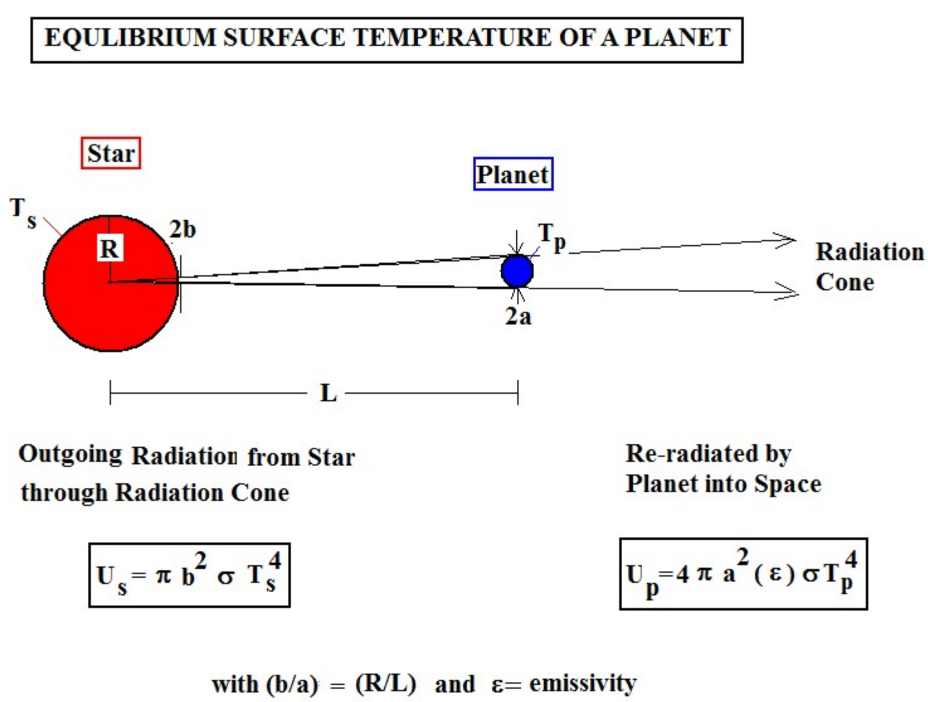
October 12, 2010 –What is the Goldilocks Zone for planets orbiting about a central star?

In the last decade or so astronomers have found the presence of several hundred planets orbiting about stars as detected by optical occultation methods. Most of these planets lie in regions about the central star incapable of supporting life , however, some probably do. The presence of such planets lends strong support for the nebular hypothesis of planetary formation first proposed by Kant and Laplace. In this theory a distributed disc of matter collapses by gravitational collapse leaving a central star plus a rotating disc of matter which eventually condenses to planets and moons all lying in essentially the same plane(the ecliptic). By the conservation of angular momentum most of the resultant planets will be spinning with a rotation axis nearly perpendicular to the ecliptic. This rotation allows a nearly uniform distribution in temperature at a given latitude of the planet and **should make the probability of extraterrestrial life quite likely provided the planet is not too close or too far away form the central star.** The zone where life is possible has been termed in the literature as the **Goldilocks Zone**. The term originated with the English writer Robert Southey who first published the fairy tale “Goldilocks and the Three Bears” in 1837.

Let us determine the approximate range of this Goldilocks Zone. We begin with the following picture-



In the figure we show a radiating central star of radius R and surface temperature T_s. According to the Stefan-Boltzmann law, the radiation coming from this star in the cone just intersecting a planet of diameter 2a at distance L from the star center is-

$$U_s=\pi b^2\sigma T_s^4 \quad \text{with} \quad (b/a)=(R/L)$$

Here $\sigma=5.672\text{x}10^{-8}$ w/m^2 is Stefan constant . We treat the star as essentially a black body for which the surface emissivity is $\varepsilon=1$. The average radiation per area reaching the planet outside of its atmosphere in watts per sq.meter will thus be the radiation constant-

$$S= U_p/(\pi a^2)=[\sigma T_s^4 R^2]/L^2$$

For the earth-sun system this radiation constant equals-

$$S=[5.67\text{x}10^{-8}\cdot(5800)^4](6.96/1496)^2=1.38 \text{ kw/m}^2$$

Handbooks give the value as 1.3677 kw/m^2. The radiation which finally gets through to the earth's surface is only about 1 kw/m^2 or 0.1 watt per sq.cm.

Let us next use a simplified model which assumes a rotating planet without atmosphere. In that case the modified incoming star radiation U_s just equals that radiated outward by the planet into space. This re-radiation equals $U_p=4\pi a^2\varepsilon\sigma T_p^4$, where T_p is the planet's surface temperature and ε its surface emissivity. Doing the math one finds-

$$T_p=T_s \,\text{sqrt}(b/a)/[4\varepsilon]^{1/4}=T_s \,\text{sqrt}(R/L)/[4\varepsilon]^{1/4}$$

One can use this approximate model also for planets with atmospheres by adjusting ε to values near unity. As an example, the earth's average surface temperature is 288K which implies an effective emissivity of $\varepsilon=0.89$ according to the simplified model above.

Next we look at the zone about a star where a planet might sustain life as we know it. The temperature range will have to be between the freezing and boiling point of water and a supply of carbon (probably in the form of methane) and the presence of oxygen and water will be needed. In terms of absolute temperature we require a planet surface temperature range-

$$273 \text{ K}<T_p<373 \text{ K}$$

The goldilocks zone for life will thus be-

$$\mathbf{(R\, T_s^2)/ (373^2\sqrt{4\varepsilon}) < L< [RT_s^2/(273^2\sqrt{4\varepsilon})}$$

For the earth-sun case where L= 1AU=$1.496\text{x}10^{11}$m and R=$6.959\text{x}10^8$m=

$4.65x10^{-3}$AU and the sun surface temperature is T_s=5800K , the Goldilocks zone with ε=0.89 will be-

$$0.5957 < L < 1.112$$

when expressed in AU units. Ones notes that our nearest planetary neighbors are Venus at L=0.72 AU and Mars at L=1.52 AU, which puts one near the edge and the other beyond the Goldilocks zone. Because of a run-away greenhouse effect the surface temperature of Venus is actually much hotter at 726K than predicted by the formula and the average temperature on Mars is a chilly 250K. Neither planet is likely to support any kind of life. We are extremely fortunate to have the earth located where it is. Of course if it weren't at the radial distance from the sun it is at, there would be no life possible within our solar system.

These facts bring us to the next aspect of the original question. Do Goldilock Zones exist outside of the solar system. The answer must be in the affirmative since there are an estimated 200 billion stars just in our own galaxy(Milky Way). **Several million of these must have planets falling into the Goldilocks range where life becomes possible.** That intelligent life should have evolved over the last ten billion years on some of these planets possessing the required carbon, methane, and oxygen seems highly likely. A few of these civilizations will be far superior to our own and posses far more scientific knowledge than we do. **However, the chance of actual physical contact appears highly unlikely because of the enormous distances involved, although listening for intelligent signals (SETI type projects) would appear to be worth pursuing.**

Back in 1961 Frank Drake came up with a probability equation for the number of advanced civilizations which may exist within our galaxy. His formula, now known as the Drake Equation (and slightly modified by us below), says that the number N of advanced civilizations existing in the Milky Way are-

N=(num.stars in our galaxy)·(fraction having planetary systems)·(fraction of planets capable of supporting life)·(fraction where life evolved)·(fraction with higher intelligence)·(fraction with scientific knowledge exceeding our own)

Putting in our best estimates we find-

$$\mathbf{N=(2\cdot 10^{11})\cdot(0.3)\cdot(0.1)\cdot(0.01)\cdot(0.001)\cdot(0.01)=600}\quad .$$

This number suggests that we are not alone but that we are a very long way from our nearest alien neighbors. Taking the volume of our disc galaxy as approximately $V=16x10^{12}$ light years cubed and assuming a uniform spread of these 600 civilizations throughout the galaxy means that the nearest neighbor is some 3000 light years away from us. Thus the answer to Enrico Fermi's question of **"Where is Everybody?"** made by him over 50 years ago is that **other civilizations probably do exist but that there is absolutely no way to make physical contact now or in the foreseeable future.** Likewise for such an alien civilization to detect our presence would take another three thousand years or so since humans did not start broadcasting radio waves until about a hundred years ago.