Creative Planetology

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One of the first things a fan notices, in SF stories spanning most of the 20th century, is the wide variation in the imaginary worlds that writers create. Some are mock-medieval fantasy worlds, some are extremely plausible alien planets, and others are merely absurd.

As you might expect, my focus here is on how you work out human-habitable planets. I'm ignoring a whole lot of worldbuilding – be it in fantasy worlds, "subcreations" predating even Tolkien, or be it in roleplaying-game worlds.

So be warned: there are EQUATIONS and MATH in this article.

And now, a confession: this subject properly calls for calculus – which I did not succeed in learning. But close approximations of orbits, and other values, can be made by algebraic equations, which are offered here.

In a nutshell: Over the course of time, a certain amount of "prior art" in worldbuilding has accumulated, mostly in astrophysics. It appears that just a few quantities – such as the mass of a star, the mass of a planet, and the distance between them – determine almost every other physical feature of a fictional environment. The mass (and age) of stars determines which types may harbour habitable planets, and at what distances; the orbital distance determines how long a year such a planet may have, and how bright the sunlight is on a planet's surface. The mass of a planet determines its surface gravity and escape velocity, how likely it is to have oceans and an atmosphere (and how much), and may be a major determinant in the length of its day. The presence of a gas giant seems to have a bearing on how frequently major meteors or asteroids may hit such a life-bearing world. The presence, mass and distance of a satellite, or satellites, determines not only the magnitude of tides, which almost certainly exceed the tides exerted by the sun; satellites will also help stabilize a planet's axis of rotation. "Rings" of dust, gravel or icy debris around a planet will probably have a climatic effect, cutting down insolation somewhat, and they are not likely to last long geologically, unless "shepherd" satellites are in orbit. Additional satellites might be found at the LaGrange points, also called Trojan points, in a planet-moon system, but are not likely to be found in the LaGrange points of a planet's orbit.

Fallacies to Watch Out For!

Some of the first few fallacies about astrophysics I noticed were the *Star Trek* references to planets as though they just hung around out there, without a light source or anything; or the references to planets around the well-known, major stars in our night sky, most of which are far so massive and bright, they will become supernovas before any of their unlikely planets can develop life.

Numerous stories, from Blish's "Cities in Flight" series to *Star Trek* to *Star Wars*, made the mistake of giving a whole planet just one climate, or weather, all over.

A famous scene early in *Star Wars* shows *two* suns setting, almost at once, on a planet; a similar scene showed up in *Aliens*. Opinion has been divided as to whether habitable planets can form in binary star systems, but a recent opinion (*New Scientist*, 2001) claims that they are possible when the bright stars are as far apart as our Sun is from, say, Uranus. (Alpha and Beta Centauri form such a system.) But in such a case, the “secondary” star would be another, very bright star; it would only appear in a planet’s sky for about half the year. No double-sunsets there.

Double planets, however – a habitable planet with another, or even a gas giant, hanging in its sky – appear to be quite possible.

Habitability: Orbit, Rotation and Size

When Stephen Dole's *Habitable Planets for Man* was commissioned by the Rand Corporation in the early 1960s, the main criteria for a life-bearing planet were derived from one demonstration proof, the Earth we know. The observed physical criteria are that such a planet be sufficiently large to retain an atmosphere, be sufficiently warm at its distance from the sun to retain liquid water, be sufficiently small not to become a gas giant, and rotate in less than 48 hours, to maintain a tolerable range of daytime and nighttime temperatures. It is also important that the angle of inclination of a planet's axis of rotation to the plane of its orbit not be too acute, or seasonal variation will be absurdly extreme. Satellites cannot be too large or too close, or tidal forces will do more than make inshore fishing difficult; they will cause storms and floods too great for life, or eliminate the atmosphere, if not causing the mutual breakup of primary and satellite alike.

“C. H.O.P.K.I.N.S. Ca.Fe”

Since then much work has been done bearing on the origins of life on the inanimate Earth. After a period in which the planet's surface was molten, it cooled sufficiently to form a crust on the surface. Numerous volcanoes emitted gas and liquids, which eventually formed seas and oceans (up to 75% of the emission of volcanoes is water). Radiation, heat, cold and electric discharge in the primordial atmosphere all work to create amino and nucleic acids. Recent work indicates that not only in the primordial seas, but especially on shoreline clays, these products formed the basis of early life: self-replicating organic chemical bodies.

All this, if the above-mentioned elements are present – carbon, hydrogen, oxygen, potassium, iodine, nitrogen, sodium, calcium, iron … you get the idea.

“Oh Be A Fine Girl Kiss Me”: Stars as Primaries

Stars and planets form when interstellar matter collects in a dust cloud, which slowly condenses, and heats up from gravitational compression. The vast majority of interstellar matter is hydrogen, the simplest element, followed by helium. A sufficient mass of compressed hydrogen undergoes sustained fusion reactions.

Observed stars can be typed in a regular progression, from the largest, brightest and most short-lived to the smallest, least radiant and longest-lived, according to types **O, B, A, F, G, K, M**. Unsurprisingly there is a relationship between a star’s mass, and its energy output, and its lifespan, illustrated by the well-known “Hertzsprung-Russell Diagram”.

Over a certain size (rather larger than our own Sun), stars eventually exhaust their store of hydrogen, undergo all possible further fusion reactions and go nova, scattering heavier elements throughout space. The remnant objects form stellar objects in another progression (**R, S, N**), which includes black holes, pulsars and white dwarfs.

I told you all that in order to tell you this. For human habitability, or at least for lifebearing planets (and useful story settings), the range of candidate stellar types is limited to types F2 through K1. (Our own Sun is now typed G2.) The reason is that, by definition, a life-bearing planet has to receive *enough* energy for liquid water to persist on the surface – and *continue* to receive that much energy for the several billions of years it takes for life to develop. This not only defines a "Circumstellar Habitable Zone", or inner and outer limits for potentially habitable orbits around any star; it means that too large a star burns out much too soon, and too small a star means that any planet receiving enough energy must orbit so closely that it will become "tidally locked", with one face always toward its sun, as our Moon is tidally locked to the Earth.

That means most SF story settings will be on planets orbiting the following types of stars:

Table I: Candidate Stellar Types

Some Spectral Classes	Mass Range (Solar masses)	Luminosity (Sun = 1)	CHZ (in AU's)
F0	1.5	4.8	-
F2	1.4	3.02	1.5 – 2.16
F5	1.3	2.3	1.24 – 1.78
G2	1.0	1.0	.776 – 1.12 (est.)
G5	0.91	0.7	.64 - .9
K0	0.74	0.3	.604 - .662
K1	0.73	0.252	.599 - .625

(From George Ochoa & Jeffrey Osier. *The Writer's Guide to Creating a Science Fiction Universe* [Cincinnati: Writer's Digest Books, 1993], p. 117, and my own notes.)

For absolute, rather than relative values, our Sun's mass is 1.99 x 10^{30} kilograms; our Sun's luminosity is 3.8 x 10^{23} kilowatts; and our mean distance from the Sun, or one "Astronomical Unit", is 1.494985 x 10^{11} meters.

To calculate the total energy output of a star, compared to our Sun,

$$L_{star} = 2.52^{(4.85 - M)} \tag{1}$$

where
L = "luminosity"
M = mass (in Solar masses)

You may wish to note that the estimates of our Sun's CZT have kept changing over the last few decades. In a recent *Scientific American* article (Gonzalez et al., "Refuge for Life in a Hostile Universe", Vol. 285 no. 4, Oct. 2001), the CZT was pictured as extending from just *outside* the orbit of Venus to outside the orbit of … *Jupiter*.

Candidate stars in the local neighbourhood

Table II: Candidate Stars

Star	Distance from Earth (light-years)	Spectral Class
Alpha Centauri A	4.3	G4
Alpha Centauri B	4.3	K1
Epsilon Eridani	10.8	K2
Tau Ceti	12.2	G8
70 Ophiuchi A	17.3	K1
Eta Cassiopeiae A	18.0	F9
Sigma Draconis	18.2	G9
36 Ophiuchi A	18.2	K2
36 Ophiuchi B	18.2	K1
HR 7703 A	18.6	K2
Delta Pavonis	19.2	G7

(From Ochoa & Osier [1993], p. 121.)

Remember, a light-year is the distance light travels in one of our years – and the speed of light (c) is nearly 300,000 kilometers per second.

Galactic "geography"

It may be as well to supply a little more context here, about our Sun and its environment. The majority of stars are in vast whirlpools, or galaxies, and within the spiral arms of the whirlpool. Our own sun is in what is called the "Orion Arm" of the "Milky Way" Galaxy, about 30,000 light years (roughly two-thirds of the distance) from the galactic centre.

It may concern you to refer back to that *Scientific American* article I mentioned. Gonzalez et al. (Oct. 2001) were concerned to establish whether there was a *Galactic* Habitable Zone. Apparently, if you go too far away from galactic centre, the "metallicity" or proportion of heavy elements in a system's primordial dust cloud will simply be too low to form life-bearing planets; certainly, too close to galactic centre, the incidence of cosmic threats such as radiation is simply too great. The Galactic Habitable Zone they picture is rather a narrow band, and our Solar system appears to lie in the middle of it.

From magnitude and luminosity to insolation and ecospheres

The perspective on the "ecosphere", the distance from the Sun within which a habitable planet may orbit, has changed in the last thirty-five years. As far as the inner limit is concerned: it appears now that the early Earth and the early Venus were extremely similar planets, but their distance from the Sun, and their consequent ambient temperature, made all the difference to their habitability. The early atmosphere of the Earth included a great deal of carbon dioxide; it was much more dense than it is today, like the contemporary atmosphere of Venus. On Earth, this reacted with water to form carbonate minerals; plants also utilized carbon dioxide in photosynthesis, releasing oxygen in the process. These steps, depending on bodies of liquid water and the presence of life, could not take place on Venus. Evidently the definition of the ecosphere has moved outward from the orbital distance of Earth; we may in fact be at the inner limit of habitability.

To calculate the intensity of light a planet receives at a given orbit,

$$I = L/r^2 \tag{2}$$

where

I = surface illumination
L = luminosity
r = semimajor axis

"Mother Very Thoughtfully Made A Jelly Sandwich Under No Protest"
Statistics from our solar system:

A simple mnemonic (above) lists our Sun's planets, in increasing order of distance: Mercury, Venus, Earth and Mars (the "terrestrial" planets), the Asteroid belt, then Jupiter, Saturn, Uranus, Neptune (the "jovian" or gas giant planets), and Pluto. Opinion is divided as to whether a tenth planet lies all undiscovered beyond Pluto's orbit. (There is also a fringe theory that a planet with a highly elliptical orbit, and a period of perhaps a million years; but this is tied up with theories about ancient astronauts and our species being "seeded" here thousands or millions of years ago.)

The things to remember about the layout of the Solar System are how *vast* it is, in human terms – and that each successive orbit is *exponentially* more distant from the Sun.

As protostellar masses condense, they form immense rotating disks; the same slow gravitational condensation that eventually forms a star also forms rocky masses, planets-in-waiting, orbiting the centre. By the time that enduring masses in stable orbits have formed, their mass accumulation comes from meteorite infall. Also, apparently, all orbiting bodies can be expected to orbit in the same direction, unless something really weird has happened.

Today, if we view our Solar system from "celestial North", all the Solar planets appear to orbit counter-clockwise ("direct revolution"), and most planets also spin counter-clockwise about their axes. The exceptions are the planets Venus, Mars and Uranus, which for some reason spin the other way ("retrograde revolution").

Two things seem pretty clear from the most elementary astronomy texts: the orbits of planets are precisely related to their masses and distances from the Sun; and yet their mass is pretty randomly distributed among the planets.

A fairly simple algebraic formula approximates the orbital periods – the lengths of year – of planetary bodies in a system orbiting about a central sun:

$$T^2 = 4\pi^2 r^2/G(m_1 + m_2) \tag{3}$$

Where
T = the length of the year,
r = the mean distance of an orbiting body of mass m_2 from a greater body of mass m_1,
G is the gravitational constant (6.667×10^{-11} Newtons x m^2/kg^2),

π is the ratio of a circle's radius to its diameter.

Real accuracy (describing the orbit as an ellipse rather than a circle) requires a formula in calculus, plus modifications for the perturbations of other bodies. Apparently all bodies orbiting can be expected to orbit in the same direction, unless something really weird has happened. Our own Earth is in the third orbit from our Sun.

More accuracy (describing the orbit as an ellipse rather than a circle) requires a formula in calculus, plus modifications for the perturbations of other bodies. The algebraic expression of an ellipse is

$$(a^2 + b^2)/a = e^2 \tag{4}$$

where

a = the semimajor axis of the orbit (i.e., half the length of the ellipse)
b = the semiminor axis of the orbit (i.e., half the width of the ellipse)
e = the natural logarithmic base

Stephen H. Dole, in his early Rand Corporation study, estimated that orbital eccentricity could not exceed 0.2.

Mass, Planetary Fate, Gravity and Escape Velocity

Above a fairly large size, planets can be expected to form immense atmospheres composed mainly of hydrogen and its compounds. These "gas giants" can be so large that their solid cores comprise an insignificant part of them. It seems to be the case that such planets will generally be in the outer planetary system, rather than among the inner planets, as the "primordial" atmosphere includes so many gases easily driven off by solar radiation: hydrogen, H_2O, methane, hydrogen sulfide, and ammonia.

If there is any rough rule, it is that "terrestrial" planets are liable to orbit closer to a sun, and "jovian" or "gas-giant" planets are liable to orbit much further away. But these are far from absolute rules.

When a sufficient mass of interstellar debris collects to form a planetoid, it forms a path, or space about its orbit, in which no other planet can form. This appears to explain why a rough algebraic rule, "Bode's Law", describes the distances of planets in our solar system from the sun.

To simulate this rule, write out the successive powers of 2: 0, then 2, then 4, then 8, then 16, etc. Then multiply each figure by 0.3. Then add 0.4 to each figure. The resulting figures nearly match the orbits of the planets, out to Uranus; the system breaks down at the orbits of Neptune and Pluto, and instead of a fifth planet as predicted, we find the asteroid belt between the orbits of Mars and Jupiter.

Current thinking, according to Stephen Gillett, is that the logarithmic spacing of stable planetary orbits is a tidal effect, which falls off as distance from the Sun increases; this seems to be supported by the fact that similar logarithmic spacing occurs in the orbits of the satellites of the gas giants. The reason why a planet did not form where we find the asteroid belt seems to be gravitational perturbation, principally by Jupiter.

That gravitational perturbation of Jupiter, by the way, is credited with sparing us a whole lot *more* meteorite infall than life on earth can deal with.

Jupiter is an interesting case. Remember the distinction between the four inner, "terrestrial" planets, mostly consisting of rocky cores, and the outer "gas giant" planets, mostly consisting of extensive atmospheres? Gillett considers the distinction to be the "Ice Line", the orbital distance beyond which ice can form on a planet. Interestingly, Jupiter is both the innermost gas giant to the "Ice Line", and the biggest gas giant in our system. It is suggested that any system where life appears, depends on the appearance of such a gas giant.

Above a fairly small size, planetoids such as Ceres are forced into a spherical shape. As each growing planet becomes larger and denser, it develops enough heat at the core to melt the interior matter, perhaps the whole mass. Heavier elements work their way inwards and lighter elements settle upwards, towards the surface; thus Earth has a core mostly composed of iron, and a crust mostly composed of silicon.

To calculate the radius of a planet from its mass,

$$R \approx \sqrt[3]{(3m/4\pi d)} \tag{5}$$

where
R = the mean radius of a planet's surface from its centre
m = its mass
d = its density, approximated as 5.5 gm/cm^3.

One Earth mass is 5.997×10^{24} kg.
From this we can fairly easily calculate the surface gravity:

$$g = Gm_p/r^2 \tag{6}$$

where

G = gravitational constant
m_p = planetary mass
r = mean planetary radius
g = surface gravity

For comparison, Earth's radius is roughly 6.371×10^6 meters; Earth's surface gravity is approximately 9.81 m/sec^2.
Alternatively:

$$dD = g \tag{7}$$

where

d = average density of the planet (relative to Earth)

$D = 2R$ (relative to Earth)
g = surface gravity (relative to Earth)

About the smallest planet we can consider habitable would mass about 0.40 times as much as the Earth.

Length of Day

Stephen L. Gillett considers the planetary rate of rotation to be pretty random, as it seems to depend partly on the original infall rate and direction of meteors to a planet while it is in formation; and partly on how strong a tidal “braking” effect is applied by a major satellite.

I once worked out another, fairly simple formula where the rotation period varied inversely as the mass of a planet, *unless* it had at least one satellite representing a significant fraction of its mass (like Earth's Moon), or is quite close to its primary (like to the Earth relative to the Moon, or like Mercury and Venus relative to the Sun).

$$T = 2\pi R / K \sqrt{2M} \tag{8}$$

Where

M = the mass of a planet,
R = the radius of a planet,
$K \approx 2.3395716 \times 10^{-10}$

Satellites

Many of Poul Anderson’s stories are set on worlds rather like ours – but significantly smaller, and without any large, close satellite like our Moon. Larry Niven (“There Is a Tide”) had an idea that a habitable world needed a Luna-type moon, to reduce the atmosphere by tidal effects, and to create intertidal zones where life might form. It now appears that an Earthlike world needs a large, close moon, but for other reasons: its tidal effects stabilize our planet’s rotation, otherwise we might find our rotational poles “migrating” all over the globe’s surface, within only a span of *centuries*. That sort of makes it difficult for life forms to maintain stable ecosystems, much less to develop intelligence and civilization.

As it is, the fact that all the planets except Venus spin in the same direction is persuasive that their spin, like their mass accumulation, comes from their meteorite infall. Venus’ slow, retrograde rotation is explained as a result of tidal forces exerted by the Sun.

There is a tide …

The height of tides can be simply calculated as

$$m_l / r_m^3 = t \tag{9}$$

where

m = lunar mass

a = orbital distance
t = tidal effect (NOT tidal height!)

A more complicated formulation is

$$h \alpha m_a r_b^4 / m_b r^3 \tag{10}$$

where

h is an index of tidal force,
a = a planet (major mass),
b = a satellite (minor mass),
r = common distance

The upshot is that if $h^2 = 2.0$, one side of the satellite ends up permanently facing the planet, as the Moon is tidally locked to the Earth.

LaGrange points

Gerard O'Neill popularized the idea of setting up permanent habitable satellites, not simply in Earth orbit, but in the "LaGrange points" preceding and following the Moon in its orbit. As a geometrical and mathematical exercise, some pogue named LaGrange came up with the argument that, equally distant from a major mass and a minor mass, and 60 degrees ahead and behind the minor mass in the same orbit, there should be points of gravitational stability, where a much smaller mass could remain in place. In point of fact there are "Trojan" asteroids oscillating around LaGrange points in Jupiter's orbit about the Sun. But due to various gravitational perturbations, any O'Neill space stations would have to be equipped with large enough positioning jets to return them to position when they are tugged out of place.

Rings – and global climate changes

Gillett discourses at some length on the effect that rings of dust, ice, or meteor-like debris would have on the climate of an Earthlike planet. The general effect is that they would occlude sunlight and reduce temperatures, especially in high latitudes in winter.

(I seem to recall a *Sky and Telescope* article, some years ago, speculating that there was volcanism on our Moon up to geologically recent times, which actually created such rings around the Earth and contributed to past Ice Ages. Any comments?)

Summary: Basic Variables, and Processes

Once you get on top of the math, it seems clear that many of the features of stars, planets, lengths of year and month, intensity of sunlight, magnitude of gravity and escape velocity, are all predetermined by a few initial factors; and many features are not predetermined.

What I have left entirely out of consideration – in this article – is what to decide about the plate tectonics and the lay of the land on a world; about the biochemistry, evolution, biology or ecology; or anything beyond astrophysics.

Now, how much astrophysics did I leave out? How many mistakes did you count? Come on, I'm waiting.

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