for natural selection to have an effect on their populations, some very interesting things might happen–or might not. Using the 100-ton dinosaur, Titanosaur as our example of maximum size of an Earth gravity land life form based on bone and muscle, we can note that no animal in the world's current ecosystem comes anywhere close. While some of this may be due to hunting by our ancestors, one suspects that what it tells us is that things don't grow to the maximum structural limits just because they can--there has to be some sort of reproductive advantage to being huge. Until, and unless, that exists on the low gravity colony world, land animals probably won't get that huge.

Birds, on the other hand, might take advantage of low gravity and do so fairly quickly (in geological terms). In evolution, wings apparently shrink rapidly when not needed, as evidenced by the flightless birds of various predator-free islands. Unlike land animals, there are many examples of birds pushing an upper weight limit--albatrosses, condors, and some eagles. Look at how marginal the albatross is in every other part of its life except flying!

Why don't we see flying birds as big as quetzelcoatlus? One suspects that feathers with all their shafts and barbs may not be as good a construction material for really big wings as stretched skin (another cube-square law thing) and would not expect to see an avian equivalent of the 15 m wingspan of the flying reptile.

8. Sentient Species' Development on Low Gravity Worlds

In addition to Earth life spreading to low gravity worlds, these worlds may have developed life of their own, including, possibly, intelligent life. How might different surface gravity affect the development of extraterrestrial intelligence?

8.1 Biological Evolution of Sentients on Low Gravity Worlds

Its easier to be large in low gravity, and it may be easier to be smart if you're large. Whales, elephants, octopi, and bears all tend to be the smartest of their kind. Ravens and parrots are large for birds. There is likely to be some minimum size for an intelligent biological brain. As people, we tend to fixate on the dramatic, but while a Titanosaur, elephant, or whale are mind-stretchingly large, they are very, very rare compared to smaller species--indeed, by any reasonable statistical standard, a dog is a large animal. By the standards of Earth, homo sapiens is big.

In lunar gravity, even invertebrates might grow large enough to support thinking brains. But one would not expect to see intelligent beings with insect-like construction (exoskeletons of chiton or the equivalent) evolving on Earth-gravity worlds or larger. The biggest such creatures on our world would be very hard pressed to carry brains big enough to be intelligent.

So, because they impose fewer constraints on shape and size given known biological materials and physics, low gravity worlds may be more likely than terrestrial worlds to produce intelligent life--even on a world by world basis--because they have more structural options to produce large brains.

There are other possible advantages for evolution of intelligence on a low gravity world. It's easier to be three-dimensional in low gravity, and three dimensional thinking is a key to anticipating future events (Hawkes, 1963). This ability to model the future and act accordingly is a significant part of what we recognize as intelligence.

On Earth, surface gravity is obviously not the constraining factor for the number of limbs of small or aquatic life forms. While large land forms tend to have four or two legs, where gravity is not a consideration six, eight, or many more seem to not be disadvantageous. Four legs may be the luck of the draw, or the most biologically efficient way of supporting a large mass (consider surface to volume ratios, for instance). But, for whatever reason, large flying animals on Earth have sacrificed one pair of limbs to have wings.

This may not hold true for low gravity. As we've already remarked, it is conceivable that the structural engineering of a six-legged and winged terrestrial dragonfly might be adequate to support a brain large enough for intelligence in lunar gravity. It is not clear that flying intelligent life would have to do without hands on a low gravity world.

Some factors that might work against the development of technological intelligence on low gravity worlds include:

1) a generally slower pace of a low gravity world,

2) the likelihood that such worlds will be found further from a high energy photon source,

3) atmospheres so high-pressure at liquid water temperatures that enough oxygen for respiration is too little for fire,

4) atmospheres too opaque to see the stars, and

5) metal-poor crusts.

A stimulating, challenging environment, the mutation rate, fire, astronomy, and the availability of metals have all been frequently cited as contributing to the rise of technological culture on Earth.

But the above are difficulties, not physical prohibitions. Their effect would likely be to lower the odds of low gravity world developing intelligence, but the numerical superiority of such worlds may well overwhelm their lower individual chances.

As mentioned in section 4, the increased vertical scale of the atmosphere of a low gravity world will limit how much cosmic radiation reaches the surface. Is this good or bad for life? One school of thought says the less radiation the better. But another holds that, as with most everything else in life, there is an optimum amount--to little can be harmful as well.

Perhaps radiation is needed to stimulate immunological systems (Hogan, 1995), perhaps to literally spark creative thoughts, or perhaps to help generate the mutations on which evolution depends. Would evolution on a low radiation world go slower, would its inhabitants have less well developed immunological systems, and would they think more slowly? Future research will, perhaps, answer these questions.

However new M-class flare stars, such as Proxima Centauri, are not necessarily radiation poor environments, because they can have significant flares, which presumably provide plenty of radiation despite their cool surfaces. Adaptations to such flares, such as being amphibious, could make for interesting aliens.

Whatever the utility of radiation, the sun puts out more of it than the vast majority of stars in the galaxy. Figure 8 is called the "luminosity function" (adapted from Bok and Bok 1981) and shows the frequency with which one finds stars of a given range of brightness in a given volume of space. It is usually presented with a vertical log scale, but this plot was made with vertical scale proportional to number. All the stars in the shaded area are dimmer and cooler than the sun. The question mark indicates where the stars have become, essentially, too dim to find and count--the shaded area may go much further to the right.

The reservations about worlds around cooler stars have centered around the planet being tidelocked--that is, rotating at its orbital angular rate so that, like our moon, it keeps one face to the primary. The atmosphere might, presumably, freeze out on the other side. We now know that:

1) Other tidal resonances, like that of Mercury, which allow rotation, are possible.

2) Giant planets can form or migrate nearer to stars than in our solar system. Their satellites may be tidelocked to the giant planet, but, like our moon, still rotate with respect to the primary, and giant planet satellites may retain deep atmospheres under proper conditions.

3) Deep atmospheres such as those of Venus and Titan can, driven by thermal energy, "super-rotate," distribute heat well and perhaps drag their planet's crust with them.

4) The primary star is not necessarily the only source of biologically significant thermal energy.

Taken together, these things suggest that planets and satellites of giant planets around K and M stars should be given full consideration as potential sites for the colonies, if not home worlds of spacefaring races.

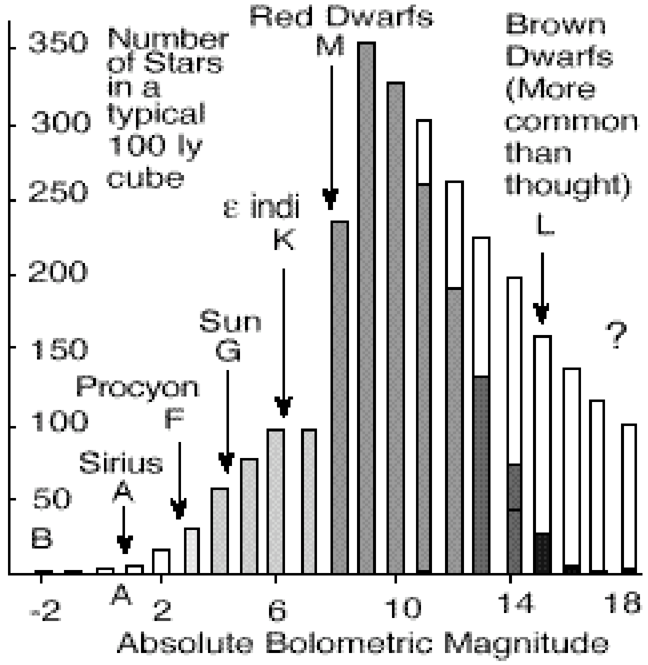


Figure 8. The luminosity function.

While conceding that, on a planet by planet basis, we may be more comfortable looking for Earth-type worlds as places where biological life is likely to evolve, there are reasons for probability to favor contact with low gravity species which may inhabit environments much different from ours. Even on Earth, there are also a number of close calls with utterly different environments and or environmental niches (octopi, elephants). There may be many highly improbable paths to intelligence as opposed to a few likely ones.

There are quite possibly more low gravity colony sites available, as life-originating worlds and as the byproducts of colonization. While the circumstances that might make a giant planet satellite habitable may be more special than for an Earth type world (though that's not at all certain) there are many more giant planet satellites.

If we could swap Jupiter and Saturn's magnetic fields, and put a Titan-class atmosphere on Europa, we'd get something of a prototype for a gas giant satellite that might be habitable. As a class, these worlds would need thicker atmospheres than habitable planets closer to their suns for more greenhouse effect and to take advantage of lapse rate to have higher temperature surfaces. Resonance heating and infrared radiation from the gas giant itself would push the "habitable zone" out even further. Indeed, one can imagine situations where having a central star is irrelevant to the question of habitability .

For a first order estimate, one out of four giant planets with large moons has a suitable magnetosphere for atmosphere retention on a moon, and two out of five giant planet major moons have sufficient tidal heating for liquid water. This gives a first estimate of perhaps ten percent of such worlds having an atmosphere and water oceans. There are five such moons in our solar system, so , as a first guess, half the solar systems encountered might have one such nominally habitable world.

If we add a nonzero probability of finding a near-habitable Mars or Mercury type world, the combined probability is greater than the one out of two that we get for Earth-Venus type worlds. The occasional presence of giant planets in inner solar systems also diminishes the probability of finding Earth-type planets due to gravitational resonance effects.

8.2 The Evolution of Technology on Worlds of Different Gravity

How might such intelligences develop on a low gravity world? Surface gravity affects a wide variety of technologies at all levels of scientific knowledge. This is a very broad topic, and here it will be necessary to simply mention a few representative cases. Before doing this, the author would like to try to step gently around a pair of terms that appear to create controversy in the anthropological world. One of these is "determinism," and the other is "contingency."

The physical laws and physical environment do not, especially by themselves, determine what people do, but they do limit what can be done and show what things are easier to do than others.

Any particular technological history is, of course, highly contingent. Someone discovers something at some point in time, and this makes all sorts of other things possible. Viewers of the James Burke television series "Connections" are well aware of that way of looking at technological history.

But many of such connections run in parallel, and however unlikely any individual path is, a particular achievement may not be that unlikely given that a large number of people are working in the area and sharing their information. Would eliminating Einstein have delayed the development of either general relativity or nuclear energy by more than a few years? Or eliminating Edison much delayed electric lighting? While it may have made a significant difference in which society had the technology first, that is a second order consideration for this kind of exercise. Clever minds fueled by accumulated data provide technological innovation and societal change on their own schedule.

Consider indoor plumbing, particularly drains and sewers. These are needed for the high density population needed to support the beginnings of a factory culture--such as occurred in our thirteenth century. (Gimple 1976). These pipes need to be slanted downward to maintain enough pressure, and thus enough flow, to keep them clean. In Martian gravity, sewer pipes would have to rise two and a half times as much for a given run to maintain the same internal pressure. But this increases the pipelength and thus the frictional resistance to flow. To compensate, the pipes would need to rise even higher, or be somewhat wider, and be even more expensive. Everything else being equal, one might expect the increased expense of sanitation to contribute to more disease and reduce the density of settlements.

In this spirit, a list of technological developments that might be affected by lower surface gravity is offered as table 11. The expectation is that, in the fullness of time, over a large number of samples, the easier things will get done before the more difficult things. In our history, some have taken a harder road, either through ignorance or willfulness, and no doubt that will be true of other sentient beings as well. But most things go the way of least resistance. On our world, horses came before airplanes, pendulum clocks before balance wheel mechanisms, and metal wire telegraphy before fiber optics.

Table 11. Gravity Effects on Technology and Culture

Technology	How lower gravity might affect performance, ease of accomplishment.
Artillery	Greater range in low gravity; improved coast defenses.
Agriculture	Maximum plant scale (fewer moving parts) may be more sensitive than animal scale.
Aircraft	Significantly easier in lower gravity, airborne trade or war becomes easier. Balloons Unaffected
Anatomy	Larger scale makes organs easier to see.
Architecture	Largest buildings scale inversely with gravity. Smaller structures more forgiving.
Astronomy	May be hindered by thick atmosphere on a low gravity world.
Bridges	Easier to build, but rivers may also be bigger.
Bows, slings & catapults	Larger scale may mean greater stress loads and greater velocity in addition to greater range for catapults at given velocity. Larger scale means greater sling-tip velocity.
Broadcast Comm	May be delayed if electrodynamics is delayed.
Ceramics	If less fire and less sun, ceramics are harder to do. Glass comes later
Chemistry	Slower precipitation in lower gravity, Capillary effects more important.
Cloth	Unaffected ? -(Larger scale may result in longer animal hair.)
Computers	If electrodynamics delayed enough, "Babbage" machines may be developed.
Communications Satellites	Earlier development with lower gravity, may Impede formation of totalitarian government.
Constitutions	Smaller worlds lead to earlier population pressure, more need to cope.
Dams	Mass increases as $1/g^3$ for a given pressure
Domestication	Largest animals can drag more mass, due both to lower friction and greater size.
Electrodynamics	Absence of a dipolar magnetic field may slow development.
Electrostatics	Should be unaffected.
Fire	Low g biospheres may have higher density air, less oxygen percentage, and less fire.
Geometry	Smaller worlds have greater curvature, perhaps leading to earlier spherical trig.
Gunpowder	Unaffected. Guns have greater range, however.
Laws of Gravity	Trajectories easier to study.
Mass production	Influenced by several other things that may be easier in low gravity
Metals	Lower gravity may mean less differentiation and, paradoxically, more native metal available. Also, it is easier to dig mines; a greater volume per unit area is accessible.
Navigation	Higher waves may make navigation more chancy, unless boats are scale accordingly. Could be bypassed by easier aviation.
Nuclear energy	If ores are very scarce, this may be delayed slightly. Payload to orbit exponentially higher.
Pendulums	Longer periods for a given length; easier to time. Air resistance is more important. (note that increasing the mass of a pendulum does not make it swing faster).
Ports	Land slopes tend to be the same, while waves are higher, therefore coastal cities may be less common.
Plumbing	More rise needed to produce a given pressure head. Larger pipe diameters to accommodate fluid friction and sludge in longer pipes.
Rockets	Mass ratios go down exponentially with escape velocity.
Steam engines	Originally developed for mining, which may go deeper and need them more.
Telescopes	Large glass objectives are easier to make and handle, but deep atmospheres obscure skies.
Thrown objects	Missiles with dangerous mass are easier to carry. Lethal range is greater.
Water power speeds	Less energy in a given fall, but flowing may not be affected.
Writing	Trees and animals are larger, bark and skins have greater clear area. Assuming eyes are similar, character size is more or less constant. So, information per page goes up as the square of dimension.

By making some technologies easier than others, surface gravity may tilt the ground on which the drunkard's walk of random variations occur, biasing the direction of technological change. On average, something that is easier to do would usually be done sooner. This is influence, not determination.

The influence of variations of surface gravity on many of these items could make a long paper in itself--this is intended as a place of departure, not a final word. Technology evolves not unlike life itself, with recognizable mutations, reproductions, and dead ends. The needs at the time determine which technologies survive, fail, or are never invented--while the effects of using the technology, reflexively, can change user needs.

For instance, consider the influence on human history if, as it would have been on a world with Mars type gravity. The range of early cannon would have been about ten kilometers instead of five. A single battery, or fort, would have been able to protect four times the area. What would have happened if the steam engines of Robert Fulton's day had been able to power heavier than air aircraft? Would railroads have ever become as dominant as they were in the nineteenth and early twentieth centuries?

Of course, many other things would have been different as well. Water power may not have been as effective a driver for early industry, leading to earlier development of steam turbines such as demonstrated by Hero of Alexandria.

Processes that depend on gravitational separation of liquids of different density, or on precipitation of particulates would go more slowly, perhaps too slowly in some instances.

On the hypothetical world of Epona, being developed as an intellectual exercise by the CONTACT group as a case study in the evolution of extraterrestrial intelligence, the native intelligences are presumed to be able to fly. While they are still exploring the implications of that, it seems clear that the kind of territorial control and relative isolation that dominated the early development of human culture could not be sustained as easily.

Lower gravity worlds will typically have less surface area, but the scale of natural and constructed objects, from out houses to empires, would likely be larger. So crowding might occur earlier.

Finally, one should reemphasize the extreme uncertainty of all the speculations above. All statements in this paper (and, a physicist would argue, in the universe as a whole) are statistical statements. To say, for instance, that "this" leads to "that" is shorthand for saying that it is estimated that over a statistically significant number of trials "this" will be followed by "that" with a statistically significant frequency. Sometimes, as with physical laws applied to near ideal conditions within the range and domain of experimental evidence, a statement approaches certainty.

But where knowledge is much less certain, and phenomena much more complex and contingent, there will always be exceptions and uncertainty. The geophysicist Birch is credited (Hartmann 1993) with the following: "Unwary readers should take warning that ordinary language undergoes modification to a high-pressure form when applied to the interior of the Earth. A few samples of equivalents follow:"

Table 12 Precision under Pressure

Ordinary meaning	High-pressure form
dubious	certain
perhaps	undoubtedly
vague suggestion	positive proof
trivial objection	unanswerable argument
uncertain mixture of all elements	pure iron

And that's from a physical science!

The development of early human technology and culture is not one the author's fields (which are physics, astronautical engineering, and systems management), and at this point it is perhaps best to leave the consequences of lower surface gravity to people who know much more about flints, dies, triremes, arches, flying buttresses and the like. A change in surface gravity may be significant in some areas, not so in others.

8.3 Gravity and Access to Space

Of greater relevance to the question of contact with other intelligences is how surface gravity affects access to space and the likelihood of colonization. Our chances of contacting a race that has settled, or at least placed observation stations, in many star systems is much greater than contacting one still bound to its home world. Here, the inhibition of gravity is extraordinary. Economical space flight from Earth is marginal for chemical rockets, which need 10 to 20 kg of propellant for each kilogram in low Earth orbit (LEO), including propulsion and structure. "Economical" in this sense means with a single vehicle that can be refueled and reused, much as a truck, ship or aircraft. While, like the Pyramids of Egypt, our Apollo lunar missions had a certain cultural and historical influence, it has not been the kind of influence the invention of the horse collar, the water wheel, the arch, or the aircraft have had.

But on a world with Martian gravity, things would have gone very differently. To support its weight and pass through the atmosphere, a rocket rising from Mars would need only about 4 km/s "delta-V." Delta-V is the change in velocity a rocket would achieve in the absence of air and gravity. A wealthy individual can make a rocket that achieves that velocity with a 19th century technology base (of course, once built, the rocket engine would reflexively redefine the technology base in which it was created). Kerosene and highly distilled hydrogen peroxide (a common bleach) would do quite nicely for fuels.

A historical note: Robert Goddard took on the difficult development of cryogenic liquid propellants because his calculations (before the first world war) showed that he would eventually have to use liquid hydrogen and liquid oxygen or very costly and complex multistage rockets (Goddard, 1914). Otherwise, he could have achieved much more impressive results, much sooner--as some of his German colleagues of the era had--with hydrogen peroxide and a hydrocarbon fuel.

To a first approximation, the muzzle velocity of a large gun is also limited by the kinetic velocity of the gasses created by the explosion of its propellant. Though it was based on sound physics in most other respects, and his propellants contained enough energy, Jules Verne's lunar cannon would have failed to generate the necessary velocity for such gas dynamics reasons. Current practical research on space guns has focused on generating extremely hot hydrogen gas, which does have the necessary velocity, then introducing that into the gun barrel. If the acceleration shock problem could be solved, Verne-type cannon would work from Mars--something H. G. Wells anticipated when he wrote "War of the Worlds." A NASA/Battelle Columbus study indicates that only about ten centimeters of nose material and 0.5 km/s velocity would be lost in the passage through the lower atmosphere, justifying Verne's treatment of this as a second order problem--though both recision of the nose tip and velocity loss would be greater going out through a deeper atmosphere with the same surface pressure in lower gravity.

Once access to space is achieved there would follow, communications satellites, world cultures, disruption of tyrannies that depend on manipulating their citizens with lies, and access to space resources--perhaps before a low gravity civilization finds itself in a population crisis.

It also seems reasonable to assume that most low gravity cultures would gain access to space on a regular and economical basis before developing electronics and nuclear energy. Attempts to establish dome type stations, or even colonies, of nearby planets or moons in their equivalent of the Victorian era are not out of the question. The need to know chemistry, the periodic table, and means of liquefying air would seem to preclude significant space activities at a stage much earlier than that, however.

Once a society has spacecraft and the means to divert the courses of small asteroids, moonlets, ring particles or other space debris of a few thousand tons of mass with precision, it has access to weapons with several times the destructive power of nuclear explosions. It seems doubtful, given the extreme difficulty of creating a nuclear explosion as opposed to a meltdown, that an attempt to make these devices would be made. One can speculate as to whether asteroid bombs would ever be used, but if used, they would at least be non-radioactive. Problems with increased albedo and lower temperatures would be,however, far worse.

How would we look to races evolved on low gravity worlds? Perhaps in all their random travels through the galaxy they've never seen a world with the surface gravity of Earth that didn't have an atmosphere to match. Besides, the sun is so hot and bright that its ultraviolet and solar wind would boil the hydrogen out of the exosphere of any normal world. Intelligent life on Earth of Sol? Not very likely!

9. Unusual Worlds and Other Complications.

Up to this point we have used 'surface gravity as if it were a single value applied to a world's entire surface. This is only an approximation. The actual acceleration one feels at a given point on the surface of a planet is influenced by a number of what are usually second and third order effects.

9.1 Centrifugal Worlds

The most important of these is centrifugal force. Centrifugal means "tending away from the center." (In an inertial frame of reference, of course, it is simply the tendency of objects to go in a straight line). It is equal to v^2/r, where v is the inertial speed of the surface of the planet and r is the radius from the center. Viewed from the surface, on the equator of a spinning planet, centrifugal acceleration feels like a force working in opposition to gravity. The force you feel holding you down is gravity minus centrifugal force.

The center of centrifugal force is the spin axis of the planet, a line through the north and south poles. As one goes north or south of the equator, one's distance from the spin axis gets less and centrifugal force gets less. Also, it always operates on a line normal to the spin axis; if the planet's surface were a perfect sphere, it would feel like the side of a hill, with up toward the equator. But Moons and planets do not stay perfect spheres; they arrange themselves normal to local "down," becoming an "equipotential" surface that feels flat wherever you are.

Globally, it looks as one might expect–the equatorial regions are thrown out somewhat, and the planet is more or less elliptical in cross section. Venus, which rotates very slowly, has little flattening. Earth is flattened about 1/3 of 1% and Saturn by almost 10%. The oceans of Earth, which connect and try to level them- selves, approximate an equipotential surface. Equipotential does not mean equal force, however, and, in Saturn's case, surface gravity is significantly higher at the poles than at its equator. This is a second order affect that on most worlds has little to do with the suitability of a planet for evolving life or being colonized.

But there may be exceptions, such as "Mesklin" from Hal Clement's novel, Mission of Gravity. Mesklin was super-massive, but spun so fast that the gravity was reduced to a barely tolerable three g's at its equator. There is as yet no real world analog for Mesklin, but it is physically possible, and the universe may have many such surprises in store for us.

9.2 Tidally Stretched Worlds

A world which is tidally locked experience a tidal stress caused by the fact that it is not a point in space, but can only move with one velocity. Thus, the parts of the world that are closer to its partner are moving at less than orbital velocity for their distance, and are trying to fall into a lower orbit, while the parts of the world farther from the center of its partner are moving faster than orbital velocity and trying to go into a higher orbit.

The world's gravity holds it together, but with diminished force at its inner and outer ends. Also, at the satellite's north and south poles, material would normally follow a trajectory towards the orbital plane, but the surface prevents this. Thus the satellite is slightly "squeezed" along its north-south axis and the apparent acceleration due to gravity is somewhat higher there. Thus the satellite's equipotential surface is elongated to and from the planet and squashed slightly north and south.

Figure 9 is an exaggerated example of this. Note that material on an equipotential surface feels no lateral gravitational or centrifugal forces, and is thus free to move from an area of high surface gravity to an area of low surface gravity with minimal expenditure of energy--following air mass movements, for instance.

Atmospheric retention on such worlds will depend on the effective escape velocity at its far ends, where surface gravity is lowest. In extreme cases, tidal stress may be sufficient to disrupt the world, or at least steal some mass from its nether ends. Amalthea (Jupiter 5) comes very close to this, depending on what one assumes for its mass. Certain stars are known to lose mass to their companions this way.

For a world made of incompressible liquid, the radius at which this starts to happen is called Roche's limit, after the French mathematician who first worked the mathematics. The equipotential surface that merges with that of its primary is called a "Roche lobe." The shape of Amalthea is very much like a Roche lobe, (except that it is pointed the wrong direction--perhaps the formation of the huge crater, Pan, had something to do with that).

Could a habitable world have such a shape? Larry Niven created a world, "Jinx," that was like this. Its atmosphere formed a band between the inner and outer poles, which were alleged to be high enough to stick above the clouds. The surface of Jinx was thus not an equipotential surface--the atmosphere would have flowed over the ends in hydrostatic equilibrium if it was. However, the crust on the inner and outer poles would have been thicker and the mountains higher than near its other poles.

Or, If Jinx gradually moved out from its primary due to tidal forces, and the crust was significantly thick, it might have what's called a "fossil bulge," an out-of-isostatic compensation reminder of ancient conditions. The fossil bulges above the geopotential surface would eventually fall fall back down, i.e. the surface would "relax," as pressures inside adjusted--but eventually can be a long time in planetology, and, in the meantime, Jinx has moves further out and the equipotential surface recedes more. Under the right circumstances, the air could be very thin indeed over the inner and outer poles of Jinx.

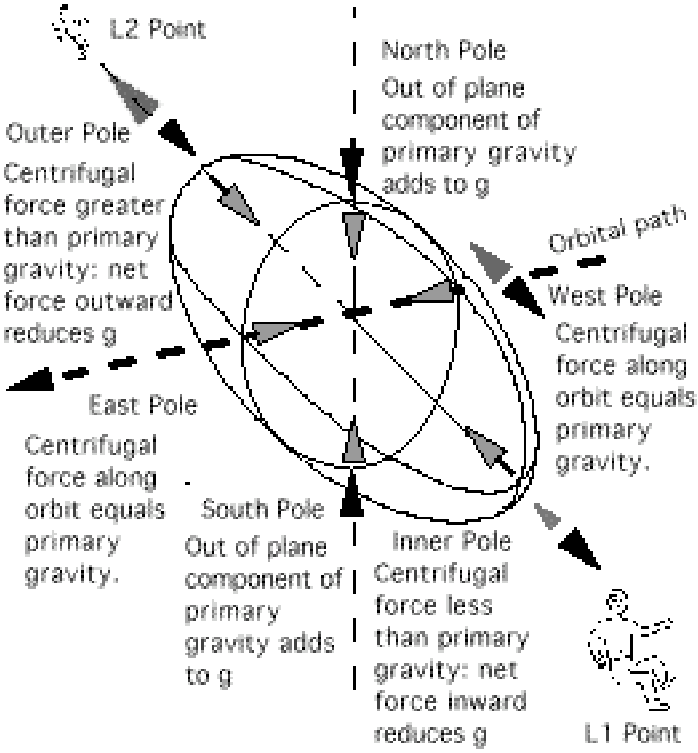


Figure 9. Gravity on a tidally locked "stretched" world.

The far side of the moon averages a few kilometers above the moon's geopotential surface. The near side is actually below the geopotential surface, but is composed largely of heavy material, and is so equally out of isostatic equilibrium--these mass concentrations affect the orbits of satellites about the moon, which is how they were discovered.

A race that evolved on a world that is significantly elongated could evolve in one gravity regime, then gain access to space from a lower gravity area. But perhaps they would move to the low gravity area, if available, for other reasons before being technically able to launch spacecraft. Life would be easier there; It may be a general rule of evolution that intelligent beings will tend to migrate to lower gravity areas, if habitable.

10. Conclusions

Worlds are diverse in surface gravity, but the surface gravities of known worlds tend to fall into groups differing from by a factor of about 2.5. There is no obvious reason for this; however it has not been the subject of much research. If this is true of other solar systems as well, Earth-like, Mars-like and Titan-like worlds may be the norm, with few in between.

In our solar system, three out of five worlds with Earth-like gravity are gas giants. Of the eleven worlds in these three groups, seven are satellites of giant planets, and while none of these has liquid water and substantial atmospheric pressure, it is easy enough to see how this could happen with a little more luck. Worlds of that size with habitable or at least terraformable surfaces may, in fact, outnumber Earth and Mars type worlds. Europa was a near miss.

Thus low surface gravity does not rule out the retention of a dense, hydrogen-compound-rich atmosphere under the appropriate conditions. These would include:

1. Older and cooler stars than the sun (which is to say most ordinary stars!) with less energetic solar winds and less ultraviolet in their spectra.
2. Benign, symmetrical magnetic fields to reduce solar wind impact and avoid additional acceleration of ions.
3. Giant planet partners with strong gravitational field that can help retain escaped gasses. For satellites outside the "zone of habitability," as defined by incident sunlight, energy input to the satellite's troposphere can be augmented by tidal heating and infrared radiation from the planet.
4. Efficient heat-radiating molecules in the atmosphere to enhance the cold trap that reduces hydrogen loss.

It seems reasonable that a space-traveling culture would colonize worlds of equal or lower gravity than the worlds from from which they came. If Earth represents the upper limit of surface gravity of worlds with solid surfaces, one would expect most colonized worlds, perhaps a very large majority, to have surface gravities less than Earth.

Even if such cultures are rare, they would take only a few million years to litter the galaxy with their artifacts--such artifacts being the bioformed satellites of giant planets.

So, with many caveats, it may be that the best place to look for space faring cultures would be the satellites of gas giant planets which are relatively close to M and perhaps low K class stars. But, with so many variable factors, and so many ways one can compensate for another to create a physically suitable environment, there should be some very surprising habitable worlds as well.

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