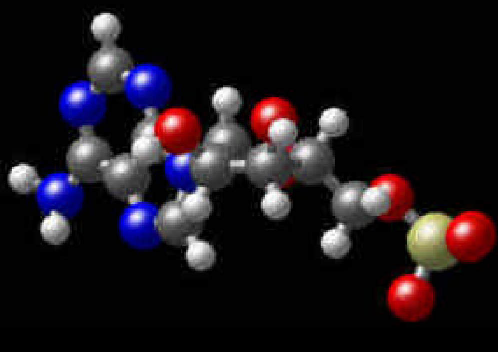
WORLD GENERATION



Generic System & Planet Building Resources

INTRODUCTION

PURPOSE
There are a lot of systems for generating other solar systems and worlds out there, both as game rules and as web sites. However, I wasn't that happy with them. Many are good for space-opera settings, but not for hard SF. Other were limited in scope (only "garden" worlds) or out-dated. So I decided to put this together myself, more as a collection of ideas than anything else.

SCIENTIFIC ACCURACY
I do not claim for this document to be scientifically correct. Many generation formulae include a random component, for instance, and others are constructed just to make "decent" results as I see it. The ideas are a collection of various sources from literature to news articles, and as always they may not be correct or interpreted correctly. Also, there may be problems with the equations I haven 't noted. Several of the formulae are however just ordinary physics, calculating the scale height or surface gravity is a straightforward thing.
There is a foundation in science, though. It may be simplified or skewed, or based upon inaccurate background data, but the intention has been "realism". If you don't like any of the charts or equations, change them by all means. And if you find any errors or strange things, do contact me.

HOW TO USE THIS DOCUMENT
Part I is in many ways designed as a "manual". There are steps in the beginning of each section, which can be followed to generate a system. Often some of the generation isn't necessary, if you already have background data or an idea you can use it just to flesh things out a bit. References to "1D10"'s and "1D100" and so on are relating to a random number from 1 to the number after the "D", as symbolized by rolling a die. Most calculators and computer math programs are capable of generating random numbers.
If you intend to generate several systems I suggest you make a simple spreadsheet program to speed up things. The steps are often involving a lot of math. Unbelievably as it may seem, things could be made even more complex than they are, but it you prefer a simpler version there are a lot of steps that can be ignored or simplified.
Part II is more of a descriptive section, and as such is mainly for inspiration about how planets work and what should be considered. There are also some templates which can be useful for planetary and system mapping.

CREDITS
I have included a reference list at the end of the document, which contains many of the works that has served as inspiration for this document. Any misinterpretations of such works are entirely my own fault. Also, I'd like to thank Peter Trevor in particular and Even Sorgjerd for their many valuable suggestions, corrections and questions, and Andy Goddard for his assistance with the Coordinate Systems section (5.3).

*Written by **Tyge Sjöstrand***

*If you have any corrections, questions and/or suggestions, or if you just find the document useful, mail me: **tyge.sjostrand@pi.se***

This incomplete version of the document is dated 2000-08-06.

TABLE OF CONTENTS

Sections in italics are not completed in this version.

PART I SYSTEM DATA

ONE/1 STELLAR DATA

STEP ONE: Determine what type the primary star of the system is. Generate a spectral class on Table 1.1.1. If you already know what class the star is, skip to STEP TWO. Note that the charts also generate brown dwarves.
STEP TWO: Determine if the star is a binary star by rolling 1D10. On a roll of 7 or more, the star is a binary. Roll again, every roll of 7+ on 1D10 resulting in another star added. Generate spectral class of additional stars normally after consulting Table 1.1.2. If you already know what the secondary stars - if any - are, skip to STEP THREE.
STEP THREE: Determine the basic luminosity and mass of all stars involved by consulting Table 1.1.3.

Table 1.1.1 Star Generation

1D100	*Basic Type*	*Size Code*	*Specification Roll*
1	Spectral Class A	V	1D10: 7+ = Subgiant (IV)
2-4	Spectral Class F	V	1D10: 9+ = Subgiant (IV)
5-12	Spectral Class G	V	1D10: 10 = Subgiant (IV)
13-26	Spectral Class K	V	
27-36	White Dwarf	VII	
37-85	Spectral Class M	V	
86-98	Brown Dwarf	-	
99	Giant	III	1D10: 1=F, 2=G, 3-7=K, 8+=K (IV, subgiant)
100	Special	-	Could be B-class stars, giants, neutron stars, protostars or other rare stellar objects

Specify spectral class by rolling 1D10 and put the number between the spectral class and size code. A roll of "10" is treated as "0". Brown dwarves and white dwarves do not have proper spectral specifications, and they have their own section that should be consulted.
Exception: K-IV class subgiants are always of class K0IV.

Table 1.1.2 Binary Stars
Roll 1D10
1-2: Second star is of identical spectral type and size class, though possibly of another higher numeric specification. Roll 1D10 - if lower than the original star, use the original star's number, otherwise use the rolled number.
3+: Second star is of random type, determined by a roll on Table 1.1.1. However, treat the Giant result and any result that would give a second star of a higher type than the original star as Brown Dwarf results.

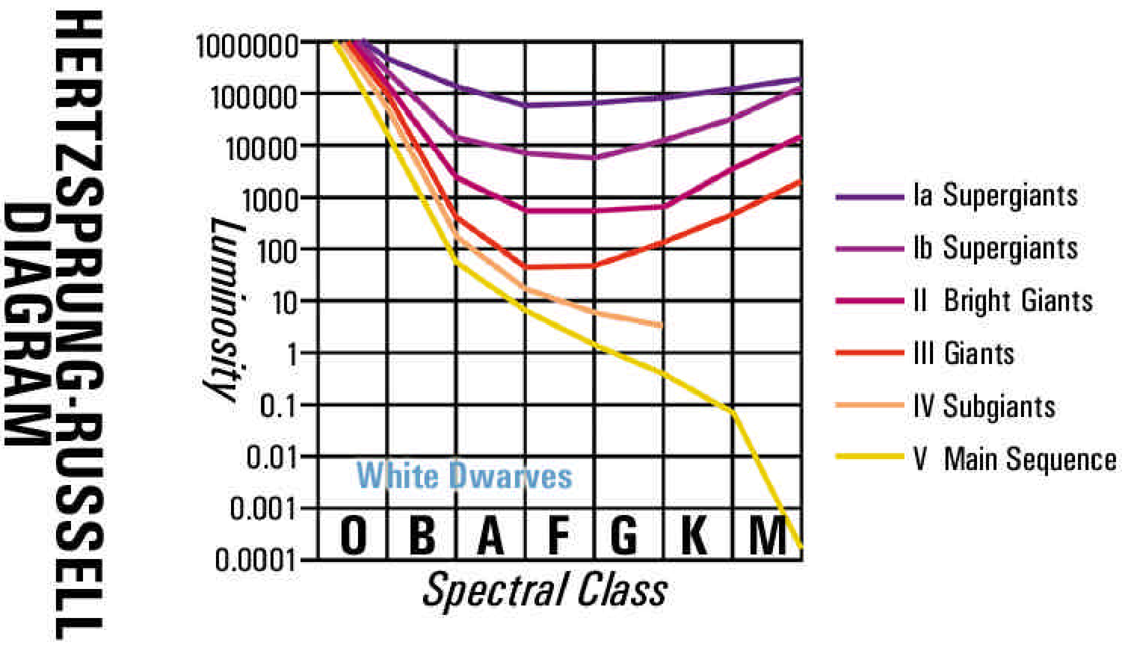
Table 1.1.3 Basic Luminosity & Mass
Note: All numbers are in solar equivalents except temperature, in the form Luminosity/Mass and Surface Temperature (K)/Radius

	0	1	2	3	4	5	6	7	8	9
B V	13000 / 17,5 28000 / 4.9	7800 / 15.1 25000 / 4.8	4700 / 13.0 22000 / 4.8	2800 / 11.1 19000 / 4.8	1700 / 9.5 17000 / 4.8	1000 / 8.2 15000 / 4.7	600 / 7.0 14000 / 4.2	370 / 6.0 13000 / 3.8	220 / 5.0 12000 / 3.5	130 / 4.0 11000 / 3.2
A V	80 / 3.0 10000 / 3	62 / 2.8 9750 / 2.8	48 / 2.6 9500 / 2.6	38 / 2.5 9250 / 2.4	29 / 2.3 9000 / 2.2	23 / 2.2 8750 / 2.1	18 / 2.0 8500 / 2.0	14 / 1.9 8250 / 1.8	11 / 1.8 8000 / 1.7	8.2 / 1.7 7750 / 1.6
F V	6.4 / 1.6 7500 / 1.5	5.5 / 1.53 7350 / 1.5	4.7 / 1.47 7200 / 1.4	4.0 / 1.42 7050 / 1.4	3.4 / 1.36 6900 / 1.3	2.9 / 1.31 6750 / 1.3	2.5 / 1.26 6600 / 1.2	2.16 / 1.21 6450 / 1.2	1.85 / 1.17 6300 / 1.2	1.58 / 1.12 6150 / 1.1
G V	1.36 / 1.08 6000 / 1.1	1.21 / 1.05 5900 / 1.1	1.09 / 1.02 5800 / 1.0	0.98 / 0.99 5700 / 1.0	0.88 / 0.96 5600 / 1.0	0.79 / 0.94 5500 / 1.0	0.71 / 0.92 5400 / 1.0	0.64 / 0.89 5300 / 1.0	0.57 / 0.87 5200 / 0.9	0.51 / 0.85 5100 / 0.9
K V	0.46 / 0.82 5000 / 0.9	0.39 / 0.79 4850 / 0.9	0.32 / 0.75 4700 / 0.9	0.27 / 0.72 4550 / 0.8	0.23 / 0.69 4400 / 0.8	0.19 / 0.66 4250 / 0.8	0.16 / 0.63 4100 / 0.8	0.14 / 0.61 3950 / 0.8	0.11 / 0.56 3800 / 0.8	0.10 / 0.49 3650 / 0.8
M V	0.08 / 0.46 3500 / 0.8	0.04 / 0.38 3350 / 0.6	0.02 / 0.32 3200 / 0.5	0.012 / 0.26 3050 / 0.4	0.006 / 0.21 2900 / 0.3	0.003 / 0.18 2750 / 0.25	0.0017 / 0.15 2600 / 0.2	0.0009 / 0.12 2450 / 0.17	0,0005/ 0.10 2300 / 0.14	0.0002/ 0.08 2200 / 0.11
A IV*	156 / 6 9700 / 4.5	127 / 5.1 9450 / 4.2	102/ 4.6 9200 / 4.0	83/ 4.3 8950 / 3.8	67/ 4.0 8700 / 3.6	54/ 3.7 8450 / 3.5	44 / 3.4 8200 / 3.3	36/ 3.1 7950 / 3.2	29/ 2.9 7700 / 3.1	23/ 2.7 7500 / 2.9
F IV*	19 / 2.5 7300 / 2.7	16.9 / 2.4 7200 / 2.7	15.1 / 2.3 7100 / 2.6	13.4 / 2.2 6950 / 2.6	12.0 / 2.1 6800 / 2.5	10.7 / 2.0 6650 / 2.5	9.5 / 1.95 6500 / 2.5	8.5 / 1.90 6350 / 2.5	7.6 / 1.80 6200 / 2.4	6.7 / 1.70 6050 / 2.4
G IV*	6.2 / 1.60 5900 / 2.4	5.9 / 1.55 5750 / 2.4	5.6 / 1.52 5600 / 2.5	5.4 / 1.49 5450 / 2.6	5.2 / 1.47 5300 / 2.7	5.0 / 1.45 5200 / 2.8	4.8 / 1.44 5100 / 2.8	4.6 / 1.43 5000 / 2.9	4.4 / 1.42 4900 / 2.9	4.2 / 1.41 4800 / 3.0
K IV*	4 / 1.40 4700 / 3.0	-	-	-	-	-	-	-	-	-
A III*	280 / 12 9500 / 6.2	240 / 11.5 9250 / 6.1	200 / 11.0 9000 / 5.9	170 / 10.5 8750 / 5.7	140 / 10 8500 / 5.6	120 / 9.6 8250 / 5.5	100 / 9.2 8000 / 5.3	87 / 8.9 7750 / 5.2	74 / 8.6 7500 / 5.1	63 / 8.3 7350 / 4.9
F III*	53 / 8.0 7200 / 4.7	51 / 7.0 7050 / 4.8	49 / 6.0 6900 / 4.9	47 / 5.2 6750 / 5.1	46 / 4.7 6600 / 5.2	45 / 4.3 6450 / 5.4	46 / 3.9 6300 / 5.7	47 / 3.5 6150 / 6.1	48 /3.1 6000 / 6.5	49 / 2.8 5900 / 6.8
G III*	50 / 2.5 5800 / 7.1	55 / 2.4 5700 / 7.7	60 / 2.5 5600 / 8.3	65 / 2.5 5500 / 9.0	70 / 2.6 5400 / 9.7	77 / 2.7 5250 / 10.7	85 / 2.7 5100 / 11.9	92 / 2.8 4950 / 13.2	101 / 2.8 4800 / 14.7	110 / 2.9 4650 / 16.3
K III*	120 / 3 4500 / 18.2	140 / 3.3 4400 / 20.4	160 7 3.6 4300 / 22.8	180 / 3.9 4200 / 25.6	210 / 4.2 4100 / 28.8	240 / 4.5 4000 / 32.4	270 / 4.8 3900 / 36.5	310 / 5.1 3800 / 41.2	360 / 5.4 3700 / 46.5	410 / 5.8 3550 / 54
M III*	470 / 6.2 3400 / 63	600 / 6.4 3200 / 80	900 / 6.6 3100 / 105	1300 / 6.8 3000 / 135	1800 / 7.2 2800 / 180	2300 / 7.4 2650 / 230	2400 / 7.8 2500 / 260	2500 / 8.3 2400 / 290	2600 / 8.8 2300 / 325	2700 / 9.3 2200 / 360

***Randomizing subgiants (IV). Roll 1D10: 1-2 use listed value, 3: decrease mass 10%, 4: -20%, 5: -30%, 6: -40%, 7: +10%, 8: +20%, 9: +30% and 10: +40%. Luminosity is affected at double that rate. Recalculate radius as shown on the next page. Randomizing Giants - see 1.1.4 next page.**

STELLAR DATA - REFERENCE

SPECTRAL CLASS: A star's spectral class depends on the temperature, and thus basically upon its mass. More massive stars are hotter. But more massive stars are also less common. Spectral classes are subdivided into numeric distinctions from 0 to 9, where a star with 0 is hotter than one with 9.
O: These very massive blue stars are also very rare. One of the closest to Earth is Mintaka in the belt of Orion, almost 1000 LY away.
B: Blue-white massive stars. B-stars are also uncommon. One of the closest to Earth is Alpha Gruis, slightly more than 100 LY away.
A: White stars. Sirius, Vega and Altair are of this type.
F: Yellow-white stars slightly larger than the Sun. Usually considered the most massive stars capable of harboring Earth-like life.
G: Yellow stars. Our sun is class G2, while Alpha Centauri is G0.
K: Orange stars. They are less massive and cooler than the Sun. Epsilon Eridani is a typical example.
M: Small red stars often called red dwarves. They are very common and faint. Proxima Centauri and Barnard's Star are typical. Some very cool red stars are "L"-class, and these could well be brown dwarves or their close relatives.
Other Stars: Spectral classes C (previously R & N) and S are uncommon cooler stars. See sidebar.
White Dwarves: These are very dense, hot and small (in size, not mass) stars which are formed from old stars. White dwarves are common - about 10% of all stars. The closest to the sun is Sirius B.
Brown Dwarves: "Stars" which are too small to ignite stellar fusion in earnest. Few brown dwarves have been found, but they are believed to be common though hard to detect. It is possible there are more brown dwarves than 1.1.1 indicates perhaps 1/3 of all "star" systems are brown dwarves. Both brown and white dwarves are described on the next page.
Other Objects: Neutron stars and black holes are formed from very massive stars, and thus they are uncommon. The closest known neutron star is over 400LY away, though one may find one or two within 100LY. Protostars are stars in the process of contraction to stellar fusion - they are also rather uncommon as this stage is very short compared to a star's total lifetime. Black dwarves are white dwarves that have cooled off, but no white dwarf has cooled off enough during the life span of our Galaxy.
SIZE TYPE: Most stars are main sequence (size type **V**). The Sun, Sirius and Proxima are all main sequence. This is the stage where most stars spend the majority of their active "lives". When a star leaves the main sequence to become a red giant it becomes a subgiant (**IV**) and later a giant (**III**). Larger giants formed from massive stars can be bright giants or supergiants (**II, Ib, Ia**) but they are as we already have mentioned rare. Typical giant stars include Pollux and Arcturus (K-class **III**). Giants and subgiants are less predictable concerning size and luminosity - they vary considerably more within their parameters than the main sequence stars. Older classification used code **VI** for subdwarves (very old main sequence stars lacking in heavy elements) and **VII** for white dwarves.



The Hertzsprung-Russell diagram is a way of showing the relation between spectral class (and thus temperature) and luminosity. Brown dwarves would exist off the lower right corner of the H-R diagram.
Sun-size stars spend most of their time on the main sequence, then move up and to the right on the diagram, becoming subgiants and red giants. More massive stars move more to the right than up. The actual development of stars in their final stages is complex, and involves several distinct processes which causes the star to vary in temperature, radius and luminosity. A decent astronomy textbook is recommended for further insight see References at the end of the document for suggestions.
Note how the subgiant branch stops at K0, as less massive stars not yet have had time to evolve to subgiants.

RANDOMIZING GIANTS AND SUBGIANTS: Unlike main sequence stars, which tend to be rather similar within a spectral classification, giants and subgiants vary significantly in size, luminosity and radius. The random roll described under Table 1.1.3 symbolizes this for subgiants, while 1.1.4 does so for giants.

1.1.4 Randomizing Giants

1D10	1	2	3	4	5	6	7	8	9	10
Mass	0.3x	0.4x	0.5x	0.6x	0.7x	0.8x	0.9x	1.0x	1.25x	1.5x
Luminosity	0.3x	0.4x	0.5x	0.6x	0.7x	0.8x	0.9x	1.0x	1.5x	2.0x

(**SURFACE TEMPERATURE:** Stars vary in temperature with spectral class. Subgiants and giants of a spectral class are cooler than main sequence stars of the same spectral class. The temperature of a star is primarily important to calculate its radius, as shown below.

STELLAR RADIUS: Compared with the sun, use the following equation: $R = L^{1/2} * (5800/T)^2$ where R is the radius, L the luminosity and T the effective temperature (in Kelvin).

CONVERTING MAGNITUDE TO LUMINOSITY: If you try to detail a star system where you already know the absolute visual magnitude of the star, it might be useful to know how to recalculate that value into luminosity (compared to the Sun). As every step in magnitude indicate a 2.512 increase in luminosity, this doesn't seem to be very hard. However, for stars cooler or hotter than the sun much of their bolometric luminosity is in UV or IR spectrum, and thus a small red star would end up much less luminous than it really is for purposes of system generation. To solve this a bolometric correction (*BC*) is added to the absolute magnitude (a correction depending upon the temperature - i.e. spectral class - of the star) and luminosity is calculated afterwards. The bolometric correction has been fitted to:

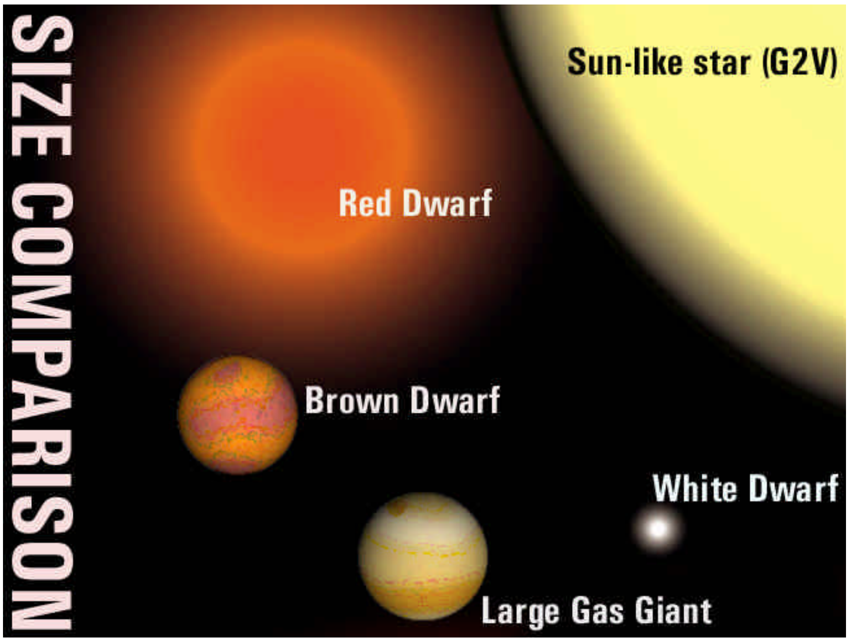
$$BC = -8.499[\log(T)-4]^4 + 13.421[\log(T)-4]^3 - 8.131[\log(T)-4]^2 - 3.901[\log(T)-4] - 0.438$$

And thus the bolometric luminosity compared to the Sun is $L = 2.512^{(4.68-M-BC)}$, where M is the absolute visual magnitude of the star.

MASS-LUMINOSITY RELATIONSHIP: For main sequence (V) stars, there is a connection between mass and luminosity. If a star has a mass of 0.5 to 4 solar, it has an approximate luminosity of M^4. For more or less massive stars, the connection is about $M^{3.3}$. This can be used to calculate the mass of a main-sequence star from its luminosity.

GENERATING STELLAR NEIGHBORHOODS: Using our own stellar neighborhood as a template, and considering not all faint red dwarf stars nor nearly all brown dwarves are discovered, a 10LY cube (1000 cubic light years) would contain 1-5 star systems, including brown dwarves. About half of these systems would be binaries or multiple stars. For random generation, just make a cube, roll 1D5 (1D10/2) and place the systems by random generation of X, Y and Z-axis.

INTERSTELLAR GAS & DUST: The galaxy contain not only stars but also gas, dust and molecular clouds. The solar neighborhood (about a 300 LY radius) is sparse in interstellar gas, though there is a warm cloud of gas about 70 LY away, towards the center of the galaxy. About 20% of the galaxy is in such warm clouds, which may have an average radius of tens of LY. If gas is close to a hot star it will be visible as a nebula, but most gas clouds are not visible as such. Interstellar dust is found everywhere, but the densest areas are dark nebulae.



SPECIAL STELLAR TYPES

Wolf-Rayet Stars: These are O-class stars that seem to have a gas envelope. Such envelopes are also sometimes found around B-stars and is probably ejected from the star.

C-stars (carbon stars): Of spectral types R & N, these stars seem to be rich in carbon and carbon compounds. Many are found in the Magellanic clouds, where they are more common than in our galaxy. C-stars roughly conform to G4-M9 spectral classes in terms of size.

S-stars. These are usually very cool red giant stars with an abundance of zirconium oxide and lanthanum oxide.

Peculiar A-stars: These A-class stars have very strong absorption lines of metals.

Strong Magnetic Fields: About 1 in 10 A & B-class stars have very strong and variable magnetic fields. Hot stars often rotate very rapidly (up to 100 times faster than the sun) and may be noticeably flattened.

Novae: A nova is a white dwarf that has a companion that loses mass to it, usually a giant star. When a white dwarf receives this matter it eventually sets off hydrogen burning and blows off gas. The longer time between these flashes the stronger it tend to be. A nova can reach up to 100 000*L*, but generally this is less. If the white dwarf receives so much matter it passes the 1.4 solar mass limit it becomes a supernova of the most violent kind, a Type Ia, which tears the white dwarf apart (along with the companion). The other kind of supernova exists when a massive star "dies" and forms a neutron star or black hole.

Pulsar: A fast-rotating neutron star. Pulsars are young neutron stars that have not slowed down and a neutron star is an object so densely packed it is made up of neutrons far denser than even a white dwarf. When neutron stars undergo disasters perhaps collision or merger they produce large amounts of gamma radiation

Magnetar: This is a kind of neutron star with an iron shell. It generates intense magnetic fields.

ONE/1 Continued: WHITE AND BROWN DWARVES

WHITE DWARVES:
These stars are very hot, very compact and very small in size - about the size of the Earth. White dwarves have masses ranging from 1.44 solar masses and downward. A young white dwarf is very hot but it gradually cools off, so the surface temperature indicates age of the dwarf, not primarily mass. Very old white dwarves have a surface temperature equal to a red dwarf star. Interestingly enough, the more massive a white dwarf is the smaller it also is. Very young white dwarves are among the hottest stars known, but that phase is fairly short. The hottest white dwarves have spectral types DA and DO, while cooler have DC and DQ spectra.
To determine the mass and temperature of the white dwarf, check the chart below:

1.1.4 White dwarves

1D10	1	2	3	4	5	6	7	8	9	0
Mass/ Radius	1.3 0.004	1.1 0.007	0.9 0.009	0.7 0.010	0.6 0.011	0.55 0.012	0.50 0.013	0.45 0.014	0.40 0.015	0.35 0.016
Temperature	30000	25000	20000	16000	14000	12000	10000	8000	6000	4000

All numbers except temperature are compared to the Sun. Roll once for mass/radius and once for temperature. However, you might wish to wait with the roll for temperature until after stage **One/2**, when you know the age of the system

To determine the luminosity of a white dwarf, use $L = R^2 * T^4 / 5800^4$ where R is the radius and T is the temperature.
White dwarves don't have habitable planets, but it is possible that distant cold worlds could survive the stellar evolution.

BROWN DWARVES:
Brown dwarves are substellar objects of a size from 0.013 to 0.08 solar masses. They have a brief period of deuterium burning, but after that generate energy by gravitational contraction. Brown dwarves are cooler than real stars and they, like white dwarves, cool off with time. Young brown dwarves are substantially brighter and hotter than the older ones found. Unlike planets, brown dwarves can be formed separately, like stars. (Sometimes "brown dwarf" is used for all objects larger than 1.5 Jupiter masses and below 80 Jupiter masses, but here I limit the term to the bigger objects that can form independently). Brown dwarves radiate infrared heat much more than visible light.

In radius, brown dwarves are probably smaller than Jupiter, or about as large - despite being more than ten times more massive. This may seem strange, but the gravitation of a brown dwarf is enough to compress it to much greater densities. (And small red stars are much denser than the Sun - or the Earth for that matter).

1.1.5 Brown dwarves

1D10	1	2	3	4	5	6	7	8	9	0
Mass/ Radius	0.070 0.07	0.064 0.08	0.058 0.09	0.052 0.10	0.046 0.11	0.040 0.12	0.034 0.12	0.026 0.12	0.020 0.12	0.014 0.12
Temperature	2200	2000	1800	1600	1400	1200	1000	900	800	700

Roll once for mass/radius and once for temperature. However, you might wish to wait with the roll for temperature until after stage **One/2**, when you know the age of the system

Use the same formula as for white dwarves when determining the luminosity of a brown dwarf.

FLARE STARS:
These are M-class stars (ranges M3 to M9) which periodically increase in luminosity by 1D10*50% for a short time. About half (1-5 on 1D10) of all dim red stars may be flare stars, perhaps even more. The increase is due to large solar flares considerably hotter than the star, and thus richer in visible, UV and X-ray radiation. Flare stars may provide problems for life on close planets to cope with the increased radiation. Flare stars near us include Proxima Centauri, UV Ceti B, Wolf 359 and Ross 154, all closer than 10 LY.

PROTOSTARS:
These are stars in the process of initial contraction towards the main sequence. Protostars are brighter but also cooler than the star they eventually will become as they generate heat by gravitational contraction and not by nuclear fusion, and they have not formed any real planetary systems. Contraction goes much faster for a massive star than for a red dwarf, which will take hundreds of millions of years to contract. A young ($<$ 1GY) red dwarf is thus very similar to a brown dwarf.

ONE/2 SYSTEM AGE AND ABUNDANCE

STEP ONE: Determine the relative age of the system by rolling 1D10 and consult the chart, section of the primary star. This especially important to main sequence F, G and K-class stars. From the relative age, get the absolute age listed in the chart and apply it to all the other stars in the system. (In other words, in a multiple-star system all are of the same age). Note the absolute age and round it off to the nearest GY - it will become important later.
STEP TWO: Apply the percentile adjustments given from the chart - if any - to the luminosity of the star.
STEP THREE: Determine the Abundance of the system by rolling on 1.2.3.

1.2.1 System Age

1D10	1	2	3	4	5	6	7	8	9	10	Life
B0-B9	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	0.1 GY
A0-A4	- 0.1 GY	- 0.1 GY	- 0.2 GY	- 0.2 GY	- 0.3 GY	- 0.3 GY	- 0.4 GY	- 0.4 GY	- 0.5 GY	- 0.6 GY	0.6 GY
A5-A9	-20% 0.2 GY	-20% 0.4GY	-10% 0.5 GY	-10% 0.6 GY	0% 0.7 GY	0% 0.8 GY	+10% 0.9 GY	+10% 1.0 GY	+20% 1.1 GY	+20% 1.2 GY	1.3 GY
F0-F4	-40% 0.3 GY	-30% 0.6 GY	-20% 1 GY	-10% 1.3 GY	0% 1.6 GY	+10% 2 GY	+20% 2.3 GY	+30% 2.6 GY	+40% 2.9 GY	+50% 3.2 GY	3.2 GY
F5-F9	-40% 0.5 GY	-30% 1 GY	-20% 1.5 GY	-10% 2 GY	0% 2.5 GY	+10% 3 GY	+20% 3.5 GY	+30% 4 GY	+40% 4.5 GY	+50% 5 GY	5.6 GY
G0-G4	-40% 1GY	-30% 2GY	-20% 3GY	-10% 4GY	0% 5GY	+10% 6GY	+20% 7GY	+30% 8GY	+40% 9GY	+50% 10GY	10 GY
G5-G9	-40% 1 GY	-30% 2 GY	-20% 3 GY	-10% 4 GY	0% 5 GY	+0% 6 GY	0% 7 GY	+10% 8 GY	+20% 9 GY	+30% 10 GY+	14 GY
K0-K5	-20% 1GY	-15% 2 GY	-10% 3 GY	-5% 4 GY	0% 5 GY	0% 6 GY	0% 7 GY	0% 8 GY	0% 9 GY	+5% 10 GY+	23 GY
K5-K9	-10% 1 GY	-5% 2 GY	0% 3 GY	0% 4 GY	0% 5 GY	0% 6 GY	0% 7 GY	0% 8 GY	0% 9 GY	0% 10 GY+	42 GY
M0-M9	+10% 1 GY	0% 2 GY	0% 3 GY	0% 4 GY	0% 5 GY	0% 6 GY	0% 7 GY	0% 8 GY	0% 9 GY	0% 10 GY+	50 GY+
Subgiants	Age is equal to maximum age for a main sequence star of the same mass, +10%.										-
Giants	Age is equal to maximum age for a main sequence star of the same mass, +20%.										-
White Dwarves*	-4 1 GY	-4 2 GY	-3 3 GY	-3 4 GY	-2 5 GY	-2 6 GY	-1 7 GY	-1 8 GY	+0 9 GY	+0 10 GY+	-
Brown Dwarves*	+0 1 GY	+1 2 GY	+1 3 GY	+2 4 GY	+2 5 GY	+3 6 GY	+4 7 GY	+5 8 GY	+6 9 GY	+7 10 GY+	-

GY = Billions of years.
Note1: White dwarves age indicate their total age - including before becoming a white dwarf.
Note2: The main sequence life span of a typical main sequence star of the spectral class, is listed in the "Life" column.
* Use the number after the "+" as a modifier to any temperature rolls on the previous page.

1.2.2 Calculating the life span of a main sequence star

*Life span (in GY) = 10 * Mass / Luminosity*

1.2.3 Determining system abundance

Roll 2D10 and add the system age (in GY). Check on the chart below and note the system modifier.

3-9	Exceptional. System modifier is +2.
10-12	High. System modifier is +1
13-18	Normal. System modifier is +0.
19-21	Poor. System modifier is -1.
22+	Depleted. System modifier is -3.

Note: Halo stars are always Depleted (-3).

SYSTEM AGE - REFERENCE

YOUNG STARS: Here, meaning stars of less than 1 GY age. A young system is rich in dust and the planets -if any - are still forming (at least the first 100 million years). For M-class stars, actual stellar contraction takes long time and thus they are slightly brighter during this stage. Typical young stars near Earth are Vega and Epsilon Eridani. On the chart, stars with 1 GY age (and no lower listed) may well still be in the later stages of system formation.

VERY OLD STARS: Stars that are more than 9-10 GY old are often very poor in elements heavier than helium. Sometimes these stars are called halo stars, as they belong to the galactic halo and didn't fit exactly into old models of stellar evolution. Another term is *subdwarf*. A very old star close to Earth is Kapteyn's Star, a red dwarf belonging to the halo. However, an old star need not always be poor in heavy elements - supernovae enriched the early galaxy too. Young stars need not be rich in such elements either.

STARS ON THE RIGHT END OF THE CHART: Rolling a "10" for a star of G0-4 and upward indicates that the star is about to leave the main sequence (class IV-V) and become a subgiant.

GIANTS AND SUBGIANTS: A typical star spends perhaps 10% of the time as a main sequence star as a subgiant, and slightly less as a real giant. We understand that only the more massive stars (G and up) has had time to enter this stage, and that the less massive a giant or subgiant is the older it is, in absolute age. A subgiant close to Earth is Beta Hydri, which has a spectrum similar to the Sun but is brighter, heavier and at least two billion years older.

WHITE DWARVES: It might be considered a bit strange that white dwarves with masses below 0.7 exists - after all no giants of so low mass are found and no 0.7 mass star could possibly have evolved fast enough. The explanation is that stars lose a lot of mass due to the often rather pyrotechnic displays during the later stages as a giant, and thus these white dwarves had a much larger mass while they were main sequence stars.

PROTOSTARS: Are very young. A protostar of similar mass as the Sun is a protostar for about 10 million years and during the later part of that time it is variable and stop diminishing in luminosity. Such stars are called T Tauri stars.

BURSTS OF STAR CREATION: Some astronomers believe stars are created in much greater numbers during certain periods of the galaxy's history, while in other times star creation is very low. This has not been considered in the chart, however.

LUMINOSITY INCREASE WITH AGE: A normal star like our Sun continuously becomes brighter. When the system was young, it was perhaps 40% less luminous, and when the Sun leaves the main sequence it will be perhaps 40% brighter. As a subgiant and later as a giant luminosity increase further, and in the giant stage the star grows enough to "eat" any close planets and fry others. The effects of the normal main-sequence increase will be discussed in section ONE/6.

BUT MAY IN SOME CASES DECREASE: We have already mentioned that white dwarves and brown dwarves cool off with age. This also applies to the smallest red dwarves (less than 0.15 solar masses) which gradually will fade; though it will take many billions of years.

SYSTEM ABUNDANCE: This tells how rich the system is in heavier elements. It will primarily be used in ONE/4 and ONE/5. Some systems may be rich in specific elements a system that has an abundance of carbon (instead of oxygen, like our own) may have different chemical makeup of planets. See the sidebar at THREE/2 for more information.

PLANETARY NEBULAE: Really have nothing to do with planets. Instead these are shells of gas ejected by stars during their final stages in life, before becoming a white dwarf or neutron star. More than one such nebulae can be ejected by a large star, but the nebula disperse fairly rapidly (roughly 100 000 years). A typical planetary nebula has a decent mass (0.1 solar masses or more) and a radius of several tenths of LY. Planetary nebulae are uncommon because they survive so short time before dispersing.

POPULATIONS: Sometimes stars are divided into "young" Population I stars, and "old" Population II stars. Population I is found in the disc of the galaxy, Population II stars in the halo and galactic "bulge".

MOVEMENT: All stars move as they orbit the center of the galaxy. They also move in respect to each other, so over hundreds of thousands of years the stellar neighborhood changes. Old stars tend to move more inclined to the galactic plane many belong to the galactic halo. Also, the older a star is the more likely it is to have experienced close encounters that have disturbed the orbit. (This in turn makes it likely such stars have lost planets in such interaction). Movement shifts may also be induced by the cataclysmic final stages in a star's life.

STELLAR REGIONS

Spiral Arms: Our sun lies at the edge of a small spiral arm in our galaxy. Spiral arms contain many young stars.

Disc: The entire area of the spiral arms is called the disc. The area of the disc closest to the galactic equator is the place where star formation takes place the closer to the upper and lower edges of the disc one get the older the stars are and the more sparse they are.

Bulge: The central region of the galaxy is more spherical and here are many older stars, many rich in heavy elements. Towards the center of the galaxy density of stars increase. This region is comparatively rich in neutron stars, black holes etc.

Halo: The galaxy also is surrounded by a halo of stars mostly old stars. The halo is spherical and extend farther than the spiral arms. It has a very low stellar density.

Open Cluster: An open cluster is a group of stars, up to perhaps a thousand, which are young (hundreds of million years, at most). The clusters are found in the spiral arms, and stellar densities are higher than normal (from 2 to 20 times). Old stars may be present in the area too. Open clusters are about 30 LY across.

Globular Cluster: This is a large association of very old stars, found in the halo and bulge. A globular cluster can have 100000 stars within a 100-250 LY sphere. As the stars are so old they are poor in heavy elements and only low-mass main sequence stars remain, the heavy stars have become giants or white dwarves. As the stellar density in a globular cluster can be 1000 times above normal in the spiral arms, any planets originally found are likely to have been disrupted.

ONE/3 MULTIPLE STARS

CONVENTION: The most massive star will be called **A**. The second most massive **B**, the third most massive **C** and so on.
STEP ONE: Determine the mean separation of the two first stars involved - the **AB** pair. (1.3.1 below) Then determine the eccentricity (1.3.2), closest separation, furthest separation, and orbital period.
STEP TWO: If there is a third component (**C**) determine if it orbits **A**, **B** or both. Roll 1D10: 1-3=A, 4-6=B, 7-10=AB. Determine mean separation and eccentricity, limiting the possibilities by the original pair. As a rule, multiple stars orbiting each other cannot orbit in such a way as their orbit get within 3 times of the closest separation and furthest separation of another orbit. So, if the AB pair orbit between 3 and 6 AU, the C-star must orbit either star closer than 1AU when furthest or 18 AU when closest.
STEP THREE: If there is a fourth component (**D**) and no more, it will form a pair with the "lone" component above on a roll of 1-7 on 1D10. On a roll of 8-9, it will orbit all three stars. On a roll of 10, it will be in close orbit with one of the already paired stars, if possible. Roll 1D10 again, on a roll of 1-7 it orbits the heavier star of the two. Determine mean separation, eccentricity etc as normal. If there is more components, continue to place them and remember that multiple stars seem to favor pairs. A six-star system is likely to be three pairs, thus.

1.3.1 Mean Separation
Roll 1D10
1-3 Very close. Mean separation is 1D10*0.05 AU.
4-6 Close. Mean separation is 1D10*0.5 AU
7-8 Separated. Mean separation is 1D10*3 AU
9 Distant. Mean separation is 1D10*20 AU
10 Extreme. Mean separation is 1D100*200 AU

Modification: If system age is above 5 GY, add 1 to the roll. If system age is below 1 GY, subtract 1 from the roll. Reroll any results below 1 or above 10 without modifications.

1.3.2 Orbital Eccentricity
Roll 1D10
1-2 Eccentricity is 1D10*0.01
3-4 Eccentricity is 0.1+1D10*0.01
5-6 Eccentricity is 0.2 + 1D10*0.01
7-8 Eccentricity is 0.3 + 1D10*0.01
9 Eccentricity is 0.4 + 1D10*0.01
10 Eccentricity is 0.5 + 1D10*0.04

Modification: As for table 1.3.1. If binary is Very Close: -2 modification. Close = -1 modification.

Calculations

Closest separation = $M(1-E)$

Furthest separation = $M(1+E)$

Orbital period = $(M^3 / (m_A + m_B))^{0.5}$

Where E = eccentricity, M = mean separation, m_A and m_B = masses of the components A and B.

MULTIPLE STARS - REFERENCE

VERY CLOSE STARS: Sometimes the stars are so close as to be visibly deforming each other, or perhaps even in contact. This can also happen when one of the stars in a binary leaves the main sequence and becomes a giant, and in these cases mass can actually transfer from the giant to the smaller companion. In other very close binaries, so called BY Draconis stars, one or both of the companions is a flare star and this may create a certain periodicity of the variations.
VERY DISTANT STARS: When the distance between stars grows, the gravitational forces of the galaxy begin to overcome the forces of the binary. Thus very distant binaries are rather rare.
ORBITS OF MULTIPLE STARS: Unlike planetary orbits in our solar system, binaries are often distinctly eccentric and multiple stars generally orbit in pairs inclined to the main system orbit.
IF YOU GET IMPOSSIBLE RESULTS: Such as a star orbiting inside another star's radius. Reroll.
X-RAY BURSTER: When one of the stars in a binary is a neutron star (or a black hole), mass transfer can generate intense amounts of X-ray radiation or even gamma radiation. X-rays can also be generated in other types of binaries, but some sort of mass transfer is necessary.

ONE/4 PLANETARY ORBITS

STEP ONE: Determine the number of potential orbits by rolling on table 1.4.1.
STEP TWO: Determine the mean distance of the orbits by consulting the formulae under 1.4.2.
STEP THREE: Remove all impossible orbits. This include any orbit which would put a planet within a star's radius or so close as to vaporize it, and any orbit which is unstable in a binary system (within the closest separation/3 to the furthest separation*3 distance). Worlds may orbit both stars in a binary, if the more massive companion has any orbits generated beyond the 3*furthest separation distance. Only consider such orbits for the more massive companion. For white dwarves, remove all orbits within the limit provided by table 1.4.3.
STEP FOUR: Remove all orbits where a planet would be vaporized, according to the formulae in 1.4.4. Also, determine the limit of the original inner system. Note this limit, it will be used in the next section.

1.4.1 Number of Orbits

1D10	
1	1D10+10
2-5	1D10+5
6-7	1D10
8-9	1D5 (1D10/2)
10+	None

Modifications to the initial roll:
Spectral class K5V-K9V: +1
Spectral class M0V-M4V: +2
Spectral class M5V-M9V: +3
Brown Dwarf: +5
Abundance modifier: As from 1.2.3, with switched signs.
Add modifications for spectral class and abundance together.

1.4.3 White Dwarf Removed Orbits

1D10	
1-4	All within 2 AU
5-8	All within 4 AU
9-11	All within 6 AU
12+	All within 10 AU

Modification: If mass of white dwarf is 0.6-0.9, add +2 to the roll. If above 0.9, add +4.

1.4.2 Orbit Sizes

The first orbit has a distance in AU of

$$0.05 * m^2 * 1D10$$

where *m* is the mass of the star.

Subsequent orbits have a size equal to the previous orbit times a random number, determined by 1.1+(1D10*0.1), and adding 0.1 to the total.

1.4.4 Untenable Orbits and Inner System Zone

Planets cannot survive if hotter than about 2000K. Thus, remove orbits within:

$$0.025 * L^{0.5}$$

Where *L* is the luminosity of the star.

The Inner System Zone is calculated from

$$4 * L^{0.5}$$

Again, *L* is the luminosity. (To be exacting, use the luminosity of a mid-age star of same spectral class for main sequence stars) For subgiants and giants, use the Inner System Zone of a main-sequence (V) star of the same mass. For white dwarves, consider any surviving worlds to be outside the Inner System Zone.

PLANETARY ORBITS - REFERENCE

INNER SYSTEM ZONE: The area of the stellar system where the early system is too hot to allow icy planetoids. Inner system objects thus have higher density and mostly consist of silicates and metals, while the area outside is more dominated by ices.
STARS WITHOUT PLANETARY ORBITS: There may be some other objects around these stars, typically either a few icy chunks in distant random orbits (1D10*1D10 AU) or more rarely a captured planetoid. Captured planetoids have eccentric orbits (1D10 AU) and may be of any general planet type. Some planetless stars have very sparse "rings" of chunks of debris. Roll 1D10: 1-3: icy chunks, 4: captured body, 5-7: rings 8+: nothing. Old stars may have had so little heavy elements that the entire system is a sparse icy asteroid belt.
BINARIES: If any orbits where removed by the binary effects, the system is likely to have a fair deal of stray asteroids and debris.

ONE/5 PLANETARY TYPES

STEP ONE: Determine basic planetary type from table 1.5.1.
STEP TWO: Determine planetary size and density from table 1.5.2 and 1.5.3 / 1.5.6. For asteroid belts, record only density and check section THREE/4 for more information on asteroid belts. For superjovians, consult 1.5.5 for determination of mass and radius.
STEP THREE: Determine surface gravity, escape velocity and mass by utilizing the formulae in 1.5.4

1.5.1 Planetary types

1D100	Inner Zone	1D100	Outer Zone
1-18	Asteroid Belt	1-15	Asteroid Belt
19-62	Terrestrial Planet	16-23	Terrestrial Planet
63-71	Chunk	24-35	Chunk
72-82	Gas Giant	36-74	Gas Giant
83-86	Superjovian	75-84	Superjovian
87-96	Empty Orbit	85-94	Empty Orbit
97	Interloper[1]	95	Interloper[1]
98	Trojan[2]	96-97	Trojan[2]
99	Double Planet[3]	98-99	Double Planet[3]
100	Captured Body[4]	100	Captured Body[4]

1: Reroll once on the other (Inner/Outer) table to decide what kind of interloper. Only Terrestrials, Chunks and Gas Giants allowed.
2: This is (1D10) either (1-9) a chunk or (10) a terrestrial planet in the same orbit as (1D10) either (1-8) a gas giant or (9-10) a superjovian.
3: Roll again to decide what kind of double planet. Treat all results of Asteroid Belt or Empty Orbit and up as Chunk.
4: Roll again on the same table to decide what type. Reroll all results of Asteroid Belt or Empty Orbit and up.

1.5.2 Planetary Size

Generated size is equatorial radius in kilometers.

1D10	Chunk	Terrestrial	Gas Giant
1	200	2000+D10*100	15000+D10*300
2	400	2000+D10*100	18000+D10*300
3	600	3000+D10*100	21000+D10*300
4	800	3000+D10*100	24000+D10*300
5	1000	4000+D10*100	27000+D10*300
6	1200	5000+D10*100	30000+D10*1000
7	1400	6000+D10*100	40000+D10*1000
8	1600	7000+D10*100	50000+D10*1000
9	1800	8000+D10*200	60000+D10*1000
10	2000	10000+D10*500	70000+D10*1000

Note: Modify the 1D10 roll by System Abundance modifier for Terrestrial planets. Do not modify rolls of 1.

1.5.4 Mass, Gravity, Escape Velocity

Mass of planet (*m*), in Earth masses:

$$(R/6380)^3 * D$$

where *R* is the radius in km and *D* the density compared to Earth.
Surface gravity (*g*) of planet in Earth gravities:

$$m / (R/6380)^2$$

where *m* is the mass (in Earth masses) and *R* the radius in km.
Escape Velocity (*v*) compared to Earth:

$$(19600 * g * R)^{0.5} / 11200$$

where *g* is the surface gravity (in Earths) and *R* the radius in km.

1.5.3 Planetary Densities
All densities are compared to Earth.

	Chunk	Terrestrial	Gas Giant
Inner Zone	0.3+1D10*0.1	0.3+1D10*0.1	0.10+1D10*0.025
Outer Zone	0.1+1D10*0.05	0.1+1D10*0.05	0.08+1D10*0.025

Modification: Modify the D10 roll by the abundance modifier. If you don't use **1.5.6** below, modify A and B-star inner system planets/chunks by another +1. The roll can't be increased above 11 or reduced below 1, in such case use 1 or 11.

1.5.5 Superjovians

1D10	Mass
1-4	500+1D10*50
5-7	1000+1D10*100
8-9	2000+1D10*100
10	3000+1D10*100

All results are in Earth masses.
Radius is 60000+(1D10-1/2 Age in GY)*2000

1.5.6 More Precise Density Generation
For inner system chunks and terrestrials, it is likely to assume planets are richer in heavy elements closer to the star. To simulate this, replace the "*0.1" factor with

$$* 0.127 / (0.4 + (a / L^{0.5}))^{0.67}$$

where *a* is the orbital distance in AU and *L* is the luminosity of the primary. (Or, to be specific, the luminosity of a mid-age main sequence star). Densities cannot be higher than 1.5.

PLANETARY TYPES - REFERENCE

VERY YOUNG SYSTEMS: In systems younger than about 100 million years terrestrial planets will not yet have fully formed. These systems will be rich in random planetoids of a size somewhat like large chunks. Gas giants and superjovians form faster. Systems younger than 1GY probably still have dust in distant orbits and a fair amount of random planetoids in the outer system. Systems rich in dust generate IR-radiation.
CHUNK: A small airless body with trace or no atmosphere. Chunks in the inner system are rocky, those in the outer system more likely icy.
(TERRESTRIAL) PLANET: Larger than chunks, these worlds are big enough to retain an atmosphere (not all do, however) but not big enough to be gas giants.
GAS GIANT: Big planets that are mostly gas and usually have systems of moons. Detailed along with superjovians in THREE/5.
SUPERJOVIAN: The stage between gas giants and brown dwarves, these massive planets provide significant heat from gravitational contraction. Superjovians tend to disrupt other close planetary orbits.
SIZE CLASSIFICATION: The division into Chunks, Planets, and Gas Giants is a somewhat nebulous one. Indeed, a large chunk in the outer regions might have a significant atmosphere, and a small planet may be like a chunk.
ASTEROID BELT: Lots of small chunks in a more or less defined orbital area. All systems have stray chunks, but systems with large belts tend to have more. Also, younger systems are typically more rich in stray asteroids. If a massive planet (50-100 Earth masses or more) orbits just outside or inside an asteroid belt, the planet's LaGrange points typically contain a lot of asteroids, indeed a significant percentage of the actual belt's mass. Skip sections TWO/1 to TWO/3 when detailing asteroid belts.

LaGrange Points: The points in an orbit 60 degrees before and after the main body. They can provide stable orbits in planetary and lunar orbits. The one preceding a body is called L-4 and the one trailing L-5.

EMPTY ORBIT: An orbit that is empty. Perhaps you understood that?
INTERLOPER: A planet of a type and density typical of the outer or inner system but orbiting in the other one. This may be a high-density or low-density planet thrown into a distant orbit, or an anomaly in system creation. Interlopers are likely to have large eccentricities. Optionally, an interloper may be a planet with a much greater orbital distance than the rest of the system - treat the original orbit as an Empty Orbit and place the world 1+1D10 times the outermost orbit's average distance. Or, the interloper could be in the same but retrograde orbit.
TROJAN: Typically a sizable chunk but rarely (1 on 1D10) a terrestrial planet which orbits in the LaGrange point of another planet - a gas giant, very massive terrestrial planet or superjovian.
DOUBLE PLANET: This is two planets which are so close in size that the term "moon" no longer is very descriptive. Double planets are tidally locked to each other - thus their rotation period is equal to their orbital period. Pluto and Charon are a double planet system. Due to tidal stress double planets are more likely in the outer system. Another option possible with chunk-sized bodies close to the star is that the chunks are in shared orbits and exchange them periodically. To generate a double planet roll twice on the same column, and generate distance by checking the distance for lunar objects (TWO/3). A double planet can also possibly be a large terrestrial moon of a gas giant, or even a gas giant "moon" of a superjovian.
CAPTURED BODY: This is a planet (chunk, terrestrial planet, gas giant, superjovian) which didn't originate with the system. It may be older or younger, and is typically in an inclined eccentric orbit, possibly even retrograde.
OORT CLOUD: Not a part of regular system generation, but most systems have such clouds of distant comets, remnants of the gas that formed the system. Oort Clouds typically lie up to 1 LY away.
NAMING: A simple way to identify planets is to take the stellar name and add a roman numeral to it, in order of distance from the star. Empty orbits and asteroid belts are usually not numbered. In this way, Earth would be "Sol III". Moons may be named with a letter in order of their distance from the planet, very small moons may be omitted. Thus, Luna would be Sol IIIa. This is just one way. Moons in our solar system is given roman numerals in order they were discovered and rings are given letters, sometimes in Greek.

SPECIAL STAR SYSTEMS
Red giants: A star that has evolved to a red giant will have several effects on the system. First of all, worlds close to the star will be engulfed by it, and thus they spiral inwards to be destroyed. It is possible that a world can survive if it does not endure this process for too long especially if the red giant is cool and very big. Second, other worlds in the system will be heated. For worlds this can lead to a significant amount of mass is lost by outgassing the world "boils" away and leaves a remnant core of silicates.
Another problem is that red giants seldom are very stable in luminosity they often vary. This would also have large effects on worlds. Red giants also undergo mass loss from stellar wind.
White dwarves: The disastrous formation of a white dwarf is likely to influence the system. Atmospheres may be blown away, the mass change of the star initiate orbit changes, gas giants may lose much of their atmosphere only leaving the dense core etc.
Thus, close worlds to white dwarves are unlikely to exist. The red giant phase would have destroyed such worlds. In the same way, icy worlds may have been significantly affected by the previous stage.
Neutron stars: Neutron stars are formed by supernovae, and supernovae will destroy the system planets will be torn apart. However, neutron stars may have planetary systems though very strange ones. A blasted companion star may provide material for new "planets". These worlds are not habitable, the radiation from a neutron star is very high.

ONE/6 LIFE ZONE

STEP ONE: Use the formulae below to determine the inner, optimum and outer limit of the life zone. Calculate life zone for all stars in a multiple system, but for Very Close binaries you can add the luminosities together before calculating the life zone.

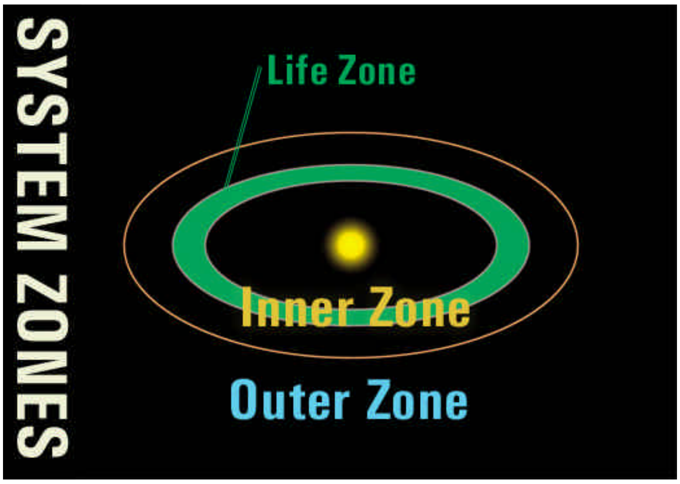
Life Zone Calculation

Inner Limit = $0.75 * L^{0.5}$

Optimum Distance = $1.0 * L^{0.5}$

Outer Limit = $1.4 * L^{0.5}$

Where *L* is the luminosity of the star and life zone distance is in AU.



LIFE ZONE - REFERENCE

WHAT IS THE LIFE ZONE?
It is the approximate distance from a star where a planetary body similar to Earth could be warm enough to have liquid water, but not so warm as to boil said water away. Earth-like life require liquid water, thus the name "life zone". We generate the life zone to determine which worlds-if any-are candidates for life based upon liquid water.

DOES ONLY PLANETS WITHIN THE LIFE ZONE HAVE LIFE?
Not necessarily. First of all, the life zone is an approximation. The exact temperature of a world is calculated in much more detail in the section on **Atmospheric Data**. A planet might have a very high greenhouse effect, or a moon be heated by tidal deformation, and thus be warm enough despite being outside the life zone. For the same reason, a planet within the life zone might be inhospitable to life. Life not based upon water may have very different life zones - a life zone based upon liquid ammonia would be more distant, for instance. Life of low complexity have wide life zones, while complex life has a less wide one.

LIFE ZONES IN MULTIPLE STAR SYSTEMS: Though it may be rather rare, a world might lie outside the life zones of two stars but inside their combined life zone. Consider a planet orbiting just outside the life zone of a small red star, but that star in turn orbit a much brighter star which provide enough additional radiation to heat the world. This may work well for a planet orbiting two close red dwarves too.

LIFE ZONE AND SYSTEM AGE: We have already seen that stars change luminosity with age. Typically, the life zone moves outward, and this means that worlds that once were habitable will become too hot with time. It also mean cold planets may be heated in the late life of the system. The optimum for a world is to be within the life zone (near the outermost limits) during the early years of a system, as this grants the longest possible time to evolve life. If a world that was too cold much later gets into the life zone, it is likely that life wouldn't start as easy. Much of the primordial gasses would have escaped, volcanism might have died down etc. To approximate where the life zone was in the early system age, check the luminosity modifications from the **System Age** section and use that luminosity to calculate life zones. In very young systems planets will still be warm from their formative stages and have fairly extensive atmospheres which has had little chance of escaping, but at 1 GY this will have settled down.

SOME WORLDS BECOME COOLER ANYWAY: On the other hand, there are possible ways a once habitable world can get too cold to sustain life. One way is if the star loses luminosity - most typical among brown dwarves who while they may have life-bearing worlds, usually tidally locked, lose luminosity due to their cooling. A large brown dwarf may drop 200K /GY for the first billions of years.

Another way to cool a world is if the atmosphere changes, perhaps by becoming thinner due to escaping gas (typical on low-gravity worlds) or by sunlight breaking down greenhouse gasses. A third one is a change of axial tilt or eccentricity of the orbit. Also, all worlds cool off after their creation, and if volcanism dies down gasses like carbon dioxide and water vapor might not be released in the same degree as they are removed. Other options include growing glaciations that lead to a high albedo and thus lower temperature. Such glaciations could be triggered by continental drift and axial/orbital changes, but also by huge amounts of dust in the atmosphere which would block sunlight - an asteroid impact or especially explosive volcanic event are possible triggers.

TWO/1 YEAR AND TIDAL LOCK

STEP ONE: Consult 2.1.1 to calculate the year of the planet.
STEP TWO: Check 2.1.2 to determine if the planet is tidally locked to the primary.

2.1.1 Year (Orbital period around primary)

$$(a^3 / m)^{0.5}$$

where *a* is the orbital distance in AU and *m* is the mass of the primary, in solar masses. If the planet has significant mass compared to the star (like a large superjovian and a small red star or brown dwarf), add the masses together. Result is in Earth standard years.

2.1.2 Tidal Lock

Calculate the tidal force the primary exerts upon the planet.

$$T = (m*26640000) / (a*400)^3$$

Where *m* is the mass of the primary (in solar masses) and *a* is the orbital distance, in AU. From that, calculate

$$(0.83+1D10*0.03) * T * Age / 6.6$$

Where *Age* is in GY. If the result is above 1, the world is tidally locked to the primary.

YEAR AND TIDAL LOCK - REFERENCE

EFFECTS OF YEAR LENGTH: If an Earth-like world has seasons (due to axial tilt or eccentricity), the longer the year is the more notable the differences tend to be between the seasons. This is far more affected by axial tilt and eccentricity, however.
TIDALLY LOCKED WORLDS: A world that is tidally locked to the primary experience huge differences in temperature over the planetary surface. On a gas giant or superjovian, this might produce immense wind patterns. A terrestrial planet will have one "hot pole" and a "cold pole", and it is possible that the world might be habitable in certain regions - typically the hot pole or the twilight region. Part II describes tidally locked terrestrial planets in more detail.
ALTERNATIVES TO TIDAL LOCK: When the tidal force is around 1 and higher, it is possible that a world isn't locked but in a regular rotation. Typically, the world has a fairly eccentric orbit (0.1-0.2) and has a day of 2/3 or 1/2 the year (thus, the slightly deformed planet "lines up" at closest separation). Mercury is an example of a world in this situation. Note that for a regular rotation of this kind to occur the world must have a rather distinct eccentricity. Faster regular orbits of this kind occur with higher eccentricities. It is likely that a world with high eccentricity eventually would settle in the closest "stable" eccentricity range.

Eccentricity	Day/Year Ratio
0.0	1/1
0.21	3/2
0.39	2/1
0.57	5/2
0.72	3/1
0.87	7/2

Another alternative may be a somewhat chaotic rotation, due to tidal influence from other bodies (such as a close binary or a superjovian orbiting nearby). Small chunks may be so irregular that they are easily put into chaotic motion.
TIDALLY LOCKED WORLDS AND SATELLITES: Tidally locked worlds (due to high tidal force from the primary, and not merely a very slow rotation or a very old system) typically don't have moons. (The tidal force would lock them too, and the stress would either tear them apart or rip them away, into orbits where they later may impact with the world) However, a special case with a large enough moon that can lock the planet and moon together may prevent tidal lock to the star, at least for a while, if the lunar tidal force is greater than the solar tidal force.
Ring systems may survive for a while around tidally locked worlds, and so might very small chunk-moons. However, worlds that aren't locked due to very high tidal forces but merely by an abnormally slow rotation might have satellites and rings.

TWO/2 ECCENTRICITY, DAY & AXIAL TILT

STEP ONE: Determine the orbital eccentricity of the world by consulting 2.2.1.
STEP TWO: Determine the rotational period (solar day) of the world by rolling on table 2.2.2. Ignore this for tidally locked worlds.
STEP THREE: Determine the axial tilt of the world by rolling on 2.2.3. Ignore for tidally locked worlds.

2.2.1 Orbital Eccentricity

1D10	Eccentricity
1-5	0.005*1D10
6-7	0.05+0.01*1D10
8-9	0.15+0.01*1D10
10	0.25+0.04*1D10

Closest approach to star is $a(1-E)$ and furthest separation is $a(1+E)$, where *a* is the orbital distance and *E* is the eccentricity.
Modification: If a captured body, add +3 to the roll.

2.2.3 Axial Tilt

1D10	Axial Tilt
1-2	1D10 degrees
3-4	10+1D10 degrees
5-6	20+1D10 degrees
7-8	30+1D10 degrees
9-10	40+1D100*1.4 degrees

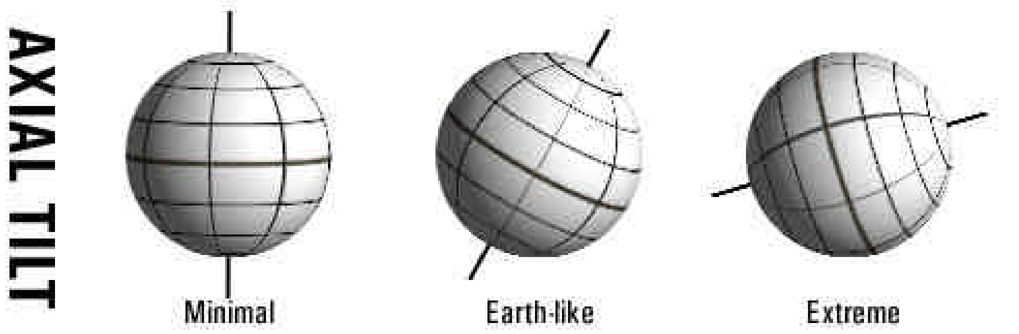
2.2.2 Rotational Period

1D10	Chunk	Planet	Gas Giant/Superjovian
1-5	1D10*2 hours	10+1D10*2 hours	6+1D10/2 hours
6-7	1D10 days	30+1D100 hours	11+1D10/2 hours
8-9	1D100 days	1D100*2 days	16+1D10 hours
10+	Very long (check reference)	Very long (check Reference)	26+1D10 hours

Modification to the roll: Add *T* (2.1.2) multiplied by Age (in GY), rounded down
Modifications to the result:
Add *T* (2.1.2) multiplied by Age (in GY), rounded down
If world is a massive (4 Earth masses+) terrestrial planet, subtract 2.*
If world is a small gas giant (less than 50 Earth Masses), add 2.
These modifications are added together and then the generated rotational period above is multiplied with $1+(\text{mod}*0.1)$.
*Optionally, subtract $m^{0.5}$ where *m* is the world's mass.

ECCENTRICITY, DAY & AXIAL TILT - REFERENCE

VERY ECCENTRIC ORBITS: Planets in very eccentric orbits tend to also be inclined towards the standard orbital plane to a significant degree. These worlds also may experience extreme seasonal temperature variations. For instance, a world might be in the life zone during the spring and autumn only, and be far too hot during the short summer and frozen over in the winter.
ORBITAL INCLINATION: The orbits are inclined towards the rotational plane of the system too, but aside from very eccentric orbits the inclination is rarely above 10 degrees, and commonly less than 1/3 of that.
AXIAL TILT: Is important in determining seasons. A low axial tilt indicate little seasonal change, while an axial tilt closer to 90 degrees have quite extreme seasons. (The 90-degree version experience polar seasons from utter winter to very hot summers). Axial tilts above 90 degrees show that the world has a retrograde rotation (it rotates the wrong way).



LENGTH OF DAY: Primarily important in determining the temperature variations over a local day. Long days have greater difference between day and night temperatures and may influence wind patterns. (See Part II). The day determined here is the solar day (time between sunrises), not the actual rotation period (the so-called sidereal day). The relation between solar day and sidereal day is

$$\textit{Solar Day} = 1 \,/\, (\,(\,1 \,/\, \textit{Sidereal Day}\,) \quad (\,1 \,/\, \textit{Year}\,)\,)$$

and generally easiest to calculate by using standard days.

SPECIAL CASES/VERY LONG DAY: In these cases, the local day is either very long (100+1D1000 days), almost infinite (counted in years, decades, centuries or longer) or stopped (tidally locked). If the rotation is very slow one gets sort of a tidal lock situation, where an Earth-like world gets a "hot" and "cold" pole slowly moving. However, a world with a very slow rotation and fairly close to the star is also very close to get fully locked or in a regular rotation. Life on a world with a slow rotation may cope by migration or hibernation.

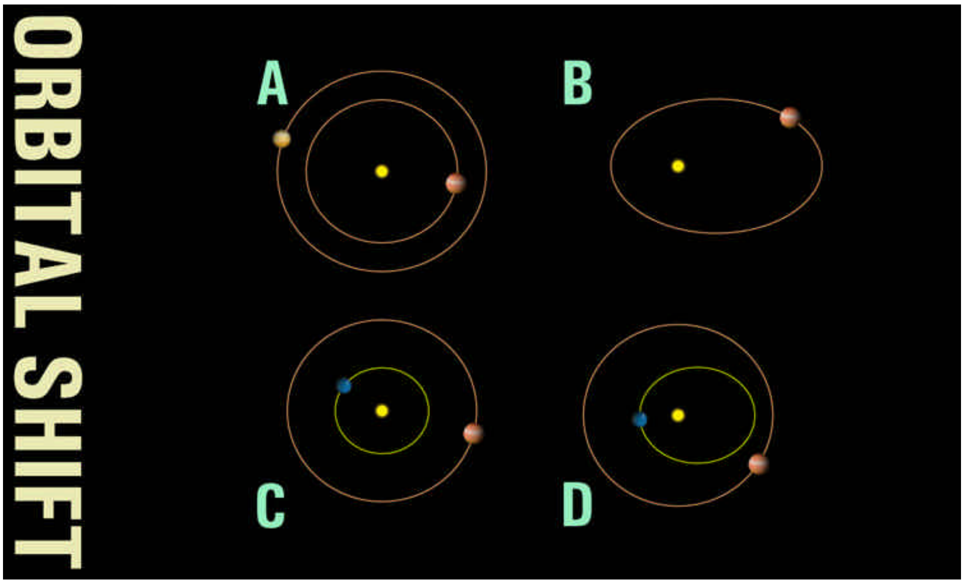
VARIABLE AXIAL TILT: It is quite likely that a world may change axial tilt over time (100kY-1MY), in a more or less random fashion. This can influence climate on a world significantly in the long run, and explain long-term climate variations. Worlds without large moons to stabilize the rotation can change tilt within a range of 25-30 degrees, stabile worlds more along the range of 5 degrees. The axial tilt change is likely influenced by the presence of other large bodies too Jupiter may be responsible for Martian axial tilt changes and Earth's too, for that matter.

VARIABLE ECCENTRICITY: Eccentricity can also be changed, generally by in-system gravitational forces. See sidebar.

LIBRATION: Tidally locked worlds and moons will have a slight "wiggling" effect which will allow them to not be exactly locked to the primary. This is caused by the eccentricity of the orbit of such moons or planets. If the eccentricity is very small the libration effect will also be very small.

SPECIAL EFFECTS OF SMALL AXIAL TILT: The big effect is to create large potential temperature difference between poles and equatorial regions, and as seasons won't moderate this worlds with low axial tilts often have very cool polar regions due to low solar infall, unless they have a thick atmosphere. This can allow polar caps on otherwise hot worlds, for instance.

SPECIAL EFFECTS OF LARGE AXIAL TILT: The larger the axial tilt, the larger the seasonal differences will be. For worlds with axial tilts above 45 degrees, the polar regions actually receive more solar infall than the equator, though on a very seasonal basis.



This illustration shows how a system can change over time. In **A** (see sidebar) two massive gas giants have ended up in orbits a bit too close to each other during formation. The outer, smaller gas giant is ejected and the ejection leaves the remaining gas giant (**B**) on an eccentric orbit which in turn can disrupt the inner system. In **C** a large gas giant, perhaps a superjovian, is in fairly close orbit. The terrestrial planet inside it is continually influenced by the large neighbor, and in **D** the orbit of that planet has become highly eccentric. Eventually it may be ejected. This increasing eccentricity can have large influence of the evolution of an otherwise Earth-like world.

SYSTEM DISRUPTION

Systems can be disrupted in several ways, but all of them induce distinct changes to the generated system. Basically, gravitational action serves to throw away system bodies perhaps in a more distant orbit, perhaps into the primary, and perhaps out of the system altogether. This has already been considered somewhat when generating binary systems, but long-term action can still disrupt systems. What happens is 1: that a planet's orbit is affected and the orbital eccentricity changes or 2: the presence of another body inhibits the planetary formation, as the planetesimals are disrupted. A big jovian planet can thus prevent the buildup of terrestrial planets.

By Companion: In binary or multiple systems, planets are susceptible to being disrupted and thrown out by the influences of the stars.

By Other Planets: Continual interaction with other planets can also serve to affect the orbital eccentricity (Mars has an eccentric orbit due to Jupiter influence, for instance) and in the end throw out planets. Two close large gas giants could interact and finally lead to an ejection of one of them and an eccentric orbit of the remaining. The remaining planet could in turn with its eccentric orbit affect other worlds.

Jovian and superjovian worlds may prevent the formation of smaller planets nearby. The larger a planet is the more able it is to influence and disrupt other worlds. On the other hand, large worlds tend to also be able to remove stray asteroids and chunks from the system and thus lessen the impact rate in the system.

By Close Encounters: When a star system passes close to another star planets can also be thrown out or eccentricity changed. While such close passes uncommon, they are more common in more crowded stellar neighborhoods. Distant worlds are more susceptible to being disrupted this way.

TWO/3 LUNAR OBJECTS

STEP ONE: Check for presence and number of lunar objects on chart 2.3.1.
STEP TWO: Determine lunar orbits on 2.3.2.
STEP THREE: Determine size and density on 2.3.3. Determine the Roche Limit on 2.3.5. Check for rings.
STEP FOUR: Calculate mass, gravity and lunar year from 2.3.4.

2.3.1 Lunar Objects

1D10	Chunk	Planet	Gas Giant/Superjovian
-4-0	None	None	None
1-5	None	None	1D10/2
6-7	None	1	1D10
8-9	None	1D10/5	1D10+5
10-13	1	1D10/2	1D10+10
14+	1	1D10	1D10+20

Modification: If planet in outer system, +5. If planet is tidally locked due to tidal force from primary, no normal lunar objects are possible.

2.3.2 Lunar Orbits

1D10	Size
1-4 (Close)	1+1D10*0.5
5-6 (Average)	6+1D10*1
7-8 (Distant)	16+1D10*3
9 (Very Distant)	45+1D100*3
10	Special (see Reference)

Roll once for every lunar object.

All orbit values are compared to the radius of the central planet.

2.3.3 Lunar Radius & Density

1D100	
1-64	Tiny chunk (1D10*10km)
65-84	Chunk (1D10*100km)
85-94	Large Chunk (1000+1D10*100km)
95-99	Small Terrestrial (2000+1D10*200km)
100	Terrestrial. (4000+1D10*400km)

Modify the roll by the System Abundance Modifier, doubled if negative (Poor and Depleted systems).
Density is 0.3+1D10*0.1 if in inner zone, 0.1+1D10*0.05 in outer zone. See reference for more details.
Rings are usually formed by lunar objects of Chunk-size and upwards which orbit within the Roche limit (see 2.3.5 or use 2.5 radii) of the main planet. Tiny chunks in this area are also likely to produce faint rings. Small moons can survive within the Roche limit.

2.3.4 Mass, Gravity & Year

The mass of the satellite, in Earth masses, is $(R/6380)^3 * D$ where R is the radius in km and D the density compared to Earth.

The surface gravity of the satellite, in Earth gravities, is $m / (R/6380)^2$ where m is the mass (in Earth masses) and R the radius in kilometers.

The lunar year of the satellite is $((a/400000)^3 * 793.64 / m)^{0.5}$ where a is the orbital distance in kilometers and m is the mass of the central planet, in Earth masses. If the moon has significant mass compared to the planet, add the masses together. Result is in Earth standard days.

2.3.5 Roche Limit

The Roche Limit in planetary radii is $2.456 * (D_{planet} / D_{moon})^{0.33}$ where D is the density of the world and moon respectively.

LUNAR OBJECTS - REFERENCE

GENERAL: Moons can be considered much the same as normal chunks and planets - they have the same basic properties and the sections on atmospheric and geophysical data applies to them too. The main difference is of course that they orbit a larger planet to which they typically are tidally locked. Thus, the "day" of a moon is really the lunar "year", the orbital period around the main planet. Moons normally don't have axial tilt (as long as they are tidally locked), but the main planet has one that will carry onto the moon as well as moons tend to orbit in a rough plane around the equator of the planet. Similarly, moons are affected by the eccentricity of the main planet's orbit. Very large moons within the stellar life zone could well be habitable.
SPECIAL ORBITS: The moon (not applicable to rings) has a odd orbit. Some such cases could be (roll 1D10):
1: Retrograde: The moon orbits the wrong way. This isn't too uncommon. Reroll to decide orbital distance, but ignore Close and Special distances. These moons often have distinct eccentricity and inclination too, and are often small. Roll twice for size and select the lower roll.
2-4: Shepherd: This is one (40%) or two (60%) moons of Tiny Chunk-size which is accompanying a ring. It is in Close orbit. Shepherds are common.
5-6: Trojan: The moon is in the same orbit, but in the LaGrange point of the previously generated moon in a non-Special orbit. (If it is larger than the previous moon, that moon is actually the Trojan). A maximum of three moons can share orbit, and the largest one must

be at least on size class larger than the two Trojans. If no moon is generated before this one, reroll. Trojans are not in Very Distant orbits.

7: Shared Orbit: The moon is actually two moons, of Tiny Chunk size, which shares almost the same orbit. Unlike Trojans, these moons "catch up" with each other and exchange orbits regularly. Shared orbits are Close.

8-9: Eccentric. The moon has a very eccentric orbit. It is not in Close orbit. These satellites are generally small - roll twice and select the lower result.

10: Inclined. The moon has a very inclined orbit compared to the planet's rotational plane. Extreme inclination includes polar orbits. As with Eccentric moons, the satellites are usually small.

DENSITY SEPARATION: Lunar objects of gas giants and superjovians are typically formed along with the planet. Lunar objects of terrestrial planets are typically either captured bodies (chunks) or formed by collision between planetesimals in the early system. Moons formed by collision will have lower density than the parent planet, because lighter material will form the moon. Captured moons may have any density. For average-sized gas giants, the moons have no significantly different density depending on distance from the world. Larger moons may be slightly denser, as they are compressed by gravity and the formation process might have ejected some of the lighter materials.

But for large gas giants and superjovians (about 200 Earth Masses and up) in the outer system, the gas giant radiated enough heat during formation to leave more dense moons close to the planet and less dense further away, much as in the star system itself. If you wish to simulate this, consider multiplying the density of moons within 8 planetary radii by 2, and those within 8-12 radii by 1.5. For superjovians, use 7+(Mass in Earths/300) to determine the *2 limit, and 1.5 times that distance as the *1.5 limit.

UNLOCKED LUNAR OBJECTS: If a moon orbits so far from the planet as to bring the tidal force down below 7-8, the moon may rotate around its axis. Note that this typically is a very big distance most applicable to moons in the outer system. Also, irregular moons slightly closer may be in chaotic orbit due to influences from other (big) moons. Stable orbits are also possible having 2/3 orbital periods etc.

CRASHING MOONS: If a moon orbits a world faster than the world rotates, tidal forces will eventually cause the moon to crash onto the planet. It could get especially fast for worlds with large extensive atmospheres. Large moons tend to break up first as the Roche limit tear them apart, but smaller (<100km) moons or remnants pieces of a big one may survive to impact in almost one piece.

RINGS: There are many types of rings, and some amount of imagination is recommended. What the chart generate as one ring may well be half a dozen rings. Rings can consist mainly of very fine dust (these rings are almost undetectable), of ice particles of larger size (like the famous rings of Saturn) or by darker, ribbon-like rings of meter-size and larger material, or incomplete ring "arcs". In the inner system rings are stony or perhaps metallic (though stony is far more likely), while in the outer system ices (dark, reddish, gray or whitish) form the bands and ribbons. Ring material may range in size from dust and grain to blocks 10, even 100 meters across. Rings are formed either by breakup of satellites (collision, tidal stress etc), remnants from the old lunar creation or by dust and grain blown off moons, typically by volcanic activity.

SEASONS: A moon has seasons based upon the eccentricity of the planet, and the combined axial tilt of the planet and the inclination of the moon's orbit to the planet's rotational plane. Moons are seldom much inclined towards the plane, so usually it is the axial tilt of the planet that counts. But there are of course exceptions, some moons may be inclined 20 or 30 degrees, or even more.

TIDAL STRESS: Moons who are affected both by the strong tidal forces of the central planet (being fairly close to the planet, thus) and other sizable moons get a significant deal of heating from tidal deformation. Io and Europa are two such moons. In extreme cases this powerful tectonic activity may turn an otherwise promising moon into an inferno. In other cases it may be enough to melt water and allow oceanic life on an otherwise frozen world. Tidal stress of this kind require a central planetary mass of at least 30 to be really effective as a heat source.

SUPERJOVIAN HEATING: Many gas giants radiate more heat than they receive, but only superjovians radiate enough heat to make them possible heat sources for lunar life zones. Superjovians, like brown dwarves, contract and cool with age. The big problem with superjovians as a source of heat is that they cool off fairly rapidly and start with lower temperatures than brown dwarves. A superjovian ten times the size of Jupiter and about 1GY old would have a surface temperature of about 700K, and the life zone would be within the tidal instability region (the "Roche" limit). Smaller and older superjovians would have even lower temperatures, dropping down to 300K or less in a few GY, and have no tenable life zones either. Superjovians cooler than 750K (any superjovian older than a few hundred million years) do not generate any visible light, only heat.

Habitable moons of superjovians are outside the life zone and must get the majority of heat from a stellar primary. Superjovians contract in size too, but not much compared to the loss of temperature. All superjovians are roughly of Jupiter-size (70-80000 km in radius).

Size (Earths)	Surface Temperature (K)	Luminosity(1Gy)	Rough Tidal Stability Limit (radii)
500	200	1.6E-8	3
1000	240	3.4E-8	3.7
1500	280	6.2E-8	4.2
2000	340	1.4E-7	4.7
2500	400	2.6E-7	5
3000	460	4.5E-7	5.3
3500	530	8.0E-7	5.6
4000	610	1.4E-6	5.9

Using this chart: You can use the chart to see the evolution of a superjovian. For every 1GY after the first, move up one step from the first on Surface Temperature and Luminosity, but keep the Tidal Stability Limit. This simulates the cooling of the superjovian.

THREE/1 COMPOSITION

STEP ONE: Take the density of the planet, if a chunk or terrestrial, and look up the composition on 3.1.1. (For gas giants and asteroids, skip to THREE/4 and THREE/5. Small Chunks are best treated as single asteroids. (THREE/4).

3.1.1 Composition

Density	Inner Zone	Density	Outer Zone
0.4-0.7	Silicates, likely small metal core	0.15-0.30	Ices.
0.7-1.0	Iron-nickel, medium metal core	0.30-0.45	Silicate core, ice mantle.
1.0-1.3	Iron-nickel, large metal core	0.45-0.60	Silicates. Possible small metal core.

Density is compared to Earth. 1 Earth Density = 5.5 g/cm3.

COMPOSITION - REFERENCE

BASIC PLANETARY STRUCTURE: All planets aside from the smallest chunks and the gas giants have three layers, the core, the mantle and the crust. Lighter materials tend to end up in the crust and heavier, like metals, in the core, through the process of differentiation all larger chunks and planets go through. An inner zone planet with high density is thus likely to have it because it has a big metal core, not because all the material is composed by heavier elements. An inner zone planet with low density comparatively has a small metal core, or perhaps none at all. In the outer system metals are comparatively rare, so the core (heavy material) is likely to be silicates (rock) and the lighter crust and mantle more composed of ices, such as water, ammonia, carbon dioxide etc.
CORE: The core of a world is the densest part. It may be molten or partly molten. Some small planets and chunks in the outer system may have a not-very defined core very similar to the mantle. Comparatively large cores may indicate that parts of the mantle has been blown off by early impacts during system formation. Outer system cores are typically made of silicates to a high degree.
MANTLE: This part of the world lies outside the core but inside the crust. It can be molten, semi-molten or solid. In worlds in the inner zone, the mantle is generally a mix of silicates and metals, while in the outer system the mantle is commonly made of ices.
CRUST: The surface region. Density of the crust is typically lower than the average density of the planet. In the inner system, crusts are typically silicate-based, while in the outer systems crusts are generally icy. The thickness of the crust vary with tectonic activity. Plate tectonics indicate a thin crust.
COMPRESSED AND UNCOMPRESSED DENSITY: The density question is complicated by the fact that planets due to their gravity compress materials. Thus a large world have a higher density than a small world even if their chemical composition is the same. In this document, it is the compressed density we refer to, for simplicity.
ICY BODIES: Icy planets, those made up to a significant degree of water ice, carbon dioxide, ammonia etc, are generally found only in the outer system. The building blocks of icy bodies don't condense close to the star. Icy bodies have very different tectonics than bodies made out of silicates and metals, volcanism may be in the form of gas geysers, large parts of the crust and even mantle could be molten by tidal stress. Impacts could melt large parts of the surface.
SYSTEM ABUNDANCE: A system rich in heavy elements tend to have more and larger planets, in addition to a higher amount of heavy metals. Very old (poor) systems may have only gas giants and perhaps small icy worldlets, as no serious amount of material heavier than hydrogen and helium existed when the star formed.
RADIOACTIVES: The presence of radioactives in the core of planets provides internal energy to melt the core and generate tectonic activity. This is affected not only by how common radioactives are, but also the size of the planet. Large worlds have more volume compared to the surface to generate energy, and thus they stay active longer. System rich in radioactives may have been enriched by a nearby supernova explosion during formation.
CHUNKS: These small worlds may have undergone little differentiation and thus may have little or no core/mantle/crust division. However, even the small chunks in the inner system has gone through some small heating. Larger chunks, like the large moons, always have some sort of differentiation and has had at least brief periods of activity during formation. Small chunks (<200km radius) are usually irregular, larger ones are more or less spherical.
INITIAL CONDENSATION: The process that forms the planetary system condenses matter at differing distances. In the outer system, ices are the norm mixed with some silicates. In the inner system, close to the star, elements like calcium, titanium, aluminum and radioactives, and many rare elements condense. Further out, iron metal and related minerals, and some non-metals like carbon and germanium condense. Even further out magnesium and silicon begin to condense (creating a large amount of silicates), and still a bit away sulfur, sodium and potassium begin to appear, mixed with iron oxides, pyroxenes and olivine. But this initial composition gets disturbed during planetary formation, when the planetesimals begin to collide and distribute the material more evenly.
ANOMALIES: Big impacts, orbital changes etc can all produce planetary bodies with different composition.

THREE/2 TECTONIC ACTIVITY

STEP ONE: Generate the tectonic activity factor by using the formula in 3.2.1. Note the factor, it will be used later.
STEP TWO: Roll on Table 3.2.2 to determine the tectonics of the world.

3.2.1 Base Tectonic Activity Factor

$$T_{Factor} = (5 + 1D10) * m^{0.5} / Age$$

Where *m* is the mass of the planet, in Earths and *Age* is in Gy.

Modify the Base Tectonic Activity Factor as follows:
-Differential Tidal Stress: If the world has significant tidal influence from anything other than the primary (large moon, moons in multiple lunar systems etc), multiply with 1.0+0.25*Tidal Force. (For Earth, this would mean *1.25).
-Icy worlds: For worlds made up mostly of ice (Typically, Outer System 0.45 Density or below), multiply by Density.
-Rotation: If the world has a shorter day than 18 hours, multiply by 1.25. If the world has a longer day than 100 hours, multiply by 0.75. If the world has longer day than year or is tidally locked, multiply by 0.5.

3.2.2 Tectonic Activity Generation

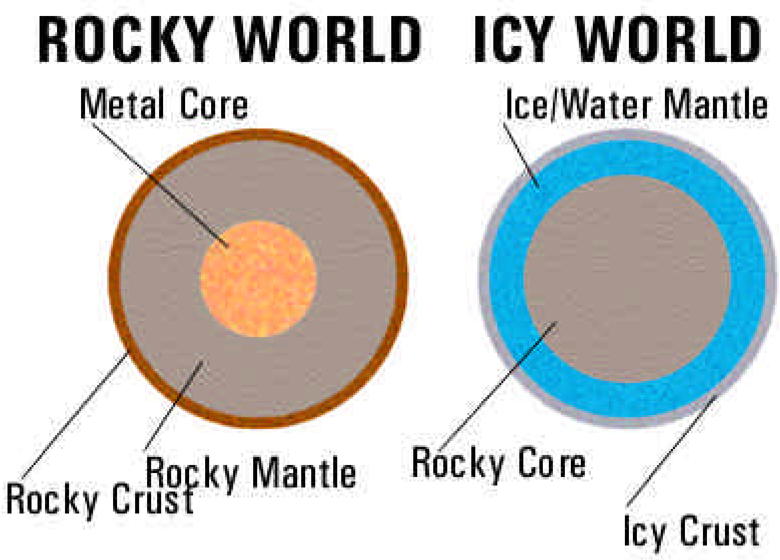
	Tectonic Activity Factor					
Roll (1D10)	＜0.5	0.5-1.0	1.0-2.0	2.0-3.0	3.0-5.0	＞5.0
1	Dead	Dead	Dead	Hot Spot	Hot Spot	Plastic
2	Dead	Dead	Hot Spot	Hot Spot	Plastic	Plate Tectonic
3	Dead	Dead	Hot Spot	Plastic	Plastic	PlateletTectonic
4	Dead	Dead	Hot Spot	Plastic	Plate Tectonic	PlateletTectonic
5	Dead	Dead	Hot Spot	Plastic	Plate Tectonic	PlateletTectonic
6	Dead	Dead	Plastic	Plastic	Plate Tectonic	PlateletTectonic
7	Dead	Dead	Plastic	Plate Tectonic	Plate Tectonic	PlateletTectonic
8	Dead	Hot Spot	Plastic	Plate Tectonic	Plate Tectonic	Extreme
9	Dead	Hot Spot	Plastic	Plate Tectonic	PlateletTectonic	Extreme
10	Dead	Plastic	Plate Tectonic	Plate Tectonic	PlateletTectonic	Extreme

TECTONIC ACTIVITY - REFERENCE

AGE MODIFIERS: As a world ages, it cools off. The radioactivity in the core which generate internal heat die down, etc.
SIZE MODIFIERS: Smaller worlds cool off faster, and they also have more surface area compared to the heat-generating core.
TIDAL INFLUENCE: Stress from different tidal forces, like a primary and a moon, tend to increase tectonic activity. If a world rotate faster it also generates more stress and coriolis force.
TYPES OF TECTONICS: On 3.2.2. there are six different "types" of tectonics listed. These are just suggestions, and they are listed in general order of increasing tectonic activity.
DEAD: This world has none or almost none tectonic activity. Small quakes may be possible, or brief activity after a big impact. Dead tectonic worlds once were active, and their surface tend to show signs of older tectonic activity as erosion is very slow. Dead worlds do not recycle atmosphere lost unless by impacts.
HOT SPOT: This world has volcanic activity in a few distinct areas, generally as large volcanoes. It is common on smaller worlds. Much of the world is not active, though, and craters and similar old signs remain.
PLASTIC: The world has a thick crust that deforms plastically. Unlike Hot Spot worlds, this tend to affect the entire world and creates distinct "continents" of higher lying terrain. There generally is some very weak plate activity too. Volcanoes are concentrated in hot spot regions, typically the highest areas of the surface.
PLATE TECTONIC: The crust moves as plates. Some plates are thin and young, (on Earth this would be the ocean plates), other are thick and old. Mountain ranges form when plates collide.
PLATELET TECTONIC: As for plate tectonic, but the crust is thinner, plates smaller and the plates recycle themselves much faster. These worlds have much volcanic activity.

EXTREME: These worlds have so abundant tectonic activity as they do not really fall into any of the categories. It can be seen as a mix of Platelet and Hot Spot tectonics. These worlds are likely not very habitable unless they have an extensive ocean cover. Moons severely deformed by tidal forces fit into this category.
ANOMALIES: Large impacts can start at least short-lived tectonic activity. On smaller worlds impact craters are the important way of surface shaping, as the internal tectonic activity is too small. Worlds with high-density (radioactive) cores can also maintain tectonic activity longer than those with cores depleted in heavy elements. Other options include tectonic activity from the shrinking of the core or mantle (as it cools off), forming scarps and ridges. This is most likely on smaller rocky worlds.
GRAVITY EFFECTS: High gravity does not really influence tectonic activity, but it affects how high mountain ranges (volcanic, impact based or plate-tectonic) can be - as the rocks which builds mountains cannot support an infinite amount of weight. Thus, on a world with 1/2 the gravity of Earth mountains can be about twice as high.
LACK OF HYDROSPHERE: A world without liquid oceans typically water cannot sustain normal plate and platelet tectonics as well as a world with a hydrosphere can. Continental plates tend to grow fast and thicken the crust, but as heat still is generated from the interior one gets "melt-throughs" instead and wide-scale volcanism, such as basaltic flooding. These melt-throughs can shape the surface radically. In effect, the world behaves much as world with plastic crust but more actively.
ICY WORLDS: As icy worlds have a very different composition their tectonics are also different. Icy mantles and crusts made up of ices and frozen gasses need less heat to be active, and on these worlds water and ammonia may take the place of lava on rocky worlds. Such tectonic activity could be fueled both by internal energy and sunlight. Icy worlds in the inner area of the Outer Zone tend to have flat surfaces (as ice at those temperatures can't support much vertical surface features). Other types of tectonics can be seen when the watery part of a icy world's mantle freezes and expands, cracking the surface, forming parallel ridges and flooding craters even forming equivalents of plate tectonics.
TECTONIC EVOLUTION: Worlds of any size above a few kilometers across have a period of tectonic activity - the process of formation and cooling. The larger a world is the longer time it will be active. Primarily during the first hundreds of million years of a system, impacts will also serve to remodel the surface of worlds, and sometimes to remodel their interior composition too. On small worlds the tectonic activity dies down rather quickly, though. In a billion years, chunk-size worlds will lose activity. In another 2-3 billion years, small terrestrial worlds will also become inactive. Plate tectonics slow down, perhaps to be replaced by plastic or hot spot tectonics, which in turn fade. This mean that the geological recycling of a world slows and finally stops. Erosion becomes less effective, water freezes or binds, lost atmosphere will not be replaced by new tectonic activity. These worlds can still support life, but not in the same way an geologically active world can. Of course, if the system is rich in stray asteroids of a small enough size, a certain replacement of atmosphere and elements may be possible anyway.

PLANET INTERIORS



CHEMICAL ABUNDANCES
Systems are rich (or poor) in various elements. This can be important. The systems that are poor in heavy elements (old systems) seldom form large planets terrestrial planets, as an example. But there are other variations that can be contemplated:
Carbon: In our system oxygen dominates over carbon, but some stars show an abundance of carbon instead. This will affect the system carbides and graphites will be common minerals. If metals are uncommon too planets may be very alien to us.
Sulfur: Similarly, sulfur could be comparatively more common than silicon. Systems rich in sulfur will have different abundances of various minerals and compounds as hydrogen sulfide and sulfur dioxide.
Rare Elements: Some (rare) stars show an abundance of more exotic elements such as lithium (a light reactive metal), or even such comparatively uncommon metals as yttrium or vanadium.
Radioactives: Young systems enriched by supernovae can be rich in rare radioactive elements. Technetium, a rare light radioactive, has been discovered in abundance in certain C-class stars, for instance.
Noble Gasses: Neon and argon are two such gasses neon is common in the universe though not that common in our solar system. Noble gasses are chemically inert.

Different proportions of elements than in our system can be a potentially important factor not only for mineralogy, but also for native life.

THREE/3 MAGNETIC FIELD

STEP ONE:. Generate the Magnetic Field Factor on 3.3.
STEP TWO: Roll on 3.3.2 to determine the strength of the magnetic field, compared to Earth.

3.3.1 Magnetic Field Factor

$$Mag_{Factor} = 10 * 1 / (d / 24)^{0.5} * D^2 * m^{0.5} / Age$$

Where *m* is the mass of the planet and *D* is the density (in Earths), *d* is the rotation period in hours and *Age* is in GY.

Modify the Base Magnetic Activity Factor as follows:
-Icy worlds: For worlds made up mostly of ice (Typically, Outer System 0.45 Density or below), multiply by another 0.5.

Note: A world that is tidally locked or having a rotation period longer than the year use the year as rotation period.

3.3.2 Magnetic Field Strength

	Magnetic Field Factor					
Roll (1D10)	＞0.05	0.05-0.5	0.5-1.0	1.0-2.0	2.0-4.0	＞4.0
1-3	None	None	None	1D10*0.001	1D10*0.05	1D10*0.1
4-5	None	None	1D10*0.001	1D10*0.002	1D10*0.1	1D10*0.2
6-7	None	1D10*0.001	1D10*0.002	1D10*0.01	1D10*0.2	1D10*0.3
8-9	None	1D10*0.002	1D10*0.01	1D10*0.05	1D10*0.3	1D10*0.5
10	None	1D10*0.01	1D10*0.05	1D10*0.1	1D10*0.5	1D10*1.0

MAGNETIC FIELD - REFERENCE

MAGNETIC FIELD GENERATION: To have a magnetic field of a decent size, a world must have at least part liquid metallic composition, typically in the core. It does not have to be that much, Mercury has a weak magnetic field despite most of its core is believed to be solid. The strength of the magnetic field is also dependant upon how fast a world rotates. It also is likely to be affected by specifics of the core (liquid FeS abundance, in particular), and thus two rather similar worlds like Earth and Venus can have very different magnetic fields (Venus has 1/1000th the magnetic field of Earth). Magnetic fields can vary in strength over time.
NO MAGNETIC FIELD: Though all worlds probably have some magnetic field, it may be so small as to be uninteresting. Venus and Mars both have very small magnetic fields. Water can also generate weak magnetic fields.
GAUSS VALUE: Earth has a magnetic field of about 0.305 Gauss.
INCLINATION: Magnetic fields tend to be inclined to the rotational axis of a world. If you wish to simulate this, you may decide the inclination (compared to the axis) by rolling on the Axial Tilt table (**2.2.3**).
EXTENSION: The stronger a magnetic field is, the further away from a world it extends. A world with a weak (0.01-0.001) magnetic field has a magnetospause about 1world radii away from the surface. For an Earth-sized field, 10 world radii are more typical. Worlds with magnetic fields 10 times the size of Earth's have magnetospauses perhaps 50-100 radii away. Actually, the magnetic field extends much farther in the "tail" direction from the primary, and for gas giants the magnetic field may be significantly offset compared to the center of the planet too.
MAGNETIC FIELD EFFECTS: The magnetic field of a world helps to shield it from the solar wind and cosmic radiation. However, a dense atmosphere may cover for the lack of a average magnetic field. It also generates the phenomena we know as *auroras*.
REVERSALS: Magnetic fields change inclination (on Earth, we use this fact when we see that the deviations of compasses change from decade to decade), but they also reverse (changing North and South poles) from time to time.

THREE/4 ASTEROIDS

STEP ONE: Determine predominant asteroid type (in the belt) on Table 3.4.1.
STEP TWO: Determine total asteroid mass of the belt, on table 3.4.2.

3.4.1 Belt Type

Roll 1D10

-2 and below:	M (metallic)
-1 to 5:	S (silicate)
6 to 10:	C (carbonaceous)
11+:	Icy

Modifications:
In outer zone, add +6 to the roll
Closer than life zone: -2 to the roll.
If density of the belt is 0.6 to 0.8, subtract -1.
If density of the belt is 0.8 to 1.0, subtract -2.
If density of the belt is 1.0 to 1.2, subtract -3.
If density of the belt is above 1.2, subtract -5.

3.4.2 Asteroid Mass

Roll 1D10

<5:	0.0001*1D10
5-6:	0.001*1D10
7-8:	0.01*1D10
9-10:	0.1*1D10
11+:	1*1D10

Modifications to the initial 1D10 roll:
System Abundance Modified (**1.1.3**): -3 to +2
Outer Zone: +2
Inner Zone: -1
System is older than 7 Gy: -1
Belt around two or more stars: +2

ASTEROIDS - REFERENCE

BASIC TYPES: Here, we define four basic types of asteroids.
M: Metallic. These asteroids are made up largely by metals and are differentiated. They can be thought of as the remnants of metal cores of destroyed proto-planets.
S: Silicate. These asteroids can be differentiated (part of old crust/mantles) but most are primitive.
C: Carbonaceous: These asteroids are dark and include carbon compounds and water bound to silicates. They are primitive.
Icy: These asteroids are mostly made up of ices and various frozen gasses. When getting heated, they become comets. These asteroids are only found in the outer zone on a permanent basis.
Any asteroid belt in life zone or closer than life zone orbit will have both M & S type asteroids, and perhaps a few C-types. Any asteroid belt in the inner zone but outside the life zone will have all three sort. In the outer zone, C & I-types will be the ones found.
SPECIAL CASES: There are many sub-types of asteroids. Some may be intact smaller but differentiated bodies, with a core like any small planetoid. These are rare, and the older a system is the greater is the chance that they have been hit by other asteroids and broken up.
BELT SIZES: Asteroid belts are generally as wide as half the distance between the next inner and outer orbit, but if any of the orbits contain a big gas giant or superjovian it may be significantly thinner. Most asteroid belts contain rather small amounts of material compared to planets, but large outer belts may have a lot of material. This generation do not cover Oort clouds (which are much larger and also can have much more mass), nor do it cover the protoplanetary disks and planetoids of very young systems. These cases allow for much larger belts. Belts around binaries are also often larger.
ASTEROID SIZES: Most asteroids are small - less than 1km across - but there will almost always be larger objects, up to several hundred of kilometers across or in exceptional cases, perhaps even above 1000 kilometers in radius. The denser the belt is the less likely it is large objects will survive, of course, and time tend to favor creation of small objects.
DUST DISKS: These are not asteroid belts but usually features of young (<1GY) systems. A dust disk typically lies tens of AUs from the star and has about 0.1 to 0.001 Earth masses total.
SHAPES & COLORS: Only a few large asteroids are spherical - most are irregular bodies. Some may even have small moons or act as double chunks. They have numerous small craters from smaller impacts. Some asteroids are grayish, while C-types tend to be dark. Icy bodies are often reddish.
ECCENTRICITIES AND INCLINATIONS: While most asteroids are within the main belts and in the normal orbital plane, there are always those much more eccentric and/or inclined. Asteroid belts do not form a "sphere" around a star, however. Too few have inclined orbits for that effect. (Oort clouds, on the other hand, may be more spherical)
DIFFERENTIATED OR PRIMITIVE?: A differentiated body is a body that has been extensively heated and thus have different composition in core than crust. Asteroids of differentiated nature may be remnants of destroyed larger bodies or small mini-planets in their own right. Primitive asteroids have condensed directly from the young system, and while they have been heated somewhat leading to a certain geological evolution they are not really differentiated.

THREE/5 GAS GIANTS

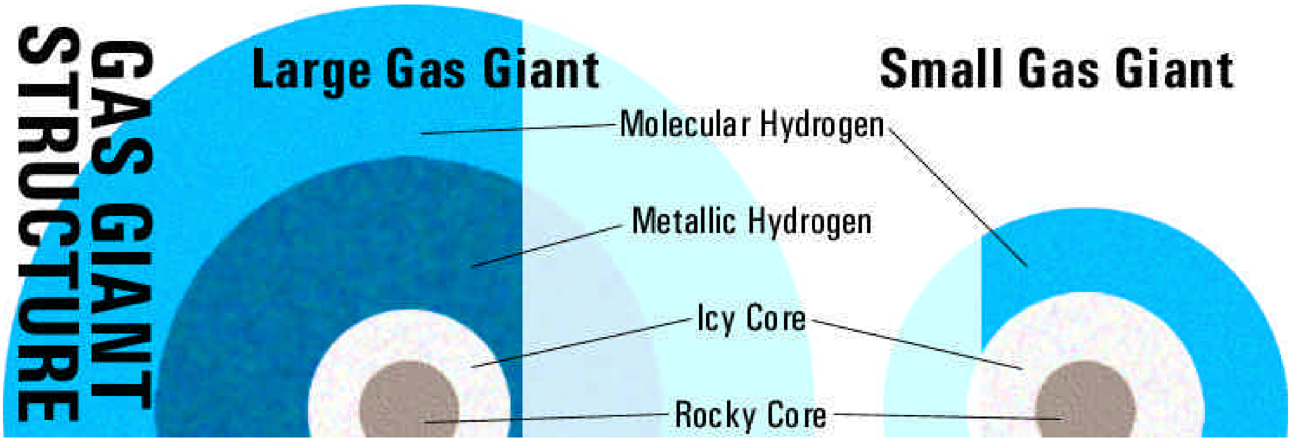
STEP ONE: Determine magnetic field strength from Table 3.5.1.
STEP TWO: Go to FOUR/1 to decide the base temperature of the gas giant.

3.5.1 Magnetic Field

	Mass			
1D10 roll	< 50 (small)	50-200 (medium)	200-500 (large)	500+ (Superjovian)
1	1D10*0.1	1D10*0.25	1D10*0.5	1D10*1.5
2-4	1D10*0.25	1D10*0.5	1D10*1	1D10*2.5
5-7	1D10*0.5	1D10*0.75	1D10*1.5	1D10*5
8-9	1D10*0.75	1D10*1	1D10*2	1D10*10
10	1D10*1	1D10*1.5	1D10*3	1D10*25

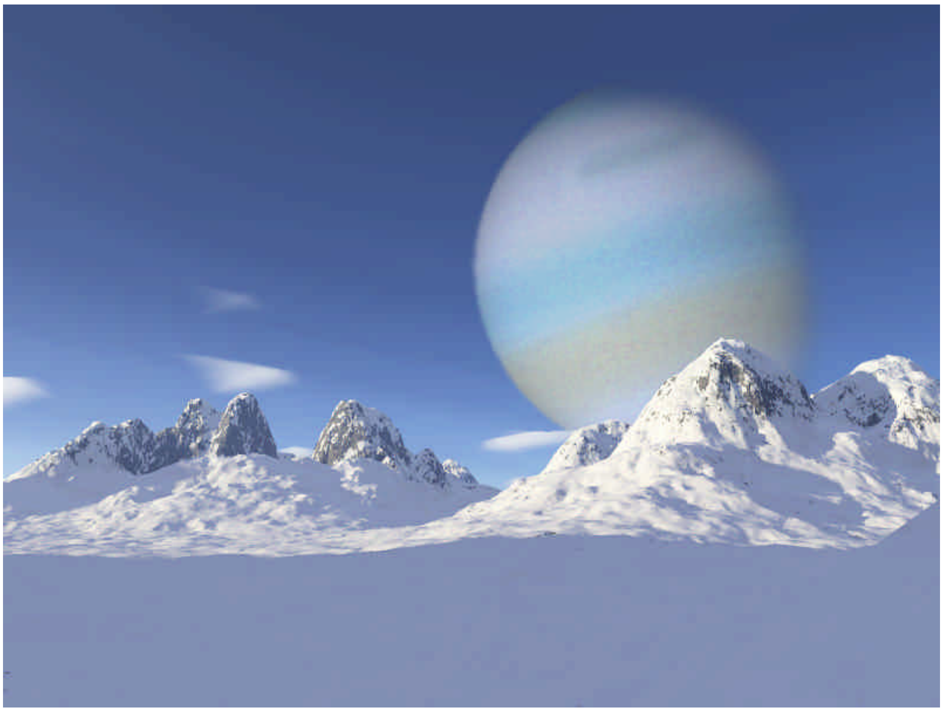
GAS GIANTS - REFERENCE

SIZES: For ease of reference, gas giants are divided into three size classes - small (like Uranus and Neptune), medium (like Saturn) or large (like Jupiter), and into superjovians. Maximum radius is reached at about 600 earth masses.
STRUCTURE: Gas giants are composed of gas, but for small gas giants the majority of their mass is actually the core of rock and ice. Gas giants have a core of rock and metal, surrounded by an outer core of liquid/solid "ices", compounds made out of carbon, oxygen, nitrogen and hydrogen - such as water, ammonia, carbon dioxide etc. Large and medium gas giants have a layer of metallic hydrogen outside that (a layer that is most of the planet on large gas giants, but not at all as large part on medium gas giants), and all gas giants have a deep atmosphere primarily made up of hydrogen forming the final part of the world. The pressure deep in a gas giant is far greater than anything on normal planetary surfaces. Hot gas giants (those close to the star) are a subject less known, but the basics should be about the same.



FORMATION: Gas giants can form in two ways - they can condense from the protostellar disc or they can be "budded off" by the protostar. The later formation is more likely for close gas giants and superjovians, while more distant gas giants conceivably could form in both ways. Another way to explain close gas giants is that they formed farther away but spiraled inward while the protostar nebula still existed, as the nebula provided certain friction. In these systems the inner planets that existed must have been disrupted. In any way, gas giants tend to have a composition very similar to the star in elements, as they are made of the basic building blocks much more than planets and chunks, which are composed mainly by heavier elements.
COMPOSITION: A gas giant's atmosphere is mostly hydrogen. About 90%. About 10% is helium. On some gas giants, the helium part is smaller - because helium can precipitate in the planetary atmosphere. Cold gas giant atmospheres (those in the Outer Zone) also have parts of ammonia, methane and various carbon compounds - hot gas giants more likely have carbon dioxide and water vapor.

INTERIOR ENERGY SOURCE: Most gas giants generate interior energy, either by gravitational contraction (common on large gas giants) or helium precipitation (common on cooler gas giants. This interior energy is important mainly to create the complex cloud patterns on many gas giants - giants with little interior energy will have much less in the way of patterns as there is so little internal convection. However, many gas giants also have distinct east-west bands due to their fast rotation.
OBLATENESS: Gas giants tend to rotate fast, and this gives most of them, especially the medium and large ones, a distinct flattened shape, or oblateness. Most planets are oblate, including terrestrial ones, but generally it is significant only on gas giants.
COLOR: Gas giants are tinted by their atmosphere, and while this may only be interesting as a note to world generation these are some suggestions:
-Hot gas giants will tend to be bluish, perhaps dark blue, due to atmospheric scattering of sunlight. Sulfuric compounds may form whitish or yellowish clouds, perhaps tinted by phosphorous compounds.
-Warm gas giants (Life Zone) will also tend to have a basic bluish color, but water clouds would form notable white systems and they may be tinted by various other chemicals.
-Cool gas giants (outside life zone, but within the Inner zone) will have pale blue clouds of water and carbon dioxide, mostly covered by yellow-orange-brown clouds based upon ammonium hydrosulfide.
-Cold gas giants (inner part of the Outer Zone) would have clouds of ammonia covering most of them. Ammonia clouds are white, but they will be stained yellow, red or brown by various other chemicals. Slow rotation or little convection may diminish the bandedness of these worlds.
-Very cold gas giants (further out) will likely have clouds of methane and a bluish color, with whiter clouds of methane ice.
-Extremely cold gas giants will be dark blue and virtually without clouds, as methane freezes out.
Still, there are many possibilities. Atmospheric smog, haze, internal convection - all can affect how a gas giant look. Superjovians will also be affected by this, of course, tinted by the clouds that condense in their warmer atmospheres.



Large moons of gas giants in the life zone may well be capable of sustaining life. The potential problems for moons are the rather long day (as the "day" is the orbital period around the planet) which gives the moon itself a weaker magnetic field and distinct diurnal temperature differences, and that some large gas giants and superjovians may have strong magnetic fields which could provide too much dangerous radiation, like the Io's position around Jupiter. Another problem may be that moons of enough size could be rare, though arguably moons of gas giants in the inner zone have the potential to become rather big.

ROGUE PLANETS
Although planets probably can't form on their own (except for superjovians and maybe the largest gas giants) it is likely to be a large amount of rogue worlds out between the stars, worlds that have been lost. Some superjovians may have formed on their own, but most will have been ejected from their systems by close encounters and gravitational action.
Chunks: Most of the chunks are likely to have been ejected from systems early in formation. As all systems must lose some planetesimals in this way these must be fairly common in interstellar space but very hard to detect.
Planets: Planets can also have been ejected, of course. These worlds will be very cold, though interior heat sources may still be active of course.
Gas giants: These will also have been ejected from systems. It is quite possible that at least some of their moon systems survive, and moons heated by tidal action may stay active.
Superjovians: These can have been ejected or formed separately. Old superjovians don't generate much heat, but the younger ones may provide some heating though not enough to heat a moon it its own to life zone status.
Abundance: Any estimate of how common these rogue worlds are is bound to be very hypothetical. Still, if we don't count the smallest chunks but only consider the larger chunks, planets, gas giants and superjovians, we can have several such bodies per 10LY cube, perhaps 1D5-1. (Remember, a lot of these worlds will end up in the much sparser halo).
Roll 1D10:
1-4: Large Chunk (1000km+)
5-6: Planet
7-8: Gas Giant
9-10: Superjovian
These bodies will be very cold but otherwise much as normal worlds. Finding them will be very hard, though.

FOUR/1 BASE TEMPERATURE

STEP ONE: Calculate base temperature from 4.1.1. If you are not generating a terrestrial world or chunk, you are through. Otherwise, continue to FOUR/2.

4.1.1 Base Temperature (in Kelvin)

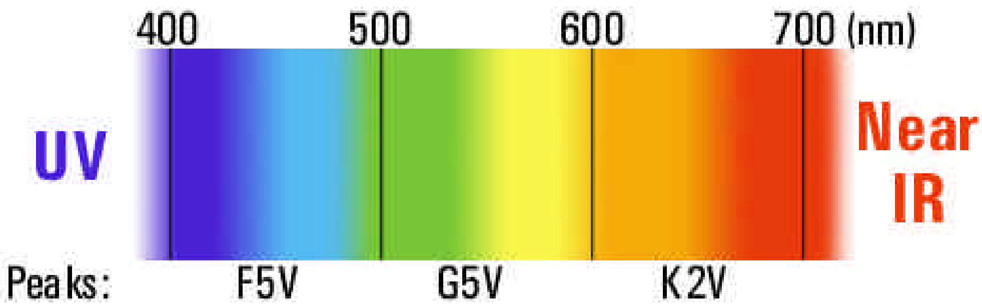
$$T = 255 / (a / L^{0.5})^{0.5}$$

Where a is the orbital distance in AU and L is the luminosity of the primary, in solar equivalents. Subtract 273 to get the temperature in Celsius.

BASE TEMPERATURE - REFERENCE

BASE TEMPERATURE: The temperature here is based upon rather earth-like planetary albedo and do not include the greenhouse effect (which raises Earth's temperature by about 33 degrees). This figure (not adjusted for albedo and greenhouse effect) is a decent enough approximate to decide what atmosphere and hydrosphere a world would have. Greenhouse can only warm the world, but the albedo may cool it of or warm it. Earth's base temperature is about 255K.
SOLAR INFALL: The temperature also represent solar infall, of course. For stars hotter than the sun, the peak frequency will be shifted towards the ultraviolet, while for coolers star it shift toward the infrared.

PEAK FREQUENCY DETERMINATION: Wien's law gives us $3000000/T$ as the peak frequency, where T is the temperature and the result is in nanometers. A G2-star peaks in 520nm (visible light:green), a F0-star at the border towards UV light while a M0-star peaks in the infrared. Stars emit some radiation at all wavelengths, however. The sun heat Earth by about 8% in the UV band, the rest in visible light and IR. But for a world in the life zone a K or M-star will provide far less UV light (and far more IR) of the total reaching the planet, while an A or F-star will provide much more UV which will break down the atmosphere and increase dangerous radiation at the surface. Thus, cooler stars will be less effective in breaking down atmospheres. Note that the peak frequency isn't the same as the color of a star, but it is important for atmosphere and biosphere.



Near IR extends from 700 to 1300nm, mid-IR from 1300 to 3000nm and thermal IR (heat) beyond 3000nm. Water vapor absorbs energy to a certain degree between 900 and 2100nm, while ozone absorbs strongly in the UV-bands of 200-350nm.

STELLAR VARIABILITY: All stars vary slightly in luminosity. For normal main-sequence stars of G and K types, variability is usually only 0.1-0.3%, and not enough to do any huge impact on climate. More variable main sequence stars may vary by up to 1 percent. Instable stars, such as subgiants and giants can vary much more. Small red flare stars (see chapter ONE) can also increase briefly in luminosity. For worlds without a thick atmosphere these flares may be a hazard and raise temperature significantly. Another possible source of exceptional stellar variability could be a close companion or even a large gas giant in very close orbit, whose magnetic fields interact to provide extreme flare activity for brief periods. This would require both a gas giant with a significant magnetic field and a close orbit (within 0.5 AU, preferably even closer).
ECCENTRIC ORBITS: If a planet has a significantly eccentric orbit its base temperature will vary greatly during a year. This variation may in turn affect what the atmosphere looks like and the greenhouse effect. For instance, a world may be cold enough to deposit carbon dioxide as ice during "winter" and then turn it to gas during "summer", thus increasing the already big seasonal differences. On the other hand, increased cloud cover may increase albedo and thus regulate the temperature
GAS GIANTS: Many gas giants have internal heat which raise the temperature by up to 20 degrees. Not all have it, though, particularly some small gas giants may be without internal heat source.
COMPLEXITY: This and the following four sections are a simplified way of generating temperature. On real planets there are complex heat exchange system between various types of terrain, between oceans and air, between clouds and ground, reflection and absorption etc.

FOUR/2 HYDROSPHERE

STEP ONE: Check if the world has a hydrosphere on 4.2.1. If it has none, skip to FOUR/3.
STEP TWO: Determine the extensiveness of the hydrosphere by rolling on 4.2.2, if 4.2.1 gave a result of "Liquid" or "Ice Sheet".
STEP THREE: Determine the water vapor factor of the atmosphere, if a liquid or ice sheet hydrosphere is present.

4.2.1 Hydrosphere Determination

Base Surface Temp.	Type
>500	None
370-500	Vapor
245-370	Liquid
<245	Ice Sheet
Outer Zone	Crustal

4.2.3 Water Vapor Factor

$$W_v = (T\text{-}240)/100 * h * \text{D10}$$

Where T is the base temperature and h is the hydrosphere percentage.
Treat negative W_v as 0.

4.2.2 Hydrosphere extensiveness

	Radius (km)			
Roll(1D10)	<2000	2000-4000	4000-7000	>7000
1	None	None	None	None
2	None	None	2D10%	2D10%
3	None	1D10%	20+D10%	20+2D10%
4	None	1D10%	30+D10%	40+2D10%
5	None	10+D10%	40+D10%	60+1D10%
6	1D10%	20+D10%	50+D10%	70+1D10%
7	1D10%	30+D10%	60+D10%	80+1D10%
8	10+D10%	40+D10%	70+D10%	90+1D10%
9	5D10%	50+D10%	80+2D10%	100%
10	10+10D10%	10+10D10%	100%	100%

Modification: If in Inner Zone but outside the Life Zone, add +1 to the 1D10 roll.

HYDROSPHERE - REFERENCE

HYDROSPHERE-GENERAL: This only considers *water*. Other liquids may form pools or oceans on cold or hot worlds. Methane on cold worlds, for instance, or sulfur on hot worlds. High pressure can be a prerequisite for non-water oceans. If you see that temperatures are within a range that would allow a common enough material to be liquid, it can form pools, lakes or even oceans.
HYDROSPHERE TYPE: 4.2.1 lists five different kinds of hydrospheres:
None: The world has no water at all. There may be small deposits of ice in polar locations on an airless worlds.
Vapor: The world has water in the form of water vapor only. As water vapor seldom is very stable in an atmosphere, this is likely a small part.
Liquid: The world has a potential for liquid water.
Ice Sheet: The world can have water on the surface, but generally only in solid state. Some water may be permafrost, but ice sheets and ice caps are a definite possibility on worlds with more than 5% hydrosphere. Thick enough ice sheets may cover unfrozen oceans heated by tectonics.
Crustal: The world is an outer zone world that has not endured lunar density separation, and ice is a major part of the moon, mixed with silicates and other ices/frozen gasses. These worlds do not have a normal "hydrosphere".
LOW PRESSURE: If a world has low atmospheric pressure, liquid water cannot exist. (0.006 atm is the approximate limit). This means that liquid water is not possible on airless or near-airless worlds. The atmospheric pressure is determined in 4.2.3. Modify hydrospheres on these worlds - water may be as permafrost or ice caps if they are cold enough.
CHANGES IN FURTHER CALCULATIONS: Further developments will affect the base temperature of a world, and that means that a ice sheet world can become a ocean one. Or vice versa.
SIZE OF WORLD: According to theories how atmospheres and hydrospheres form, they are generated by 1) cometary infall in the early system and 2) volcanic outgassing. A larger world can generate more atmosphere and water, and thus larger worlds have more extensive hydrospheres. In general.
IMPACTS: Large impacts on icy worlds may melt the icy crust. In the same way, a large impact may bring dust into the atmosphere and cool off the world.
WATER VAPOR & ECCENTRICITY: In extreme cases, the eccentricity of a world may be enough to boil water at closest separation and freeze it at farthest separation. The vapor itself will add to both greenhouse effect and modify the albedo, so this can get complex.
OUTER ZONE WORLDS: These icy worlds seldom have real hydrospheres unless they are density-separated moons.
SPECIAL CASES: Ammonia-rich worlds may sustain liquid water below 273K, down to about 180K. The ammonia mixes with the water and acts as a defrosting agent. This is most likely around cool stars.
WATER ON WORLDS WITHOUT HYDROSPHERE: Small amounts of water can be found in polar locations on hot airless worlds. Water can also be chemically bound to rock, or exist in subsurface strata.

FOUR/3 ATMOSPHERIC COMPOSITION

STEP ONE: Roll on the column on 4.3.1 which correspond to the base temperature of the world.
STEP TWO: Consult 4.3.2 and 4.3.3 and remove the gasses that aren't retained by a world of this size and temperature.
STEP THREE: Modify the composition based upon UV infall and other effects as described in 4.3.4.
STEP FOUR: Determine fractions of the involved gasses by checking 4.3.5.
STEP FIVE: Determine the atmospheric pressure on 4.3.6.

4.3.1 Atmospheric Basic Composition

	Roll (1D10)				
Base Temperature	1-4	5-6	7-8	9	10
>400	N2, CO2	CO2	NO2, SO2	SO2	Special
240-400	N2, CO2	CO2	N2, CH4	CO2, CH4, NH3	Special
150-240	N2, CO2	CO2	N2, CH4	H2, He	Special
50-150	N2, CH4	H2, He, N2	N2, CO	He, H2	Special
<50	H2	He	He, H2	Ne	Special

4.3.2 Retained gasses

Calculate $0.02783 * T / v^2$ where *T* is the base surface temperature and *v* is the escape velocity, compared to Earth.
Any gas with a higher molecular weight above this value is stable, while any lighter will escape over long enough time. Lighter gasses that are constantly renewed may still be a part of the atmosphere, but in general you should remove any gasses not permanently retained. Worlds where the main gasses (above) cannot be retained will have trace atmospheres, so don't roll for pressure on 4.3.5.

4.3.4 Atmospheric Modifications

Modify Atmosphere as follows:

UV Infall: If the primary has high enough UV output, NH3, CH4, H2S and H2O in the atmosphere will break down and the hydrogen may escape if the world is small enough. Thus, remove these gasses as a major part of atmosphere if the primary is **BA-class** and **T>150K, F-class** and **T>180K, G-class** and **T>200K, K-class** and **T >230K, M-class** and **T > 260K**. See Reference for more suggestions.
Volcanism: Volcanic activity replenish atmospheres. This will primarily modify the pressure of the world, but a dead world will not typically have sulfur dioxide and hydrogen sulfide.
Life: If a world has life, such life may affect the atmosphere. Methane and ammonia may be replenished, or carbon dioxide (partly) replaced by oxygen. Worlds with liquid water may have oxygen-based life on a roll on 1-3 on 1D10, replacing carbon dioxide (or part of it) with oxygen. Such worlds should be at least 1GY old.

4.3.3 Gas Data

Name	Mol. Weight	BoilingPoint(1atm)
Hydrogen (H2)	2	20
Helium (He)	4	4
Methane (CH4)	16	109
Ammonia (NH3)	17	240
Water (H2O)	18	373
Neon (Ne)	20	27
Nitrogen (N2)	28	77
Carbon Monox (CO)	28	82
NitrogenOxide(NO)	30	121
Oxygen (O2)	32	90
HydrogenSulfide(H2S)	34	212
Argon (Ar)	40	87
Carbon Dioxide (CO2)	44	195
NitrogenDiox (NO2)	46	294
Sulfur Dioxide (SO2)	64	263

4.3.5 Atmospheric Pressure

The base atmospheric pressure is based upon the mass (*m*) of the planet. Multiply *m* with an atmospheric pressure factor from the chart below to get the final pressure. Remember that worlds that don't retain main gasses only have trace atmosphere.

Roll (1D10)	2 and below	3-4	5-7	8	9	10+
Factor	1D10*0.01	1D10*0.1	1D10*0.2	1D10*0.5	1D10*2	1D10*20

Modify the first roll as follows: Dead volcanism: -1. Extreme Volcanism: +1. One (but not all) main atmospheric gasses removed in 4.3.2: -1

4.3.6 Specifying Composition

Roll	1-5	6-8	9-10
Major (first) part is	50+4D10%	75+2D10%	95+1D10/2%

This shows how large part the main (first listed gas) is of the atmosphere.

ATMOSPHERIC COMPOSITION - REFERENCE

TYPICAL ATMOSPHERES: The most common basic gasses to form a majority of planetary atmospheres are nitrogen and carbon dioxide. Very dense atmospheres are generally rich in carbon dioxide. Very hot atmospheres may have parts of sulfur trioxide, sodium and other more exotic elements. High-G worlds may retain helium and hydrogen to a large degree - this is especially important in the outer system where there was an abundance of these gasses to begin with. (In the inner system the proto-planets were not rich in helium and hydrogen) Ammonia tend to mix with any present water - this is especially typical on cool N2/CH4 worlds (*T* between 200K and 240K). Carbon dioxide can be bound up by geological activity and also locked up in water. Cold water under normal and high pressure can dissolve carbon dioxide at an 1-1 basis. Interestingly, warm water does not dissolve carbon dioxide nearly as well. Ice-ball planets that lose atmosphere continuously tend to lose mass as well. They can keep a very thin atmosphere for as long as there are gasses to lose.

SPECIAL ATMOSPHERES: There are many variants of special atmospheres. They may signify an unusual amount of some rarer gas, perhaps because alien life utilize it, or an unusual mix of gasses.

Nitrous Oxides & Sulfur Compounds: These may be available on hot volcanic worlds or as smaller parts on very volcanic worlds. Such atmospheres would be hostile. Sulfur-rich environments may be able to sustain very alien life. (See Chapter Five) These compounds would add to greenhouse effect.

Halogens: The atmosphere has an important (typically less than a few percent, but still far more than normal) of chlorine, fluorine, bromine or perhaps iodine. These elements are highly reactive and much of them may be in liquid acid form. Halogens could also theoretically support life. Halogen compounds could add to the greenhouse effect strongly. A world rich in chlorine or fluorine would be a very strange and deadly (to Earth life) place.

Hydrogen: Explosive combined with oxygen and reactive. Hydrogen-rich atmospheres are called *reducing* but most terrestrial worlds don't retain hydrogen.

Carbon Monoxide: Also mainly found in reducing hydrogen-rich atmospheres. Carbon monoxide is very unhealthy.

Noble Gasses: Helium, neon and argon are the most common noble gasses. Argon is most common on terrestrial worlds where it may amount to a pair of percent or even more in rare low-pressure worlds, but neon and helium are common in the universe. These gasses do not react with other materials.

Water Vapor: Water vapor can also be a significant part of an atmosphere, but this is fairly rare as UV infall break up the water and the hydrogen escapes. Still, on massive ocean worlds water could be a major part of the atmosphere.

Very Dense: This is a world dead in volcanism which still has a very dense atmosphere, perhaps due to extreme infall or history of dense atmosphere. It could also be a world which retains an atmosphere it probably should have lost under 4.3.2 - perhaps it is on the border to keep/lose some of the gasses, but still rolls for normal atmospheric composition and pressure.

ADDITIONAL GASSES: A lot of gasses are found in the atmosphere, but most only in miniscule fractions. Several of these gasses may be important in cloud formation (H2SO4, ammonium compounds, various photochemical organic smog compounds etc) however, so their importance should not be underestimated. Small amounts of certain fairly common gasses are enough to kill humans.

PRIMORDIAL ATMOSPHERES: In a young system, before UV has broken down molecules, atmosphere has escaped and volcanism have settled down, atmosphere *may* have basic building blocks like methane and ammonia even within the Inner Zone. Planets may have denser atmospheres than they can retain over a longer time. Carbon dioxide may also be an important part of primordial atmospheres.

PRESSURE: Pressure may vary significantly over a year or even day on worlds with sparse atmospheres, if some atmospheric gas freezes out during cold periods and vaporizes during warmer ones. Carbon dioxide could have this effect on cool worlds, and thus pressure could vary by perhaps 50% over time, regularly. We know that the atmosphere on Mars varies like this.

UV INFALL: UV infall breaks down molecules, and if part of the molecule can get lost into space (hydrogen, generally) the compound cannot be recreated. This is what happened to water on Venus, and to the possible ammonia and methane on Earth. Ozone layer (which needs free oxygen to reach a decent size) can protect from some of this radiation, but this is only a slowing-down radiation slowly depletes all atmospheres. UV radiation also serve to create more complex compounds and organic smog. Worlds orbiting brown dwarves (which have very low UV radiation) would not be affected much at all.

VOLCANISM: Volcanic activity replenish the atmosphere. Bound water, carbon dioxide and other compounds can be brought back into the atmosphere. Thus, a world without volcanism is slowly losing atmosphere and faces a shortage of critical building blocks for life.

LIFE: The presence of life tend to influence the atmosphere. Most importantly right now, it can create free oxygen. This takes time, however, and all forms of life do not need or produce oxygen. A young world may have oxygen-producing life but the oxygen is removed by geological processes (On Earth, it took perhaps 3 GY to produce free atmospheric oxygen). Thus, worlds with low tectonic activity may get oxygen-rich faster. Some miniscule amount of oxygen is also likely to be present in any carbon dioxide or water-rich atmosphere. Other types of life may sustain methane and/or ammonia levels, or perhaps sulfur or nitrogen oxides. Oxygen levels also vary over time Earth's oxygen level have been higher hundreds of millions of years ago, for instance.

The amount of free oxygen may vary depending on how abundant and advanced local life is, but in general a world with large warm oceans could produce more oxygen. This is easiest to simulate by tweaking the generated oxygen level upwards or downwards. For Earth-like worlds this can be a guideline

$$\text{Oxygen percentage} = (T-240)/200 * h * (5+1D10) * 10$$

where *T* is the surface temperature calculated from FOUR/5 (*not* the base temperature) and *h* is the hydrosphere. Oxygen levels will be discussed further in chapter EIGHT, and you may consider deciding oxygen levels by the more detailed rules there.

Free oxygen will react with hydrogen, ammonia, carbon monoxide and methane, thus limiting the extent of such gasses. Free oxygen is also important in the creation of any serious ozone (O_3) layer. Life based upon the more exotic types of molecular building stones, such as sulfur, silicone or halogens does not necessarily produce free oxygen.

ODDITIES: Cometary infall on planets can serve to provide more gasses or shift the balance of existing ones. On small worlds, impacts usually strip away more atmosphere than they provide, so here the infall has the opposite effect.

VARIABILITY: The atmospheric composition may change distinctly over time, not only because of outgassing, freezing and overheating but also because of life and geological processes. If erosion becomes less effective gasses generated from tectonic activity will build up, for instance. This can form a regulatory process to keep worlds form freezing over. More on long-term climate change is in Part II.

SCALE HEIGHT: The scale height is a measure of how extended an atmosphere is. Heavy gasses and low temperatures give a more compact atmosphere, while hot and light atmospheres are much deeper. Scale height is calculated from

$$H = kT/ mg$$

where *k* is Boltzmann's constant ($1.38*10^{-23}$ J/degree), *T* is the temperature of the atmosphere, *m* is the mean molecular mass of the gas (4.3.3.shows molecular weight, to get the mass multiply by $1.66*10^{-27}$) and *g* is surface gravity. Scale height is an approximation, as the temperature tend to vary within an atmosphere too.

PRESSURE ABOVE SEA LEVEL: Pressure decrease with altitude, and on some worlds this may be important, especially if they have distinct topography. Liquid water needs a certain pressure, and high levels of oxygen and nitrogen can be dangerous. To calculate this, we need the scale height (*H*) from before. At a certain point above sea level the pressure is

$$P = p * 2.718^{(-h/H)}$$

where *p* is the base atmospheric pressure, *h* is the altitude and *H* is the scale height.

Sea level may be rather uninteresting on a world without oceans. In such cases, use the lowest land as reference.

ATMOSPHERIC MASS: The mass of an atmosphere (in Earth atmospheric masses) is related to pressure as follows:

$$M = 2.46*10^{-8} * p * R^2 / g$$

where *p* is the base atmospheric pressure, *R* is the radius of the planet (in kilometers) and *g* is the surface gravity (in Earths).

BREATHABLE?

Pressure: High atmospheric pressure is not healthy to humans. Very dense atmospheres are not breathable due to the pressure alone.

Oxygen: To humans and Earth's animal life, oxygen is absolutely necessary. Oxygen pressure should be less than 0.3 atm and more than 0.05 atm for humans. Too little oxygen and brain damage due to oxygen depravation and troubles breathing will occur. Too high oxygen will destroy eyes and lungs and send people into fits. High oxygen levels are also increasing flammability and attack materials. Plants, bacteria and alien forms of animal life may not need free oxygen or not at all as much.

Nitrogen: Is necessary to plant life and bacteria, but not in the same huge amounts as oxygen is to animals. High levels of nitrogen is unhealthy to humans - anything beyond 2.0-3.0 atm of nitrogen induces nitrogen narcosis and dense nitrogen atmospheres can be outright dangerous. The long-term effects of living in a higher-than-normal nitrogen environment is unknown.

Carbon Dioxide: Carbon dioxide is not lethal in small amounts, but more than 0.05 atm of CO_2 can lead to unconsciousness and higher amounts to suffocation.

Methane: Methane is flammable in any larger amounts (above 0.06-0.08) and can cause explosions.

Hydrogen: Like methane, flammable. Hydrogen is not toxic, but it will not be found in larger amounts with free oxygen.

Ammonia: Toxic to humans in even small concentrations.

Helium, Noble Gasses: These are not toxic.

Other Gasses: Virtually all other gasses are dangerous to humans. Carbon monoxide (which could be common in young systems before it has reacted with other elements) and halogens are toxic in small concentrations.

FOUR/4 ALBEDO

STEP ONE: Generate the basic albedo factor of the world by consulting 4.4.1.

4.4.1 Albedo Factor

Roll (1D10)	1 (and below)	2-3	4-6	7-9	10 (and above)
Inner Zone	0.75+1D10*0.01	0.85+1D10*0.01	0.95+1D10*0.01	1.05+1D10*0.01	1.15+1D10*0.01
Roll (1D10)	1-3	4-5	6-7	8-9	10 (and above)
Outer Zone	0.75+1D10*0.01	0.85+1D10*0.01	0.95+1D10*0.01	1.05+1D10*0.01	1.15+1D10*0.01

Modifications for Inner Zone Worlds:
No or trace atmosphere: Add 2.
Heavy atmosphere (5atm+): Subtract 2.
Extremely heavy atmosphere (50atm+): Subtract 4.
Ice sheet world (50% of world surface is ice sheet): Subtract 2*
Frozen over world (90%+ of world surface is ice sheet): Subtract 4*
* not cumulative with modifications for atmosphere. Use the lowest modification.
Modifications for Outer Zone Worlds:
Dense Atmosphere (1atm+): Add 1.
Density Separated Moons: Roll on Inner Zone row.

ALBEDO - REFERENCE

ALBEDO FACTOR: There are several different ways to measure a planet's *albedo* or *reflectivity*, and the albedo factor used here is purely a rough estimate to generate surface temperatures. Here, an albedo factor of 1 is Earth-like. A lower albedo factor actually represents a *higher* albedo, as it will in FOUR/5 generate a lower temperature. In effect, more of the solar infall is reflected. A high albedo factor represents a lower albedo, or a more effective energy absorption.
VARIOUS ALBEDO FACTORS: Albedo factors can provide additional information about a world. Take a world very similar to Earth, but with a higher albedo factor. This world could have much more plant life, more rocky surfaces or perhaps much less clouds. A lower albedo factor could indicate large polar ice caps or much clouds, or perhaps large deserts of sand.
Low Albedo Factors: Common for worlds that either are covered in ice (very common in the outer system) or have an extensive cloud cover. Sand may also explain such albedo.
Moderately Low Albedo Factors: This could be a world with a fairly extensive cloud cover, large ice caps, large deserts or a dirty ice satellite.
Moderate Albedo Factors: These worlds may have varied surfaces, including clouds, oceans or fairly reflective rocks.
Moderately High Albedo Factors: These worlds could be cloudless worlds, all-ocean or jungle worlds but more commonly rocky worlds with some clouds or volcanic rocky worlds.
High Albedo Factors: This may be an atmosphere rich in photochemical compounds (typical in outer system worlds), a world with a dark organic-compound surface (C-class asteroid relatives - these would have very high albedo factors), or a typical rocky world (common on in inner system airless worlds).
CHANGING ALBEDO FACTOR: Albedo factors can change. Over a year, perhaps, on a world with temporary cloud or ice cover. Over long time if a world freezes over by expanding ice or loses atmosphere. Impacts could trigger cloud covers that could trigger ice ages.
ALBEDO FACTOR AND SURFACE TEMPERATURES: Worlds with little greenhouse effect, and varying albedo factors on the surface, can thus vary in temperature significantly depending on the albedo at a particular spot. This can generate weather effects and is more discussed in Part II.

FOUR/5 SURFACE TEMPERATURE

STEP ONE: Calculate greenhouse effect, if any, from 4.5.1.
STEP TWO: Modify base temperature by greenhouse effect and albedo to get the surface temperature of the world, on 4.5.2.

4.5.1 Greenhouse Effect

The Greenhouse gas pressure is the combined pressure, in atm, of the greenhouse gasses carbon dioxide, methane, sulfur dioxide and nitrous dioxide. Water vapor is also included if it is a major part of the atmosphere. Note this combined pressure, P_{gr}.

Final Greenhouse Effect

$$\textit{Greenhouse Factor} = 1 + p^{0.5} * 0.01 * 1D10 + P_{gr}^{0.5} * 0.1 + W_v * 0.1$$

Where p is the atmospheric pressure, P_{gr} is the greenhouse gas pressure and W_v is the water vapor factor from 4.2.3.

4.5.2 Surface Temperature

*Surface T = Base T * albedo factor * greenhouse factor*

Resulting surface temperature is in Kelvin. Subtract 273 to get the temperature in Celsius.

SURFACE TEMPERATURE - REFERENCE

GREENHOUSE EFFECT: The greenhouse effect of certain gasses prevent heat from escaping the atmosphere. Gasses like carbon dioxide, water vapor, CFC's and methane are highly effective for this. The small parts of greenhouse gasses likely to be present on all worlds with an atmosphere is simulated by the $p^{0.5}$*0.01*1D10 factor (such as the small amounts of greenhouse gasses on Earth). Large amounts of greenhouse gasses do not add up to produce an arithmetically higher greenhouse effect.
SPECIAL CASES: Certain gasses, like CFC's, are very effective greenhouse gasses. Small amounts can have a strong effect. If a greenhouse gas freezes out during the cooler periods and vaporizes during the warmer ones, this could amplify normal seasonal temperature variations.
CHECKING BACK: The final surface temperature should be back-checked towards hydrosphere and atmospheric composition. It is possible that the world is significantly cooler or warmer than it began. This can affect a hydrosphere (freezing it). If a hydrosphere is heated so much it would boil, it is lost and contributes to the greenhouse effect by heating the planet further. If gasses are cooled enough to freeze out or become liquid, they may still be a part of the atmosphere. After all, on warmer spots on a world temperatures may be high enough to vaporize them. The Surface Temperature is an average. Equator region will be warmer.
VARIATIONS: This is discussed in more detail in SIX/1. But these are some basics.
VARIATIONS WITH DAY: Temperatures rise during the day and fall during the night. The longer the rotation period, the greater differences.
VARIATIONS WITH LATITUDE: High latitudes are cooler and equatorial regions warmer. Solar infall falls in at an angle that decreases towards the poles, and this means stellar radiation must heat a larger surface than in the equatorial regions.
VARIATIONS WITH SEASONS: Axial tilt of a world makes solar infall on a given area vary with which pole is tilted towards the primary. Low axial tilt give small effects, but extreme axial tilts (close to 90 degrees) may give very strong effects as one pole is in perpetual "day" during a full season.
VARIATIONS WITH ECCENTRICITY: Eccentric orbits produce variations in solar infall. These are easy to calculate, assuming albedo and greenhouse effects will be the same. If not, it gets more complicated. Very eccentric orbits may give very strong effects - a low albedo factor and low greenhouse effect at furthest separation, and a higher albedo factor and greenhouse effect when closer.
MODERATING FACTORS: Thick atmospheres, preferably cloudy and greenhouse-effective, moderate temperature. A strong enough greenhouse effect could moderate even very long days. Oceans also moderate temperature as they "store" heat. This is further discussed in Part II.
GAIA?: Some people believe that a living ecosphere could regulate itself. I.e., the life adjusts greenhouse levels (and perhaps albedo) to allow a world to have an optimal or at least decent temperature. This has *not* been considered here at all. If you feel "habitable" or "Earth-like" worlds are too uncommon, just tweak the equations/rolls a bit.

FIVE/1 CONVERSION DATA

Comparative Data
1 Solar Mass = $1.989*10^{30}$ kg = 333 000 Earth Masses = 1050 Jupiter Masses
1 Solar Luminosity Unit = $3.83*10^{26}$ W
1 Solar Radius = $6.960*10^{8}$ m = 696 000 kilometers = 109 Earth radii = 0.0046 AU
1 AU = 149 600 000 km = 1/63240 LY
1 Earth Radius = 6380 kilometers = 1/11.2 Jupiter radii
Earth's Density = 5.52 g/cm^{3}
Earth's Mass = $5.977*10^{24}$ kg = 1/318 Jupiter Masses
Mass of Earth's atmosphere = $5.14*10^{18}$ kg
Earth's Escape Velocity = 11.2 km/s
Other Units used:
1 atm = the average Earth atmospheric pressure (100000 Pa)
1 AU = Astronomic Unit, the semimajor axis of Earth's orbit around the Sun ($1.496*10^{11}$ m)
1 g =1 Earth Gravity (9.81 m/s^{2})
1 GY = One Billion Years (1 000 000 000 years)
1 LY = 1 Light Year, the distance light travels in vacuum in one year ($9.461 * 10^{15}$ m)

FIVE/2 RARE STARS

The chart below details certain types of stars that were left out in ONE/1, such as bright giants and supergiants. These stars are very rare compared to the main sequence stars, and just as common giants their mass and luminosity vary within the class.

Table 5.2.1 Luminosity & Mass for Rare Stars
Note: All numbers are in solar equivalents except temperature, in the form Luminosity/Mass and Surface Temperature (K)/Radius

	0	1	2	3	4	5	6	7	8	9
O V	2000000 / 80 50000 / 19.0	1200000 / 70 48000 / 16.0	700000 / 60 46000 / 13.3	400000 / 50 44000 / 11.0	285000 / 45 42000 / 10.2	200000 / 40 40000 / 9.4	125000 / 35 37500 / 8.7	75000 / 30 35000 / 8.0	40000 / 25 32500 / 6.6	20000 / 20 30000 / 5.3
O IV*	2500000 / 80 48000 / 23.1	1500000 / 70 46000 / 19.5	900000 / 60 44000 / 16.5	600000 / 55 42000 / 14.8	500000 / 50 40000 / 14.9	340000 / 45 38500 / 13.3	250000 / 40 36000 / 13.0	160000 / 35 33500 / 12.0	110000 / 30 31000 / 11.6	80000 / 25 29000 / 11.3
B IV*	60000 / 20 27000 /11.3	30000 / 18 24000 / 10.1	15000 / 16 21500 / 8.9	8000 / 14 19600 / 7.8	4000 /12 16700 / 7.6	2000 / 10 14800 / 6.9	1500 / 9.4 13800 / 6.8	1000 / 8.6 12800 / 6.5	500 / 7.8 11800 / 5.4	250/ 7.0 10800 / 4.6
O III*	3000000 / 80 47000 / 26.4	1800000 / 70 45000 / 22.3	1400000 / 65 43000 / 21.5	1050000 / 60 41000 / 20.5	800000 / 55 39000 / 19.8	600000 / 50 37500 / 18.5	400000 / 45 35000 / 17.4	300000 / 40 32500 / 17.4	200000 /35 30000 / 16.7	125000 / 30 28000 / 15.2
B III*	100000 / 25 26000 / 15.7	55000 / 23 23000 / 14.9	30000 / 21 21000 / 13.2	18000 / 19 19200 / 12.2	10000 / 17 16400 / 12.5	6500 / 15 14600 / 12.7	3700 / 14 13600 / 11.1	1900 / 13.5 12600 / 9.2	800 / 13 11600 / 7.1	360 / 12.5 10600 / 5.7
O II*	3500000 / 80 46000 / 30	2600000 / 75 44000 / 28	2000000 / 70 42000 / 27	1550000 / 65 40000 / 26	1200000 / 60 38000 / 26	900000 / 55 36500 / 24	650000 / 50 34000 / 23	430000 / 45 31500 / 22	320000 / 40 29000 / 23	230000 / 35 27000 / 22
B II*	170000 / 30 25000 / 22	130000 / 27 22000 / 25	95000 / 25 20000 / 26	60000 / 23 18800 / 23	32000 / 21 16100 / 23	18600 / 19 14400 / 22	13500 /18 13400 / 22	9400 / 17 13200 / 21	6800 / 16 11400 / 21	4000 / 15 10400 / 20
A II*	2200 / 14 9300 / 18	1900 / 13 9100 / 18	1650 / 12.5 8900 / 17	1400 / 12 8700 / 17	1150 / 11.5 8450 / 16	850 / 11 8200 / 15	800 / 10.8 7950 / 15	750 / 10.6 7750 / 15	700 / 10.4 7550 / 16	650 / 10.2 7300 / 16
F II*	600 / 10 7100 / 16	575 / 9.5 7000 / 16	550 / 9.0 6850 / 17	525 / 8.5 6700 / 17	500 / 8.0 6550 / 18	510 / 8.1 6400 / 19	520 / 8.3 6250 / 20	530 / 8.5 6100 / 21	540 / 8.7 5950 / 22	550 / 8.9 5800 / 23
G II*	560 / 9.1 5700 / 25	590 / 9.3 5650 / 26	620 / 9.5 5600 / 27	660 / 9.7 550 / 28	700 / 9.9 5500 / 29	740 / 10.1 5400 / 31	770 / 10.3 5200 / 35	740 / 10.5 4950 / 39	830 / 10.7 4700 / 44	860 / 10.9 4500 / 49
K II*	900 / 11 4300 / 55	1200 / 11.5 4150 / 68	1500 / 12 4000 / 81	1800 / 13 3850 / 96	2100 / 14 3750 / 111	2450 / 14 3650 / 125	2800 / 14 3550 / 141	3200 / 14 3450 / 160	3600 / 14 3350 / 180	4100 / 14 3250 / 205
M II*	4600 / 14 3100 / 240	7400 / 14 2900 / 350	10100 / 14.5 2750 / 450	12000 / 15 2600 / 545	14500 / 15.5 2500 / 650	14900 / 16 2400 / 710	15200 / 16.5 2300 / 780	15500 / 17 2200 / 865	15800 / 17.5 2150 / 915	16200 / 18 2100 / 970
O Ib*	3750000 / 80 45000 / 32	2700000 / 75 43000 / 30	2200000 / 70 41000 / 30	1700000 / 65 39000 / 29	1450000 / 60 37000 / 30	1200000 / 55 35500 / 29	750000 / 50 33000 / 27	475000 / 45 30500 / 25	350000 / 40 28000 / 25	320000 / 37 26000 / 28
B Ib*	270000 / 35 24000 / 30	185000 / 32 21000 / 33	130000 / 30 19500 / 32	97000 / 27 18200 / 32	61000 / 25 15800 / 33	47000 / 23 14300 / 36	38500 / 21 13300 / 37	31000 / 19 12300 / 39	24000 / 18 11300 / 41	19000 / 17 10300 / 44
A Ib*	15000 / 16 9100 / 50	14400 / 15 8900 / 51	13800 / 14.5 8700 / 52	13200 / 14 8500 / 53	12500 / 13.5 8300 / 55	11700 / 13 8100 / 55	10800 / 12.8 7850 / 57	9950 / 12.6 7600 / 58	9100 / 12.4 7450 / 58	8250 / 12.2 7200 / 59
F Ib*	7400 / 12 7000 / 59	6800 / 11.6 6900 / 58	6200 / 11.2 6750 / 58	5600 / 10.8 6600 / 58	5000 / 10.4 6450 / 57	5100 / 10 6300 / 61	5300 / 10 6150 / 65	5500 / 10 6000 / 69	5700 / 10 5850 / 74	5900 / 10 5700 / 80
G Ib*	6100 / 10 5600 / 84	6500 / 10.4 5450 / 91	6900 / 10.8 5300 / 99	7300 / 11.2 5150 / 108	7700 / 11.6 5000 / 118	8100 / 12 4850 / 129	8800 / 12.2 4700 / 143	9500 / 12.4 4550 / 158	10200 / 12.6 4400 / 175	10900 / 12.8 4250 / 195
K Ib*	11700 / 13 4100 / 215	13500 / 13.5 4000 / 245	15100 / 14 3900 / 270	16900 / 14.5 3800 / 300	18900 / 15 3650 / 350	20400 / 16 3500 / 390	25300 / 16 3400 / 460	30200 / 16 3300 / 540	35000 / 16 3200 / 615	40500 / 16 3050 / 730
M Ib*	46000 / 16 2900 / 860	53000 / 17 2800 / 990	61000 / 18 2650 / 1200	71000 / 19 2500 / 1400	80000 / 20 2350 / 1700	89000 / 21 2200 / 2100	95000 / 22 2150 / 2250	101000 / 23 2100 / 2400	108000 / 24 2050 / 2600	115000 / 25 2000 / 2850
O Ia*	4000000 / 80 44000 / 35	3250000 / 75 42000 / 34	2800000 / 70 40000 / 35	2000000 / 65 38000 / 33	1600000 / 60 36000 / 33	1350000 / 55 34500 / 33	900000 / 50 32000 / 31	800000 / 47 29500 / 35	700000 / 45 27000 / 39	640000 / 42 25000 / 43
B Ia*	560000 / 40 22000 / 52	511000 / 37 20000 / 60	463000 / 35 18500 / 67	310000 / 32 16400 / 70	251000 / 30 15200 / 73	204000 / 27 14200 / 75	184000 / 25 13200 / 83	165000 / 23 12200 / 92	146000 / 21 11200 / 102	126000 / 19 10200 / 115
A Ia*	107000 / 18 9000 / 136	101000 / 17 8800 / 138	96000 / 16 8600 / 141	91000 / 16 8400 / 144	86000 / 15 8200 / 147	81000 / 15 8000 / 150	77000 / 14 7800 / 153	73000 / 14 7600 / 157	69000 / 14 7400 / 161	65000 / 13 7150 / 168
F Ia*	61000 / 13 6900 / 175	59000 / 13 6750 / 179	57000 / 12 6600 / 184	55000 / 12 6450 / 190	53000 / 12 6300 / 195	51000 / 12 6100 / 204	51000 / 12 5950 / 215	55000 / 12 5800 / 235	59000 / 12 5650 / 256	63000 / 12 550 / 280
G Ia*	67000 / 12 5400 / 300	71000/ 12 5250 / 325	75000 / 13 5100 / 350	79000 / 13 4950 / 390	84000 / 13 4800 / 420	89000 / 13 4700 / 450	91000 / 14 4550 / 490	93000 / 14 4400 / 530	95000 / 14 4250 / 570	96000 / 14 4100 / 620
K Ia*	97000 / 14 4000 / 650	99000 / 15 3850 / 720	101000 / 15 3700 / 780	103000 / 16 3550 / 860	105000 / 17 3400 / 940	107000 / 18 3300 / 1000	109000 / 18 3200 / 1080	111000 / 19 3100 / 1160	113000 / 19 3000 / 1250	115000 / 20 2900 / 1350
M Ia*	117000 / 20 2800 / 1450	119000 / 21 2650 / 1650	121000 / 22 2500 / 1850	123000 / 23 2350 / 2100	126000 / 24 2200 / 2500	129000 / 25 2000 / 3000	132000 / 26 1975 / 3100	135000 / 27 1950 / 3250	138000 / 28 1925 / 3400	141000 / 30 1900 / 3500

***Randomizing subgiants (IV). Roll 1D10: 1-2 use listed value, 3: decrease mass 10%, 4: -20%, 5: -30%, 6: -40%, 7: +10%, 8: +20%, 9: +30% and 10: +40%. Luminosity is affected at double that rate. Recalculate radius as shown in ONE/1. Randomizing Giants (III, II, Ib, Ia)- see 1.1.4.**

FIVE/3 COORDINATE SYSTEMS

OUR PLACE IN THE GALAXY: Our galaxy is a giant "pinwheel" of stars, with a close-to spherical core (the "bulge") and a flat disc containing the spiral arms. This disc is about 100 000 LY in diameter and 1000 LY thick, and rotates slowly. Outside the disc (above, below and beyond) is the galactic halo extending perhaps twice as far as the disc from the galactic core and in a sphere surrounding it. The bulge is something like 7000 LY across. For the Sun it takes about 250 MY to complete one galactic year, as we are about 28 000 LY from the center. The Sun lies about 50 LY above the plane of the galaxy, near the edge of a 15 000 LY short spur (a small spiral arm) often called the *Orion* spur. There are four big spiral arms: *Sagittarius-Carina*, *Perseus*, *Cygnus* and a fourth unnamed arm. The Orion Spur lies between S-C and Perseus, about 6000 LY away from either, and we are on the S-C side of the spur.
COORDINATE SYSTEMS: It is useful to be able to provide a defined location for star systems in the form of coordinates (X, Y, Z). The coordinates are often based upon Earth's sky, but as Earth's equator isn't the same as the galactic equator the resulting coordinates don't tell how stars are placed relative to the galactic plane and center. Thus, it may be wise to utilize *galactic coordinates*. The easiest way to generate galactic coordinates is to take the "normal" coordinates based upon right ascension, declination and parallax and convert them.
RIGHT ASCENSION, DECLINATION AND PARALLAX: These three things (optionally, distance instead of parallax) are necessary to provide coordinates. Right ascension (ra) is the celestial version of longitude, declination (dec) the latitude equivalent and parallax the displacement angle the object shows due to the annual motion of the Earth. Parallax translates into distance as

$$distance = 1/(63115.2 * \tan(parallax/206264806))$$

calculating in radians. Distance is in light years, parallax in milli-arc-seconds (mas).
The coordinates of an object, when distance, right ascension and declination are known, are as follows:

$$X = distance * \cos(dec * pi/180) * \cos(ra * pi/180)$$
$$Y = distance * \cos(dec * pi/180) * \sin(ra * pi/180)$$
$$Z = distance * \sin(dec * pi/180)$$

Use trigonometry in radians, distance in light years and dec/ra in decimal degrees.
EPOCHS: However, the right ascension and declination of an object is subject to change. One reason is that the object actually moves fast enough to make a difference, but the main reason is that Earth itself undergo changes in orbital elements. The rotational axis slowly undergo precession and thus the pole do not face the exact same spot over time. Thus, the astronomical measurements are accompanied by an "epoch", a sort of time-tag. Some star data you may find (Gliese, for instance) are 1950, while Hipparcos (another big data source) is 1991. Depending on how painstakingly precise you decide to place stars (decimal fractions of light years?) this may be more or less important.
GALACTIC COORDINATES: For 1991-data (Hipparcos), you can transform the X, Y and Z coordinates above to galactic coordinates (centered on Earth, but with X-Y-Z axis oriented according to the galaxy) by using

$$Xg = -(0.0571 * x) - (0.8733 * y) - (0.4838 * z)$$
$$Yg = (0.4938 * x) - (0.4458 * y) + (0.7466 * z)$$
$$Zg = -(0.8677 * x) - (0.1963 * y) + (0.4567 * z)$$

MOVEMENT: Stars move relative to each other. Over a short enough time, say 500 years, this will be of little importance (0.1 LY or so) unless you need very exact coordinates. (If you do, use the proper motion and radial velocity measurements many star lists provide) But over longer time it will make a difference. 1 million years ago our skies looked different and our stellar neighborhood too. The Alpha Centauri system has not been our closest star for that long (and in only a few thousand years Barnard's Star will be closer)
DISTANCES: To measure distances between star systems is simple.

$$distance = ((X_1-X_2)^2 + (Y_1-Y_2)^2 + (Z_1-Z_2)^2)^{0.5}$$

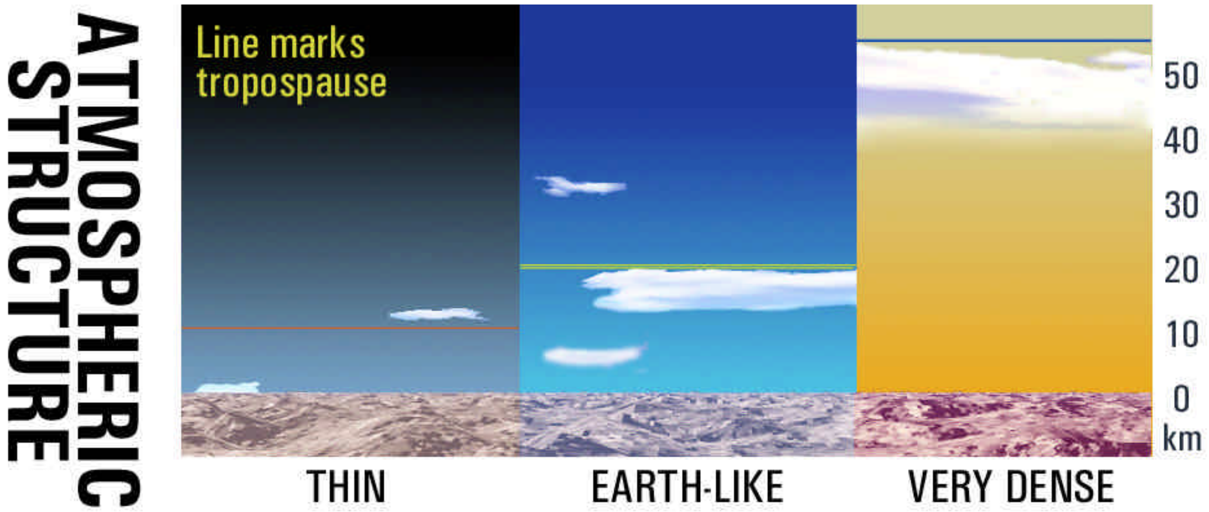
where the two sets (1 & 2) of coordinates are those of the two involved stars.

SIX/1 CLIMATOLOGY

THE BASICS: When we talk about *climate* we usually mean the general long-time conditions of temperature and moisture of an area, as opposed to *weather* which is more about clouds, winds and similar shorter-term conditions. In a sense, all worlds have climate regions and the difference between these regions is what we are interested in. Airless worlds, however, have a climate which is solely based upon energy infall (and perhaps hot spots) unmoderated by atmosphere, while hothouse worlds have very similar climate all over the surface.

Climate is usually generated by energy infall from the local primary. As the energy (sunlight) reaches the surface of a world it heats it. In chapter FOUR we calculated the "typical" surface temperature, but the typical surface temperature isn't that useful for a specific region as the temperature varies over the surface. The temperature difference depends primarily on the angle the sunlight hits the ground with. At the areas near the poles (in a case of low axial tilt) there is less light per surface unit, and thus these areas are colder than the areas near the equator. The heated surface in turn radiates energy, to provide an energy balance. The greenhouse effect "traps" some of this outgoing energy, and raises temperatures.

THE STRUCTURE OF THE ATMOSPHERE: The atmosphere of a planet can typically be divided into, from surface and upward, a *troposphere*, a *stratosphere* and a *mesosphere*. Beyond the mesosphere the atmosphere is so thin that gas can escape and particles get ionized. FOUR/3 described how the pressure falls with altitude.



The troposphere is the lowest part, where the convection (rise and fall of matter, in this case gas, of various temperatures) take place. The troposphere usually gets colder the farther up one gets, and most clouds tend to form in the troposphere. In some cases the troposphere temporarily disappear due to lack of convection. This is most common on thin atmospheres in nighttime situations. The troposphere otherwise typically extend up to 10-30km. The border between the troposphere and the stratosphere is called *tropospause* (see figure above).

Beyond the troposphere lies the stratosphere. Here is very little convection, and temperatures stop dropping. Sometimes they rise gradually towards the mesosphere. The stratosphere is typically rather clear, but clouds can form here too. On Earth, these clouds are made of ice crystals, on Mars of carbon dioxide. The stratosphere is also the place where the ozone layer is most likely to be found on worlds with free oxygen, though in very thin atmospheres it may be in the troposphere.

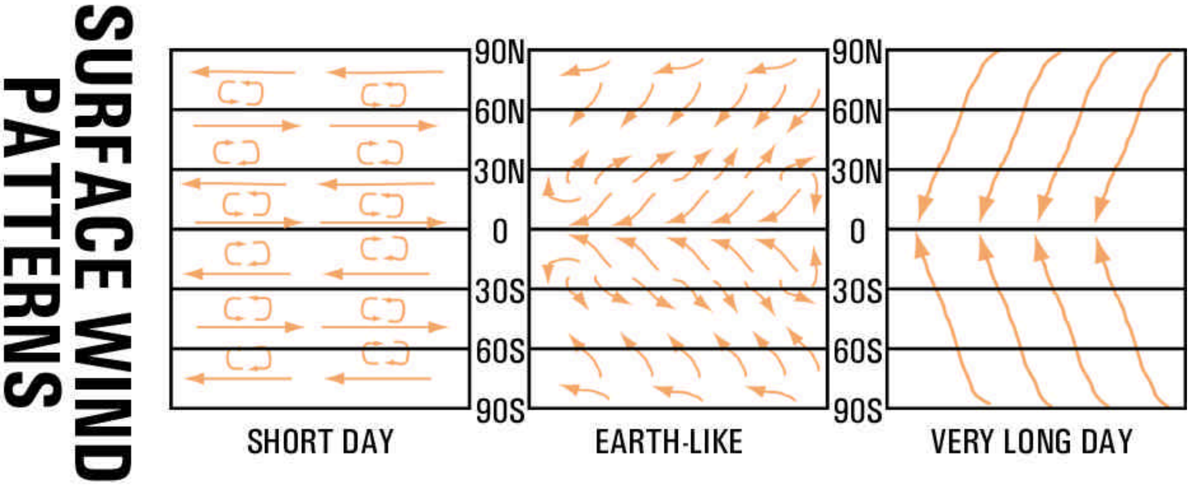
Above the stratosphere is the mesosphere. Here, temperatures rise again but the air is very thin and thus the heating effect is very small. Cloud formation in this area is rare, but night glowing (*noctilucent,* see TEN/2) clouds from meteoric dust and aerosols of smog are a possibility.

THE BIG PATTERN AND THE CORIOLIS FORCE: The basic pattern generated on a world with non-extreme axial tilt is that the air is heated in the equatorial area and cools off near the poles. Thus, the pattern would be north-south, with cooler surface winds moving towards the equator. On worlds that rotate fairly fast, this is made complex by the *coriolis force*. Due to the rotation, the winds will be deflected, to the right in the northern hemisphere and to the left in the southern hemisphere. The force is stronger towards the poles and zero at the equator, and stronger the higher the velocity of the winds are.

The coriolis force can be calculated from 2 * (angular velocity of spin) * (wind velocity) * sin (latitude). We understand that the rotation of the world is very important, a world that rotates half as fast as Earth has only half possible coriolis force. On a world with high wind speeds and fast rotation, like many gas giants, the coriolis force will be so strong as to form bands of east-west winds and no polar-equatorial winds.

On worlds with a large axial tilt the coriolis force still works, but one has to consider that the area which receives the most solar infall seldom is at the equator but closer to the poles.

The basic pattern of surface winds is very important to climate, as it not only moves cool air from poles and hot air from low latitudes, but also moves moisture from oceans.



On the truly slow rotating (slower than the "Very Long Day" above, worlds the pattern will also be influenced by the large temperature difference between night and day as opposed to not as prominent poles/equator difference. Cool air from the nightside will flow over the surface to the day-side, and heated air will be transported back to the night-side higher up in the troposphere. (In the same way, the "Very Long Day" example above has motion towards the poles in the upper troposphere).

The big pattern is also influenced by land masses, which are heated faster than oceans. This is very apparent on a world like Earth with large continents in one hemisphere. More on continental high pressure zones and ocean low-pressure zones in SIX/3. Note that the figure above relates to *surface* winds, the winds in the upper parts of the atmosphere are another matter.

TEMPERATURE DIFFERENCES/LATITUDE: As already mentioned, temperatures drop with lower angles of solar infall (for worlds with low axial tilt this is in the high latitudes). The hottest areas of a world are those with longest amount of sunlight coming in from straight overhead. This mean that the potentially hottest areas of a world are at the tropics, not the equator, as the sun is longer in zenith consecutively at the tropics than the equator. (Of course, for worlds with very low axial tilt this does not matter much).

TEMPERATURE DIFFERENCES/ALTITUDE: The higher up one goes the thinner the atmosphere gets, and the temperature drops. How fast the temperature drops depends on how much moisture the atmosphere holds and the structure of the atmosphere. For Earth-like atmospheres, temperatures can drop about 6 degrees per kilometer in the troposphere. Cooler atmospheres lose temperature slower, as would denser ones.

TEMPERATURE DIFFERENCES/DIURNAL: Naturally, temperatures vary over the local day too. This has little effect on strict climate, but will affect weather. The longer the rotating period is the hotter the day will be and the cooler the night will be. When the days are long enough (a planet rotating slowly) the diurnal difference may be the distinct one, like our seasons.

SEASONAL DIFFERENCES: This depends on how clear-cut seasons a world has, of course. There are two main reasons for seasonal variations, axial tilt and eccentricity. (A third reason can be the radiation from a binary star in eccentric orbit) Axial tilt is rather simple, the more axial tilt the more distinct seasons the world will have. A side-effect is that low axial tilt tend to stabilize climate zones and extend the equatorial and polar ones (larger deserts and ice caps, for instance). Axial tilt has by far the most effect the closer to the poles one get. Eccentricity, on the other hand, affects the entire planet and unlike axial tilt the entire world gets cooler or hotter, so moderation is less effective. In extreme-eccentricity cases, the atmosphere may undergo significant changes over a year, if for instance water vapor reinforce greenhouse effect at closest separation while frozen oceans increase albedo on furthest separation. These effects can both moderate and amplify temperatures. (Water vapor also increase cloudiness which increase albedo, for instance).

MODERATION BY ATMOSPHERE: The atmosphere moderates temperatures as it stores heat. It also increase albedo by cloudiness and the circulation of the air redistribute hot and cold air systems. Worlds with fairly thick atmospheres and distinct greenhouse effects have smaller differences between day and night, but also between seasons and latitudes. Cloudiness can vary over the surface, and areas with few clouds have more temperature difference (deserts tend to fall in this category). If the atmosphere is dense enough, it will effectively counter almost all differences, axial tilt, rotation-based and latitudes. However, such worlds are also likely to have runway greenhouse effects.

MODERATION BY OCEANS: Oceans are very effective for heat storage, and the currents also moderate latitude differences. Thus, worlds with large oceans (and locations near such oceans) will have less temperature differences. Currents can modify global climate extensively. On Earth, the difference between polar and equatorial climate would be 10-15 degrees higher if the oceans and air masses didn't moderate. (A world with fast rotation and little oceans thus would have more extreme polar and equatorial climates) Oceans also serve to produce clouds, which in themselves moderate climate. Local climate is also strongly affected by oceans the further from an ocean one gets the larger the amplitude in temperature gets, especially on a seasonal basis.
MODERATION BY AXIAL TILT: If a world undergo seasonal change due to axial tilt, this will moderate temperatures. Worlds with low axial tilt have in general larger temperature differences than those with a significant tilt.
MODERATION BY SURFACE: While the solid surface is less good than oceans as heat storage, it still can store heat and the difference in surface structure is also important for local climate. Vegetation in particular moderate climate, the denser the better, by absorbing energy and slowly radiating excess heat and water vapor. On the other hand, ice caps serve to decrease the temperature by cooling the air, so they amplify temperature differences instead of moderating them.
CALCULATING SURFACE TEMPERATURES: This is an issue of severe complexity as there are so many factors to consider. I strongly suggest using these as a guideline only, not as some way of calculating exactly how cold or warm a specific place is. And to remember that there always are differences from day to day and over longer periods. The first step is to calculate the temperature for different latitudes. For simplicity, we use ten ranges of latitudes:

Range	1	2	3	4	5	6	7	8	9	10
Latitude	0-5	5-15	15-25	25-35	35-45	45-55	55-65	65-75	75-85	85-90
Modification (Low)	1.10	1.07	1.5	1.03	1.00	0.97	0.93	0.87	0.78	0.68
Modification (Average)	1.05	1.04	1.03	1.02	1.00	0.98	0.95	0.90	0.82	0.75
Modification (High)	1.02	1.02	1.02	1.01	1.00	0.99	0.98	0.95	0.91	0.87

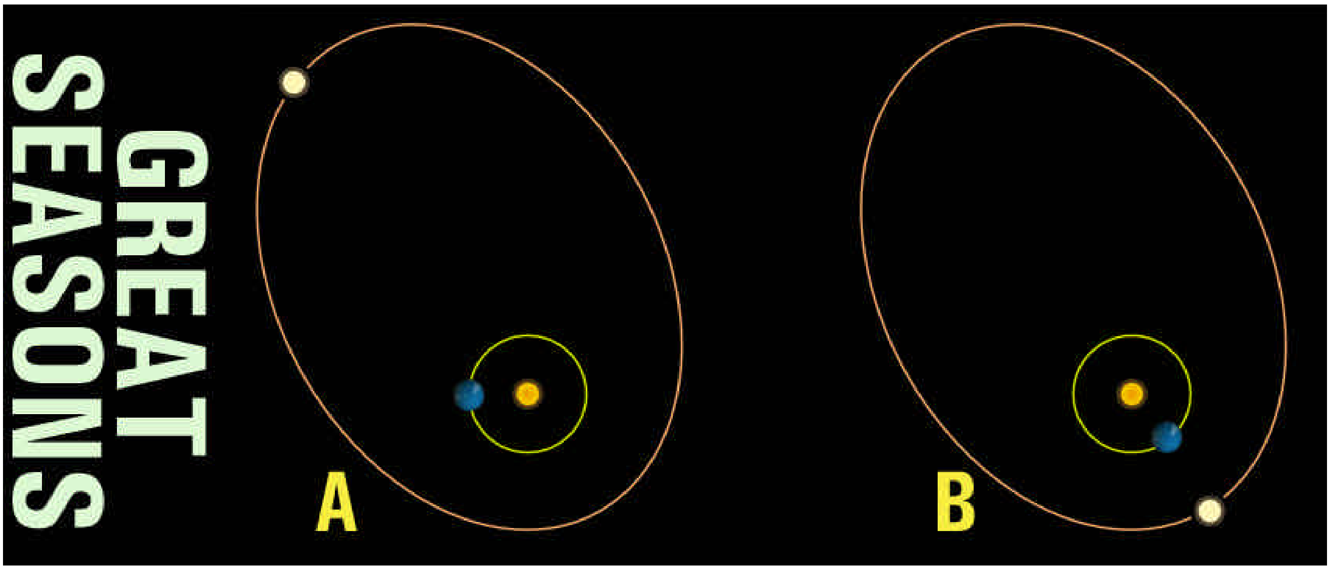
The three different modifications signify different planetary moderation potential. The Low Mod is intended for worlds with very little moderation (no oceans, fast rotation giving east-west weather patterns, low axial tilt, thin atmospheres), the Average Mod for worlds roughly Earth-like (part ocean, average rotation, average axial tilt, normal atmosphere) and the High Mod for worlds with large moderation (ocean worlds, dense atmospheres, slow rotation giving north-south weather patterns). Worlds with dense enough atmospheres (like Venus) would not moderate temperatures at all, just use 1.0 all over. Of course, you may want to extrapolate modifications for a world that is slightly less moderated than Earth, or perhaps which has very different hemispheres like one land and one ocean.

For every latitude use the surface temperature (in Kelvin) from 4.5.2 and multiply with the modification. Subtract 273 to get the temperature in Celsius. This is the base temperature for the latitude. For a specific location in the latitude, temperatures may be higher or lower, though. Ocean currents can raise or lower temperatures by up to ten degrees or even more in polar locations. Ice caps can cause a drop in temperatures of ten degrees as well, and highlands will be cooler due to elevation.

The next step is to find the seasonal effects. Seasonal effects based upon eccentricity are easiest to calculate by recalculating the average surface temperature (section 4) for closest and furthest separation. This temperature difference can be reduced on worlds with dense atmospheres and oceans, and if the eccentricity is small it can be ignored. Note however that in extreme cases of eccentricity the atmosphere and albedo of the world may differ with season.

The same sort of calculation can be done for binaries, thus part of the solar infall depends on how distant the other star is. The exact effects of binary systems can be very complex, the binary may well be eccentric and thus give longer "great seasons". The binary heat at closest separation is also likely to fall on the "night", so it will not only raise overall temperatures but also moderate night and day differences. The largest potential effects exists when a world orbits a fairly faint star which has a brighter companion, but even a fairly small change in solar infall in binaries could possibly trigger complex climatological effect growing ice caps, longer daylight period etc.

GAS GIANT CLIMATE
Unlike terrestrial planets, gas giants do not really have the same kind of climate, more of "weather" with large-scale convection. Nevertheless, weather patterns on gas giants are rather stable as there is no friction with the surface to slow them down, though the "bands" may move with time. Gas giants with strong convection (interior heat) have more violent weather, including large cyclones and anticyclones. Lighter regions on gas giants are usually those where air rises to form high clouds of ices, while the darker regions are those where air subsides and one can see down to lower clouds.
The dense atmospheres of gas giants are very good at absorbing and moderating heat. Thus, seasons play a much less significant role except perhaps in the uppermost regions of the atmosphere, and so does latitude and day length. Then, gas giants tend to rotate very quickly and this creates the typical banded pattern or winds in east-west direction and gas rising from the interior in some areas and sinking in others. The jet streams of gas giants can reach supersonic speeds, and the weather systems can certainly be far more violent than on almost all terrestrial planets, with immense storms and electrical discharges.
The closest analogy to "climate zones" of gas giants are directly attributed to depth into the atmosphere in other words the structure, pressure, moisture and heat. In some altitudes, gas giants may seem almost tolerable with water vapor and average temperatures and a more tranquil general environment. The lack of a true surface still leads to longer-lasting weather effects. Gas giants without a significant interior heat source will have far less convection and far less features.



Example of "great seasons" in a binary system. The world orbits a smaller main sequence star, while a larger brighter companion is in an elliptical orbit many times longer than the planetary year. In **A** the other star is at almost furthest separation, and aside from the bright nights the effect on the world is not big. In **B** , closest separation, the star would have a much larger influence on local climate, and one of the suns would be up almost constantly.

For the axial tilt-based seasons, the simplest way is to recalculate the "effective" latitude and then modify it. Lets assume that we are at 40 degrees latitude on a world with 20 degrees axial tilt. Thus, in the summer (when the sun is higher in the sky) the effective latitude is 40-20 = 20 degrees, while in the winter the latitude is 40+20 degrees = 60 degrees. Use the same moderation modifier as before for basic latitude temperature. Then, calculate the temperature difference for summer (by taking summer temperature-average temperature) and winter (by taking winter temperature-average temperature). These differences should be modified further depending on location and specifics of the world.

- If the location is one with much moderation due to oceans and wind patterns, you should diminish the differences by up to 50%. On the other hand, if there is very little moderation (for the world), like an interior desert, you should increase the difference by up to the same amount.
- If the location is within the tropics of a world with axial tilt below 30 degrees, you should diminish the differences by up to 75%. On the other hand, if the location is within the polar circles of a world with above 30 degrees axial tilt you should increase the differences by up to 100%, depending on how long the location is in "polar day" or "polar night", that is the sun does not set or never rises. For worlds with very large axial tilt and long years it may be advisable to use even higher modifications, though there will probably be moderating weather systems.
- If the local year is short (compared to Earth) and the world has a decently moderating atmosphere/hydrosphere (as per "average mod" for latitude), you should diminish the seasonal differences by up to 75%, depending on how short the year is and how moderated the world is. This simulates that the world hasn't had enough time to adjust to the seasons fully.
- It is possible that the area may have different on summer and winter. Ocean currents may shift with season, and so could weather patterns.

The rough summer and winter averages actually occur for a longer consequent time than the "averages", the equinoxes. It is easy to understand if one thinks how the "effective" latitude is at turning points at both summer and winter solstices. For calculating average temperatures on a location at a specific point, you have to extrapolate. If you will detail the world very thoroughly, it may be useful to create a basic temperature matrix like this one:

LATITUDE	90S	80S	70S	60S	50S	40S	30S	20S	10S	0	10N	20N	30N	40N	50N	60N	70N	80N	90N
BASIC TEMPERATURE																			
MAX SUMMER MOD.																			
MAX WINTER MOD.																			

For worlds with truly dense atmospheres, axial tilt will not matter. The surface will keep the same temperature regardless of season.

The third calculation is the effect of day length. This is not really affected by seasons and axial tilt *except* in one specific case large axial tilt that would cause extended sunlight periods at high latitudes. As the extended sunlight falls in at high angles, the heating is not that effective unless the axial tilt is very large. Otherwise, temperatures go up during the day and fall during the night. Worlds with very dense atmospheres ignore the effects of day and night temperatures just as they ignore latitude and axial tilt.

DAY LENGTH		Up to 20h	20h to 50h	50h to 250h	Above 250h	Maximum
No Moderation Mod.	Day	1.035+0.02/h	1.435+0.0005(h	1.45+0.00025/h	1.5+0.0002/h	1.75x
	Night	0.965-0.02/h	0.565-0.0005/h	0.55-0.00025/h	0.5-0.0002/h	0.25x
Low Moderation Mod.	Day	1.0+0.0035/h	1.07+0.002/h	1.13+0.0006/h	1.25+0.0002/h	1.6x
	Night	1.0-0.0035/h	0.93-0.002/h	0.87-0.0006/h	0.75-0.0002/h	0.4x
Average Moderation Mod.	Day	1.0+0.0009/h	1.018+0.0007/h	1.039+0.0003/h	1.099+0.0001/h	1.4x
	Night	1.0-0.0009/h	0.982-0.0007/h	0.961-0.0003/h	0.901-0.0001/h	0.6x
High Moderation Mod.	Day	1.0+0.0003/h	1.006+0.0002/h	1.012+0.0001/h	1.032+0.00005/h	1.2x
	Night	1.0-0.0003/h	0.994-0.0002/h	0.988-0.0001/h	0.968-0.00005/h	0.8x

The table gives the typical maximum day temperature and the typical minimum night temperature, as a modification factor to apply to the normal temperature for the region (in Kelvin). Obviously, the longer the day is the warmer it will become and the colder the nights will be. The hourly modification is calculated by seeing how many hours above the minimum for a particular column a world's day is, *not* the total hour length.
Example: A world has a rotation period of 34 hours, a surface temperature of 294K (+21 degrees Celsius) and average moderation. This means the 20-50h column, 14 hours above the minimum of 20 of the column. Day temperature maximum is 294 * (1.018+0.0007*14) = 302K (+29 degrees Celsius). Night temperature minimum is 294 * (0.982-0.0007*14) = 286K (+13 degrees Celsius).

Worlds with **No** moderation have no atmosphere and no real way of "storing" heat. Most airless worlds fall into this category. They can cool and heat slightly differently depending on the surface rocks, though.
Worlds with **Low** moderation have thin atmospheres with small greenhouse effect, little cloud cover and likely small or no oceans.
Worlds with **Average** moderation have normal atmospheres, fair amount of cloud cover, some greenhouse effect and/or oceans.
Worlds with **High** moderation have dense atmospheres, extensive cloud cover, significant greenhouse effect and/or huge oceans.
Maximum value shows that regardless how long the rotation period of a world is, it won't get warmer or cooler than this. Worlds with moderation will have lower maximums and minimums as some sort of circulation will exist.
Just as for latitude, it is certainly possible to interpolate moderation (Average-High, etc). There will also probably be regional differences inland areas on a world with few clouds and low moisture will have greater day/night temperature differences than cloudy, moist coasts.

It should be noted that maximum temperature isn't necessarily at noon, but slightly later as the moderation of the world delays the heating somewhat. For Earth, we are talking a delay of one or two hours. Worlds with denser atmospheres would have more delay in extreme cases at nightfall. The minimum temperature is just before dawn, not at midnight.

MOISTURE: The presence of humidity in an atmosphere is very important for climate, and thus for landscape, ecology and landforms. It is also very important for weather, as high moisture content creates a more variable weather due to cloud formation, precipitation etc. When the air cools off, by moving over a cooler surface, for instance, or by being forced upward at a mountain range, or just by nightfall, the moisture will fall out as rain or snow. The warmer it is the more moisture will also evaporate from the surface. While I with moisture primarily mean water vapor, it can certainly be any cloud-forming component like methane on cooler worlds. Moisture will not always be spread equally over a world's surface, but it will be moved by weather systems so it can fall as precipitation. More about that in SIX/3. For now, we need to remember that the moisture on Earth-like worlds is dependant upon evaporation from the land, from plants, from ice caps and in particular, from oceans. How it is transported after evaporating decides how the climate zones will look. Mountain ranges often create "rainshadows", drier areas, as the moisture content drops when the air passes a mountain range and much fall as precipitation. The height and orientation of such mountain ranges decide just how dry the interior gets.
POLAR CAPS: Many non-hothouse worlds will have polar caps of some kind. The low solar infall at the poles makes them significantly colder and often cool enough to have frozen water, ammonia, carbon dioxide or similar compounds. The exact composition of polar caps depend on the general coolness of the world. Very cold worlds could have methane or nitrogen-ice caps- Polar caps can be permanent (they exist year-round) or seasonal (they only exist in the cooler seasons). Seasonal polar caps are decimeters or meters thick only and highly depending on moisture.
Worlds with low axial tilt has potential for bigger polar caps than worlds with average tilt, and oceans at the poles tend to diminish the size of polar caps (as the water moderates the temperatures), while land at the poles tend to provide for bigger polar ice caps. Note that a warm Earth-like world may not have any polar caps at all, temperatures at the poles must fall significantly below 273K

(O degrees C) for an extended time to create polar caps based upon ice and the summers cannot be warm enough to melt the ice in entirety.

Polar caps of all kinds lower temperatures (due to the lower albedo and the cooling effect). This is most notable close to the ice caps.

GEOTHERMAL HEAT: On some worlds the climate may be affect by not only solar infall but also heat from the surface due to volcanism. The biggest global heating effect on volcanism is to provide more greenhouse gasses (which warm the atmosphere) and/or more dust (which cools the atmosphere). On a regional and local level, however, the heat released can affect climate and warm areas to higher temperatures than they should have. This can have distinct effect on local cloud cover and precipitation patterns. On very young worlds, where the surface has not yet cooled off, difference in cooling in various regions will be profoundly affecting climate.

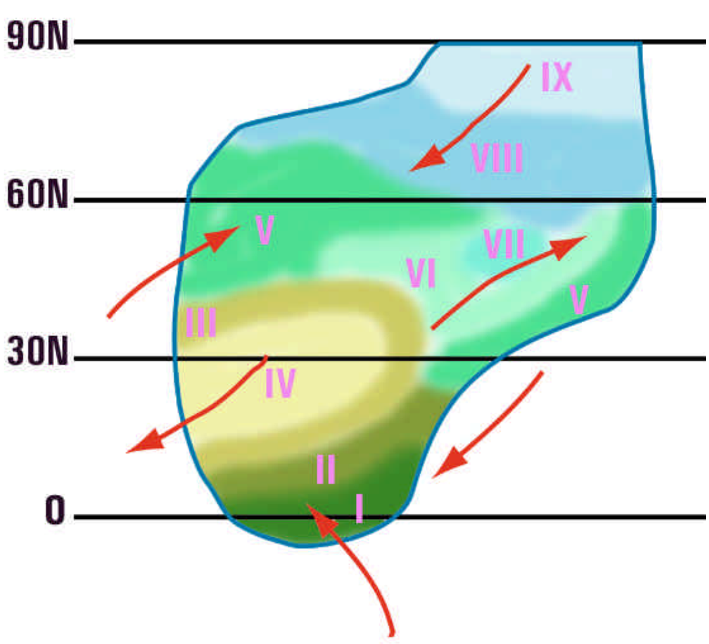
CLIMATE ZONES: For further development of a world's surface, it is necessary to evaluate the climate zones of a world. There are several systems of climate zones the *Köppen* system is perhaps the most well known, which divides Earth climate into five basic types and those in turn into several subgroups. It is often used for vegetation, but as we here will use climate for geomorphology we will use another simpler system of nine basic zones. These zones are based upon Earth-climate with moisture based upon water vapor, but will often be applicable to other worlds too. A further discussion of geomorphology for the zones is in chapter SEVEN, and of vegetation in chapter EIGHT/3. The amount of precipitation in an area depends as already have mentioned on presence to oceans, geographical location, wind patterns and how much humidity the atmosphere holds.

TYPE	**DESCRIPTION**	Mean Annual Temperature (K)	Mean Annual Precipitation (mm)
I: Hot Humid	This is the zone dominated by rain-forests on Earth.	>293	>1500
II: Hot Wet-Dry	This is savanna-monsoon climate.	>293	600-1500
III: Warm Semi-Arid	This is half-desert and warm Mediterranean climate.	>293	300-600
IV: Warm Arid	This is desert climate, Sahara-style.	>293	<300
V: Moderate Humid	This is Earth's temperate climate, dominated by forests.	273-293	>400
VI: Moderate Dry	This is grasslands and steppes.	273-293	100-400
VII: Cold Arid	This is cold desert.	<293	<100
VIII: Periglacial	This is tundra-like climate.	<273	>100
IX: Glacial	This is icecap climate.	<273	Varies

Mountain climate depends upon their elevation (as temperatures drop with altitude) and location, and how dense the atmosphere is Airless worlds do not have much of climate zones (the effect on geomorphology and vegetation is certainly not mattering much), though they could be classed as glacial, cold arid or warm arid.

A MODEL CONTINENT: The picture below shows an idealized and simplified continent on a world with a similar weather/ocean pattern and temperature as Earth. Using the dominant weather patterns, continent shapes (see NINE/2) and the temperatures this can be done for worlds in general.

MODEL CONTINENT



The red arrows show dominant winds (see the Surface Wind illustration earlier in this chapter).

The Roman numerals refer to climate zone classification.

This continent has no significant mountain ranges which otherwise would affect climate, and is of equal elevation all over.

REFERENCES

As this isn't a scientific article but a tool for creative system-building influenced by everything from press releases, popular astronomy and often conflicting scientific schools of thought, I've taken the liberty of making the reference list a bit manageable, more of "Some Suggested Further Reading Which I've Been Inspired By".

ASTRONOMY:

A decent college textbook in astronomy is invaluable. Many things like stellar evolution and orbital mechanics that this document barely touches on are covered in such works. Two good such textbooks are *Abell's Exploration of the Universe* (by David Morrison, Sidney Wolff and Andrew Fraknoi) and *Astronomy: The Cosmic Journey* (by William K. Hartmann and Chris Impey, it includes a CD too). The best multimedia astronomy computer program is *RedShift 3* (Maris Multimedia) and you can find it in any decent software store for about the cost of a good astronomy textbook. RedShift 3 includes the *Penguin Dictionary of Astronomy* too.

More specifically tying into the ideas of this document are *Worlds Without End* (by John S. Lewis), an interesting book from 1998 about how different planets would look and act. Another recent book (2000) is *Rare Earth* (by Peter D.Ward and Donald Brownlee), which discusses how rare advanced life could be. Both these books feature geoscience and biology as well and are worth looking into. For graphical inspiration, see *Cycles of Fire* (by William K.Hartmann and Ron Miller). The book is slightly dated (late 80's) but the illustrations are very nice.

The bolometric correction (ONE/1, Reference) is taken from Cameron Reed *The Composite Observational-Theoretical HR Diagram* (by Cameron Reed, in *The Journal of the Royal Astronomical Society of Canada,* February/March 1998).

GEOSCIENCE:

Some of this is certainly covered in the literature above, but not to the degree necessary for understanding the processes. One very popular and basic textbook on physical geography that covers about all Earth science divisions is *Elements of Physical Geography* (by Arthur N. Strahler and Alan H.Strahler.) For more on climate and meteorology, another classic is *Atmosphere, Weather and Climate* (by Roger J.Barry and Richard J.Chorley). It is not an overly funny read, but a thorough one. Both these books are describing the Earth, but the basic processes and concepts are the same on all worlds. For a more specialized read on geomorphology I recommend the slightly complex but amazingly wide-scope *Global Geomorphology* (by Michael A. Summerfield). It has a chapter on extraterrestrial geomorphology. You probably would like to read a more basic physical geography book first, though.

The discussion of atmospheric effects on light is based upon information from *Remote Sensing and Image Interpretation* (by Thomas M.Lillesand and Ralph W.Kiefer).

BIOLOGY:

A basic read on biology is the imaginative titled *Biology* (by James M.Barret, Peter Abramoff, A. Krishna Kumaran and William F.Millington). It is Earth biology, of course, but as for geoscience I'd say that it is necessary to get a grip on our own world before one makes up alien worlds. Simple microbial life forms can be further explored in *Microbiology* (by Daniel V.Lim); a good but a bit dated overview of bacteria, viruses and simple eukaryotes. The edition I have does not cover the very small rock-dwelling bacteria. Some knowledge about biochemistry can be useful too; *Biochemistry* (by Lubert Stryer) is a typical phone-book size textbook though you need some knowledge about basic chemistry first. Still, it may be a more interesting read to focus upon the zoology before getting into excessive detail. One zoology textbook that is easily read is *Zoology* (by Steven A. Miller and John P. Harley).

Discussions about alien life are generally more in the astronomy literature. One book, which is more of a collection of such ideas about extraterrestrial life (with a certain historical/SETI slant), is *Here Be Dragons: Scientific Quest for Extraterrestrial Life* (by David Koerner).

GENERAL SCIENCE:

A collection of formulae and data is also likely to be useful. There are a lot of these, like *Book of Data* (Nuffield Advanced Science). A good encyclopedia often has much scientific references too in my own country, *Nationalencyclopedin* is the best one.

PUBLICATIONS:

There are tons of periodica about geoscience and astronomy, but they are typically either very scientific (and thus rather hard to digest) or so much popular science that don't present a decently complete picture. I'd recommend anyone to read up-to-date textbooks (say, from the 90's) on the subjects first before putting too much weight on magazine articles, it is very easy to get overly influenced by the often biased and simplified picture these articles provide. Still, magazines such as *Scientific American* often can serve as inspiration or point toward "heavier" science.

WEB SITES

Many news releases can be found on astronomy web sites (NASA, ESO, SpaceViews, various universities, newspapers, periodica and observatories), of which there are too many to mention here. Use a search engine and locate the many link pages. There are also several sites that are devoted to system generation, exoplanets, astrobiology and such issues. They are often very nice, though their content varies.