Hey, science aficionados, this is interesting…and it needs a little critical thinkinga
This is a story of a nearby star and its planet. Here is the basic story; I've imbedded links to one of our websites that give more detail, mostly mathematical.

Recently, astronomers using the European Southern Observatory telescope in northern Chile, detected a planet orbiting the star nearest to our solar system, Proxima Centauri. The way they detected the planet, by the tiny wobble it causes the star along our direction of view, is very interesting, though not the topic I'm following up here. The star and its planet are 4.25 light-years away, so, still an extreme distance for any probe to reach that can hit even the highest speeds our spacecraft attain. Nonetheless, astronomers and their biology/physics colleagues are wondering if this planet can sustain life. (The bio/physics people call themselves "exobiologists," with "exo" meaning "outside," as in considering what's "outside our planet Earth.")

It's a weird star and a weird planet. The star is cool, about ½ the temperature of the Sun, and very small, about 1/6 the diameter of the Sun. The planet is very close to the star, about 24 times as close as our Earth is to the Sun. This helps make up for the weak radiation from the star that otherwise would provide little warmth and little light that life (as bacteria) could use for photosynthesis…and, of course, photosynthesis by bacteria and plants keeps any higher forms of life alive, providing food.

We can calculate how much energy gets to the surface of the planet, thanks to the discoveries of physicists Max Planck, Albert Einstein, Josef Stefan, Ludwig Boltzmann, and others. We consider the star as a "black body," odd, perhaps for a bright body, but it means that it emits electromagnetic radiation (light, infrared, radio waves, etc.) as we may say without preference for which kind. The intensity of radiation as energy emitted per area of the star's surface per time is proportional to the 4^{th} power (square of the square) of the temperature. For one, it means that the star emits only about 7.5% as much radiation as our Sun does, per area. Now, the energy density falls off with distance, as if we divide by the square of the distance. The short answer is that the intensity of raw energy in starlight at the planet is almost as much as that of our Sun's energy reaching the Earth – about 90% as much. I've written up some details in a link.

Calculating how much light the planet gets that can be used for photosynthesis is trickier. We have to assume that life is carbon-based, from a wide array of arguments based on chemistry. Consequently, the radiation usable in photosynthesis has to be pretty energetic, with wavelengths similar to visible light. I assume that bacteria on Proxima Centauri b can use light with wavelengths as long at 850 nanometers, nm (our green plants on Earth need more energetic light, with wavelengths of 700 nm or less). To my surprise, I estimate that there's light about 32% as abundant as on Earth, enough for a vibrant ecosystem if all other conditions are right.

A couple of problems: First, the planet is so close to the star that it is likely "tidally locked" by the star's gravity. The star pulls a bulge on the planet and then tugs the planet as if on a handle. The Earth does the same thing to our Moon, so that we only see one side of the Moon. If it's true for Proxima Centauri b, then one side constantly faces the star, getting very hot, and the other side faces away, getting extremely cold. This doesn't happen on Earth, so that the average area on Earth gets only ¼ as much energy as an area directly facing the Sun (the Earth, with radius *r*, is nearly spherical and occludes an area of πr^2 but the energy gets spread over its total surface area, $4\,\pi r^2$). Also, the Earth doesn't absorb all the energy streaming in from the Sun. The Earth, then, viewed from space, has an average temperature of -18 degrees Celsius (^oC) or about zero degrees Fahrenheit. It's warmer, on average, by 33^oC or nearly 60^oF, thanks to our greenhouse effect from CO_2, water vapor, and more. On Proxima

Centauri b, the area directly facing the star fries, but, at areas angled away from the star the temperatures might be modest. This is a proposal from the exobiologists. This requires some special conditions on how heat moves around the planet, much as it moves around the Earth through the atmosphere and oceans. I've estimated a range of angles and of corresponding land areas where temperatures might range from just above freezing to about 80°C, toasty but livable for some extremophile bacteria as you might find in hot pools in Yellowstone National Park. The zones cover about 13% of the surface.

Second, Proxima Centauri flares up massively, which can blow away the atmosphere on the planet. This could drive off the water as vapor, reducing the medium in which life exists. Loss of water would also severely reduce the greenhouse effect needed to keep the planet warm enough to avoid freezing solid; we'll look at that a bit more, later. The flares could also cause heating problems, periodically scalding the surface. Solar flares reaching Earth do negligible heating but do bombard our surface life with some nasty radiation in the form of charged particles. This is even more of a problem.

There are some other big ifs. Can the planet maintain its own magnetic field to protect life from cosmic rays and solar flares, as on Earth? Earth has a nice spin, helping with its interior dynamo making our magnetic field. Proxima Centauri b might rotate relative to the stars fast enough around its star to maintain a dynamo; after all, it appears to orbit the planet in only 12 days.

Overall, let's say that Proxima Centauri b is an interesting find. Don't count on life being there, nor on visiting it, but think about how life might evolve elsewhere…and, more so, think about how we might keep our planet livable with our unique physics, chemistry, and biology that we are changing a lot! Oh, and by the way, the star is pretty dim; you need a telescope to gather about 100 times as much light as the naked eye does.

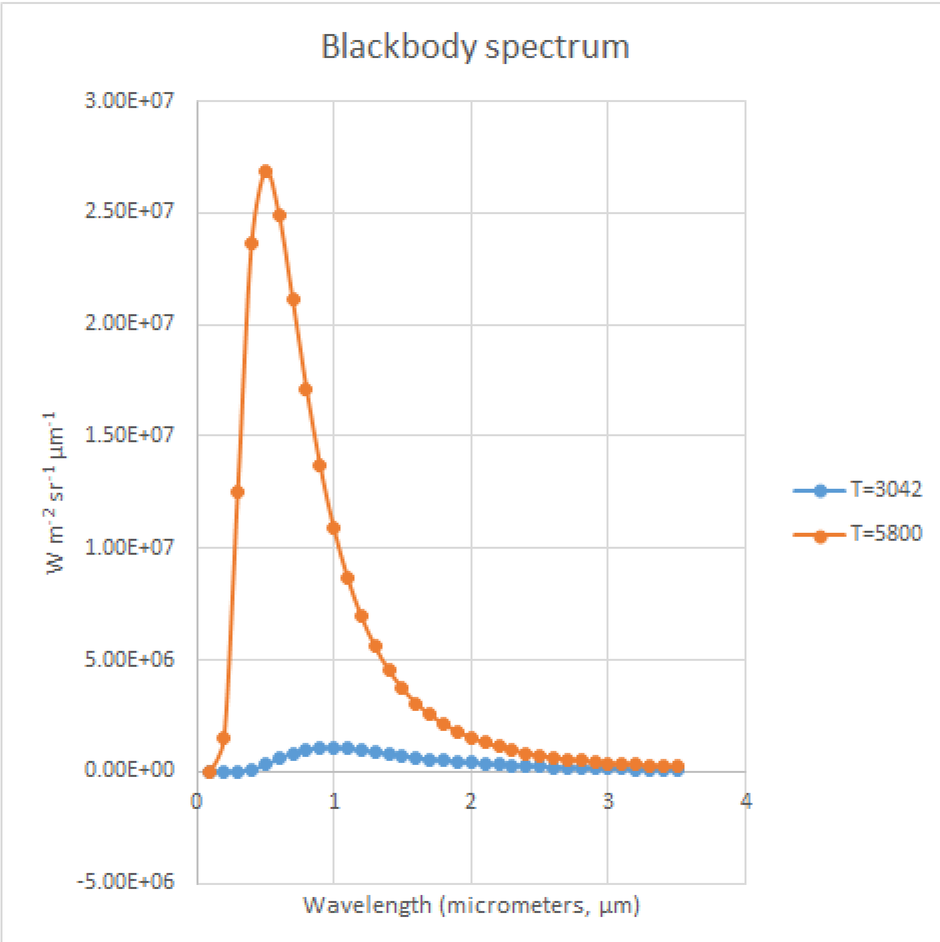
The active links in this essay lead to detailed discussions that extend to many topics, even Snowball Earth, LEDs, geothermal energy, and the discovery of the photon.

by Vincent Gutschick, Ph. D., Caltech
24-29 August 2016
For the Las Cruces Academy, Inc.

What's a black body?

A black body, in the language of physics, is a body that absorbs all light incident on it. By a principle of physics called microscopic reversibility, this body also emits light of all frequencies or wavelengths. It does not emit equally at all wavelengths but in a universal pattern of intensity that depends only upon the temperature of the body. The Sun is very closely a black body. Most other physical objects, even a book, our skin, or soil, are close to acting like a black body at long wavelengths (in what's called thermal infrared – obviously not all these look black in the visible range of radiation). Other emitters are more selective, we may say. A laser is the epitome of this, emitting radiation (light or other electromagnetic radiation) only in a narrow range of frequencies or wavelengths. Closer to everyday experience, fluorescent and LED lights in a home emit light in a few distinct wavelengths or colors, but our eyes interpret the mix as nearly white light. You can split up the light from these lamps with a simple prism or even odd edges of your eyeglasses. Here I reproduce a blackbody spectrum at two temperatures, that of the Sun, near 5800 K, and that of Proxima Centauri, at 3042 K. In astronomy and in much of physics, the measure of temperature is the Kelvin. One Kelvin spans a temperature range of 1°C or

1.8^{o}F. Kelvin differs from Celsius in starting at absolute zero, where all thermal motion stops and only quantum motion persists.

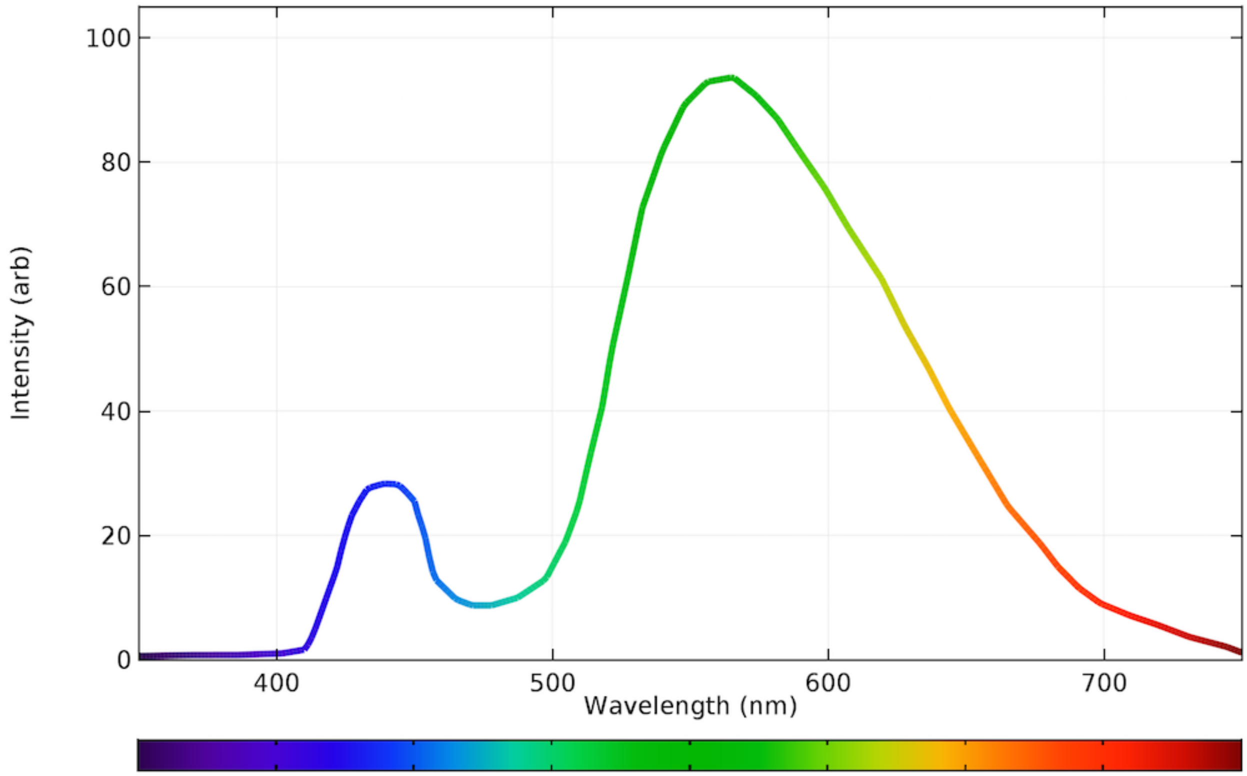


The values in the graph were calculated from the known equations for a blackbody,

$$\frac{dI}{d\lambda} = \frac{2hc}{\lambda^5} \frac{1}{(\exp(hc/[\lambda kT]) - 1}$$

If you haven't had calculus, this formula might not mean too much to you. Basically, *dI/dλ* is the increment in energy flow, *dI*, from considering a small range of wavelength, *dλ*. There are several universal physical constants, h, which is Planck's constant (connected to the finding that all energy is quantized!), c, the velocity of light, and k, Boltzmann's constant (connected to how temperature is related to energy). These all have fascinating stories of their own, which I won't go into here. In any case, you can see that a hot star such as our Sun puts out much more energy per area than a cool star such as Proxima Centauri; the total energy output is proportional to the area under the curve for each star.

For comparison, here is the spectrum of a typical LED lamp:



This graph came from https://www.comsol.com/blogs/calculating-the-emission-spectra-from-common-light-sources/.

The fourth-power law for radiation

It's a simple law, determined by almost countless observations, that a blackbody emits energy at a rate proportional to the 4^{th} power of its temperature. The temperature of note is the absolute temperature, measured from absolute zero, in Kelvin. The freezing point of water in normal conditions is 0^oC, which is 273.16K; to get the absolute temperature, add 273.16 to the Celsius temperature. If you wish to work in English units (used now only in the US, Liberia, and Myanmar), absolute zero is -459.69^oF. So, the absolute temperature in the English system is in degrees Rankine; add 459.69 to the Fahrenheit temperature to get this value.

There is a universal constant of proportionality, the Stefan-Boltzmann constant, usually denoted with the symbol σ:

$$I = \sigma T^4$$

Here, *I* is the amount of energy emitted per unit by per unit area of the body. In international (metric) units, σ has the value and units of 5.67×10^{-8} watts per square meter per Kelvin to the minus fourth power. Here I've used exponential notation, common in science, in which "10 to the power *n*" (here, n is -8) indicates basically the number of decimal places to move, positive to the left and negative to the right. Thus, 5.67×10^{-8} is 0.0000000567; similarly, a million is 1×10^6, or 1000000.

The consequences of the 4^{th}-power dependence of radiation are rather dramatic. An object acting like a blalckbody at room temperature, near 25^oC or 77^oF or 298.16K, emits electromagnetic radiation (mostly as weak thermal infrared, not light, obviously) at a rate of 442 watts per square meter ($W\ m^{-2}$). So, the floor of your home at this temperature emits at this rate. For a square meter (about 1.2 square yards in English units), that's about half the power of a hair dryer. You don't feel this because, while you're absorbing radiation from everything around you, you're emitting at a similar rate. The net effect of gaining and losing thermal radiation is commonly near zero. You really notice it only in the shade under a clear sky, which emits much less thermal radiation, making you feel colder than the air temperature alone seems to merit. Now consider the Sun. At a temperature T=5800K, it emits 64 *mega*watts per square meter, or about 145,000 times the rate of that floor. This, or course, is enough to fry anything we make. The density of energy per area decreases with distance, as the inverse of the distance squared, i.e., as $1/r^2$, where *r* is the distance from the center of the sun. So, at twice the radius of the Sun, the radiation is only $1/4^{th}$ as intense. At the distance of the Earth from the Sun, which is 214 times the radius of the Sun, the radiation is down to a mild 1370 watts per square meter when one faces the Sun directly and is sitting above the atmosphere. That's the right amount to keep our planet at a moderate temperature.

Energy balance of a planet

We can look at how much energy hits an area of planet Proxima Centauri b and gets absorbed. We'll need to know the temperature of its star, Proxima Centauri, and some geometry – how big is the star (diameter or radius) and how far out from the star this planet orbits. There are many interesting steps here, in how science can let us figure these out:

- How does this energy flux work in the Sun-Earth system?
- How intense is the radiation at the surface of Proxima Centauri?
- How intense is it at the planet Proxima Centauri b?
- How warm does this keep the planet?
- Backtracking:
    - How did we estimate the size of the star?
    - How do we estimate the distance at which the planet orbits the star?

At the Earth: Let's first look at solar energy hitting the Earth and being absorbed, for comparison. As I noted in the previous section about the 4^{th}-power law for a blackbody emitting radiation, the face-on radiation from the Sun at the Earth's mean distance is 1370 W m^{-2}. Now consider that the Earth presents a profile or silhouette with an area equal to the area of a circle with its radius, πr^2. Now, the Earth rotates, spreading out the radiation, on average, over its total surface area, which is $4\pi r^2$. So, again on average, the surface of the Earth gets ¼ of that intensity (flux density), or about 342 W m^{-2}. Only a little less than 70% of that reaches the surface because of clouds and because the surface (oceans, forests, sand dunes, …) reflects a lot back. So, the average solar radiation absorbed, call it *E*, is about 240 W m^{-2}. We can use the blackbody equation in reverse to calculate what the temperature of the Earth looks like. Mathematically, we can say

$$T^4 = E/\sigma \text{ or } T = (E/\sigma)^{1/4}$$

The exponent ¼ means the same as taking the square root and then again. Plugging in the numbers E = 240 W m^{-2} and σ = 5.67x10^{-8} W m^{-2} K^{-4}, we get *T* = 255K, which is -18^{o}C or nearly 0^{o}F! We'd be frozen without the greenhouse effect that adds about 33K *at the surface* to bring us up to an average of +15^{o}C or 59^{o}F. That average applies over day and night, all seasons, and all locations on the Earth, not to just where you live, of course. We'll go into the greenhouse effect shortly. By the way, this average *radiative* temperature of the Earth of -18^{o}C is what one sees from space, above the atmosphere.

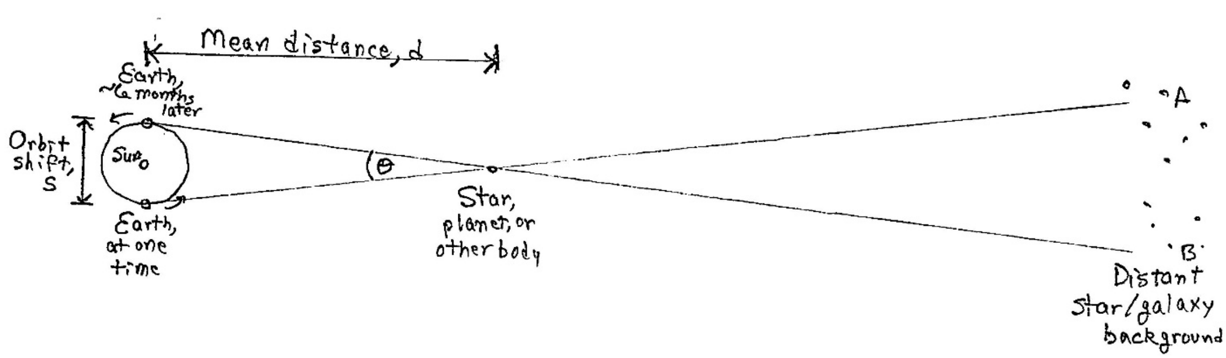
Intensity of radiation at the star Proxima Centauri: Back to comparing the planet Proxima Centauri b to the Earth, for the warming radiation it receives: we have some steps to go through. First, let's calculate the intensity of radiation (energy flux density) emitted at the surface of Proxima Centauri, the star. At a temperature of 3042K, this is 4.855 meagawatts per square meter, a lot less than the Sun but a factor of about 13. You might ask how the temperature was measured, since no one flew a spacecraft to the star with a thermometer. It was by looking at the intensity distribution of radiation at different wavelengths (and assuming that the star acts like a blackbody, pretty good for stars with their known composition of gases). Note further that the variation in star temperature explains the variation in star color. The wavelength (hence, color) at which the emission of radiation peaks is directly proportional to the absolute temperature. The energy per light particle or photon is inversely proportional to the wavelength; blue light has the shortest wavelength, then green, then yellow, then red, to use a broad brush. Blue stars are the hottest, yellow stars like the Sun are inbetween, and red stars are the coolest…and the Sun's yellow dominant light, including as it does the blue, the red, and all, we take as the norm, white light.

Intensity at the planet: Continuing: we now calculate the intensity of radiation at the orbital distance of the planet. We have to know two things: the radius of the star, r_{star}, and the radius of the planet's orbit, r_{orbit}. Then we can multiply the intensity of the radiation at the star's surface by the factor $f = (r_{star}/r_{orbit})^2$. To jump ahead for a moment, the radius of the star is estimated as 101,000 km or about 63,000 miles or about 1/7 the radius of our Sun. The radius of the planet's orbit is estimated as 6.4 million km or about 4 million miles, giving the factor f as just about 1/4,000. That brings the intensity at the planet's orbit to about 1210 W m^{-2}. That's 88% of what we get at the Earth's orbit.

How warm will this much starlight keep the planet?: We can do the same calculation as we did for the Earth. We have to assume the fraction of radiation absorbed by the planet (surface and atmosphere). in the absence of other information, we might assume it's 70%, as on Earth. This gives an average absorbed radiation rate of (1/4)*(1210 watts per square meter)*0.7 = 212 W m^{-2} (rounded). The radiative temperature of the planets' surface will average 247K, which is -26^{o}C or -15^{o}F! We'll see two considerations a bit later in the main essay – the greenhouse effect, and the fact that the planet is stuck with one face to the star!

Backtracking: how do astrophysicists estimate the size of the star and also the radius of the planet's orbit?

Step 1: estimate the distance to the star ("estimate" = "measure" – all measurements are formally estimates, with a finite precision and finite accuracy). There's detail at http://hypertextbook.com/facts/KathrynTam.shtml. Basically, it's a direct geometric measurement that's been done for many nearby stars, as well as to planets in our own solar system.



The lines from the Earth toward the star and continuing beyond are lines of sight of a telescope on Earth. The star (or other celestial body – a planet, for example) is sighted from Earth against the background of far more distant objects in the sky. This is done while the Earth is near one extreme of its orbit, in the direction perpendicular to the direction to the star. (It's not practical to view the star at a grazing angle through the atmosphere, so that the diagram is an exaggeration; one views the star at higher elevations.) Then, much later, the star is sighted again. It appears to have moved relative to the distant objects. First it appeared near the distant object *A*, at least in projection, and later, near distant object *B*. The angular distances between *A* and *B* are readily measured; they are the same as the angle ϑ (theta) in the sketch. By geometry, *d* equals the orbital shift, *s*, multiplied by the sine of this angle. Since the angle is extremely small, this sin(ϑ) equals ϑ itself, when ϑ is expressed in radians (one radian is an angle subtended by an arc that is the same length as the radius of the circle; there are then 2 pi radians in a circle, with one radian being 360 degrees divided by 2 pi, or about 57.29 degrees). For Proxima Centauri, the angle is tiny but it is measurable with excellent telescopes, though not amateur telescopes. Working backwards (not having measured the angle myself), I find that it is, again in radians, (2 Earth orbital radii)/(4.25 light-years). Using 1 Earth radius as 149 million km and figuring 1 light-year as

$$4.25\,years * 3.16x10^{7}\,s/year * 0.3\,million\,km/s \approx 40\,million\,million\,km$$

We can then divide, to get

$$\theta = \frac{2*149\,(million\,km)}{40\,million\,(million\,km)} = 7.4x10^{-6}\,radians$$

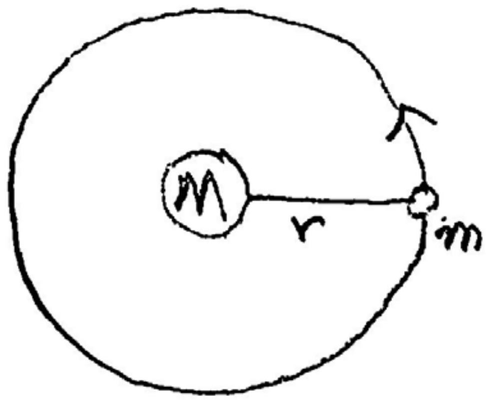
$$= 4.24x10^{-4}\text{ degrees } = 1.53\text{ arc-seconds}$$

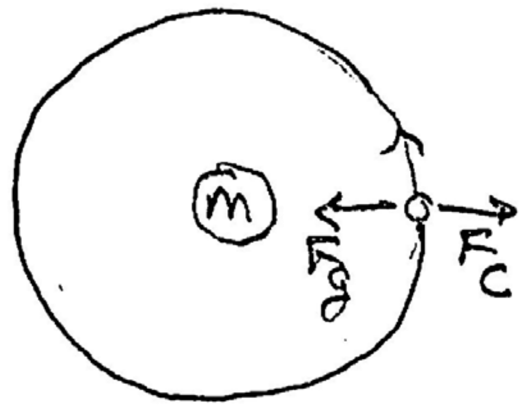
An arc-second is 1/60th of an arc-minute. An arc-minute is 1/60th of a degree. Small as this angle is, it is measurable. A great telescope can measure angles down to about 0.1 arc-second on Earth. An array of telescopes spread out over great distance can compare signals that show the same pattern of waves (a technique called interferometry) and can measure 0.001 arc-second…in a long dedicated view of one area of the sky.

To get the actual physical size (diameter or radius) of the star, we can again use geometry. For nearby stars that are large enough, one can actually see both edges of the star, which form an even smaller angle between them. For Proxima Centauri, the relevant distance is now the diameter of the star rather than the distance across the Earth's orbit. Since this diameter is about 100,000 km, the angle is 0.005 arc-seconds. Measuring this requires a telescope array. Proxima Centauri's size was measured in 2002 by two astronomers, Pierre Kervella and Frederic Thenevin.

The most common way of measuring the angular size of a star takes advantage of the wave nature of light. Light is comprised of oscillating electric and magnetic fields. Over time and over distance, the fields vary from positive to negative in a (generally) simple pattern, a sine wave. Then waves from different sources, such as different areas on the same star, meet at a point, they add their field strengths. If one wave is going positive and the other is also going positive, the added fields are stronger. If they are out of phase, one going positive and the other negative, the sum of the two fields is less than either one. In time and in space, then, there are patterns of positive and negative reinforcement, or interference. The theory is explained, with some advanced math, in several places – a book on optics (Introduction to Modern Optics, GR Fowles, Dover, 1975), a website maintained by the Astronomy Café, and another website from the University of Denver, among others. The first use of this optical theory was to measure the diameter of the giant red star, Betelgeuse, with a complicated optical setup on the telescope on Mount Wilson, near my alma mater, Caltech. Betelgeuse was found to have a diameter 280 times as large as our Sun; it would extend beyond the orbit of Mars, were it our central star! Simpler setups now work effectively, using optical theory developed by Robert Hanbury-Brown and Richard Twiss.

Step 2: estimate the distance (radius) at which the planet orbits the star: We can get this from the period of the orbit (a little under 12 days, it seems – and how do we measure that? Later!) and the mass of the star. These two items determine the relation of the orbital period of the planet around the star to its distance from the star. In essence, we figure out the balance between the force of gravity pulling the planet toward the star and the (virtual) centrifugal force "throwing" the planet away from the star.





In this figure, the large circle (OK, sphere) represents the star, with mass *M*.   The small circle represents the planet, with a smaller mass, *m*. There is a gravitational force, F_g, pulling the planet toward the star. There is also an effective centrifugal force, F_c, pushing the planet out in the opposite direction. (It's a virtual or fictitious force arising from using a coordinate system that's not rotating with the body, the planet.) The gravitational force is proportional to the product of the two masses, *Mm*, with a universal gravitational constant, *G*, multiplying this and with a factor varying with one over the square of the distances between the tow masses. Mathematically, this is expressed as

$$F_g = -\frac{GMm}{r^2}$$

The minus sign means the force is inward, tending to shrink the distance, *r*. This same formula applies on and near Earth, too.   Our own mass and the mass of the Earth pull on each other as if at a distance from each other equal to our distance from the center of the Earth. Farther away, as in an orbiting satellite, *r* is larger and the force of gravity is actually less. There are many other interesting features of gravity, including how uneven distribution of mass in the Earth is indicated by slight deviations from a uniform value of the acceleration of gravity; this even helps to locate oil deposits.

The second force, the centrifugal force, varies as the square of the velocity of the planet along its orbit and inversely with distance, as 1/r. It is also proportional to the mass:

$$F_c = \frac{mv^2}{r}$$

The sign is positive; the force tends to move the planet outward in radius. This formula can be derived several ways, which I won't go into.

The two forces have to have equal magnitudes for the radius to stay unchanged – that is, for the planet to have a stable orbit. To help us get to the relation between the orbital period (time to complete one revolution, τ, the Greek letter tau) and radius, we'll express the speed *v* in terms of the radius and period:

$$v = \frac{2\pi r}{\tau}$$

Now we can equate the two forces, in size or magnitude:

$$\frac{GMm}{r^2} = m\frac{(2\pi r/\tau)^2}{r} = m\frac{(2\pi)^2}{\tau^2}r$$

Interesting: the mass *m* appears on both sides; we can cancel it out. All that matters for this relation is the mass of the star, *M*. With a little rearrangement, we get

$$\frac{GM}{4\pi^2}\tau^2 = r^3$$

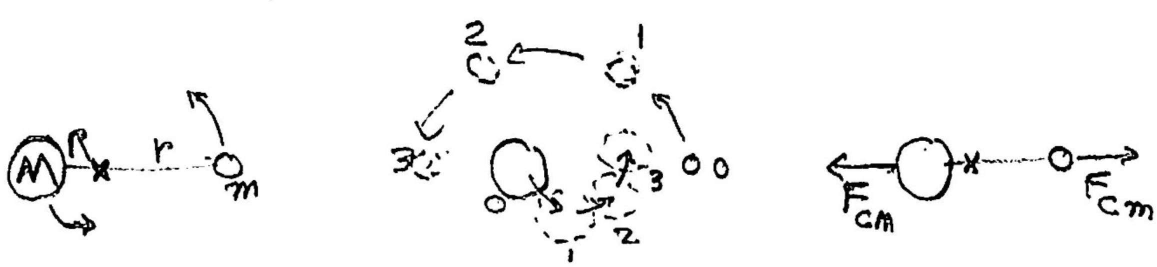
The value of the gravitational constant, *G*, is well known from clever measurements on Earth; pi is a mathematical constant; the period, τ, was measured as the period with which the star itself wobbled as the small planet pulled it a bit (more on that in a bit)…so, we can calculate the orbital radius, *r*, if we can estimate the mass of the star, *M* – that's in the next section. This relation between radius and period applies in our own solar system, of course, and it was discovered by Johannes Kepler over 400 years ago. So, Mars, which is on average 1.52 times as far from the Sun as is the Earth, has an orbital period that is $(1.52)^{3/2}$, or 1.88 times as long as our own year – that's 687 of our Earth days. (We won't get into the interesting fact that the Earth's rotation period is really one day longer because of the way we define the year.)

Step 2a: estimate the mass of the star itself:

This is done by using the same physics and math as we used above. Proxima Centauri is actually one of 3 stars orbiting each other, the other two stars being known as Alpha Centauri A, Alpha Centauri B … and being much brighter than Proxima Centauri. Simplifying it a bit, consider two stars orbiting each other. They have a measureable period of rotating about each other and we can, with luck, measure their average distance from each other. We then get a similar equation,

$$\tau^2 = \frac{4\pi^2}{(M_1 + M_2)}r^3$$

So, we can get the total mass. To separate the two masses, we realize that they are rotating about a common center of mass:



The bigger star has mass *M*, the smaller star, *m*. They rotate about a common center of mass, taking positions marked 0, 1, 2, 3 at a succession of times, with the big star moving less, in a tighter orbit. They have identical centrifugal forces. Expressing these in terms of their orbital periods, which are identical, we get

$$M_1\left(\frac{2\pi}{\tau}\right)^2 R_1 = M_2\left(\frac{2\pi}{\tau}\right)^2 R_2$$

This gives the simple relation

$$\frac{M_1}{M_2} = \frac{R_2}{R_1}$$

So, if the first star, *1*, has 4 times the mass of the other, it only moves one-fourth as far from the center of mass as does the second star. This is readily detected. Then, we know that M_1 is one-fifth of the total mass that was measured from the period and the mean separation.

I didn't say how we can determine the period of rotation. That's done by measuring the speed of the star (or the planet!) along the line of sight, assuming that the orbit is flat-on to us (there are gemoeteric corrections if this is not so). So, how do we know the speed? It's by the shift in frequency of light coming from the star, the Doppler effect for light. This is similar to the change in sound frequency of a train whistle coming toward us or going away from us. One must find light of a well-known frequency (thus, wavelength) and see how much its frequency deviates from its value from a stationary source. There are a number of such frequencies, each originating from a specific, well-known transition of electrons in atoms from one energy level to another.

For stars not conveniently in binary systems, there ae other ways to estimate the mass from known temperature and brightness, in which stars have been found to fall in uniform patterns.

Sideline: Though we don't need it to figure out if the planet is "habitable," we can estimate the mass of the planet, from the absolute amount of wobble the planet imparts to the star as it orbits the star. While the planet is small in mass compared to the star, it does make the star wobble a bit around the common center of mass of the star+planet system. The Doppler effect on the starlight is tiny, but measurable. For small velocities, the fractional shift in wavelength is (star velocity)/(speed of light). The amount of wobble of Proxima Centauri b is truly small, only about 2 meters per second or about 4.4 miles per hour, as cited in an interesting website.

Whew!

Photons for photosynthesis

Warmth from a hot source is one thing; getting high-energy light that can drive the chemical reactions of photosynthesis is another thing. After all, a little camping fire can keep you warm but it can't provide enough visible light to let a plant grow. Low-temperature sources of blackbody radiation provide a very small fraction of their total energy output as visible light. For a hot body like the Sun, about half of its radiant energy comes out as visible light, with a couple of percent coming as ultraviolet and the rest coming as invisible infrared, far infrared, thermal infrared, and radio waves. For a cooler body like Proxima Centauri, only 9% of its energy comes out as visible light. So, if its total energy output received at the planet is only 88% of what we get on Earth, and if only 9% of the energy is in the visible spectrum, then the usable light for photosynthesis looks like it's only about 8% as intense as on Earth.

Let's make an adjustment: while green plants need light of short wavelengths, less than about 700 nanometers (nm; a human hair is about 50 micrometers or 50,000 nm; an atom is several tenths of one nm), that's not true for bacteria. We can take a range down to longer wavelengths, which has lower energy per particle of radiation, or photon (there's another topic – energy in radiation is quantized into particles). We can't go too low in energy, which has to be enough to break chemical bonds. Let's take, say, 850 nm, about 20% longer.

What we have to do now is to calculate the rate at which photons of this wavelength or shorted hit each unit area on the planet. This is an interesting calculation. We need a mathematical expression for the intensity of photons (not their energy) at each wavelength, and then we have to sum up (integrate, in terms of calculus) over all the useful wavelengths from 850nm down to very short wavelengths. The math gets pretty intense (see http://www.spectralcalc.com/blackbody/inband_radiance.html); I'll summarize it below. I also have created an Excel 2013 spreadsheet that lets one calculate this "photon flux density", as well as the energy flux density, for any star temperature, star diameter, planetary orbital radius, and cutoff wavelength. You can reach me to get a copy; your request will give me a good feeling that someone is reading this!

There's a lot of physics behind the expression for the number of photons per area per solid angle that a blackbody emits, within a small range of wavelengths. It inherently involves the nature of light as quantized into the discrete particles, the photons, where at a given wavelength of radiation all photons have the same discrete amount of energy, *hv*("aich new") = *hc/ λ*. Here, *h* is the universal Planck's constant, discovered, of course, by Max Planck, *v* is the frequency of the light, *c* is the speed of light, and *λ* is the wavelength of light. Planck derived an expression that fit observations for the number of photons emitted per area per solid angle within the range of wavelengths from *λ* to *λ+dλ*. Here, *dλ* is a small increment in wavelength:

$$L(\lambda)d\lambda = \frac{2hc^2}{\lambda^5}\frac{1}{e^{hc/(\lambda kT)}-1}d\lambda$$

Here, T is, of course, the absolute temperature as discussed earlier; *k* is Boltzmann's constant. We can express the rate in terms of the energy emitted in a range of frequencies between *v* and *v+dv*,

$$L(\nu)d\nu = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/(kT)}-1}d\nu$$

What we really want is the number of photons, not the amount of energy. Bacteria or plants do photosynthesis with each photochemical reaction driven by a photon, irrespective of its energy as long as that energy is above a minimum (not strictly true, given different degrees of absorption at different wavelengths, but this is a start). The rate expressed in number of photons is this last equation divided by the energy of a photon, *hv*

$$L_P(\nu)d\nu = \frac{h\nu^2}{c^2}\frac{1}{e^{h\nu/(kT)}-1}d\nu$$

If we count all photons emitted, over all frequencies (all wavelengths, all energies), we get two expressions familiar in physics. The total amount of energy emitted is

$$B = \frac{2\pi^4 k^4}{15h^3c^2}T^4$$

The factor in front of T^4 is the Stefan-Boltzmann constant, 5.67x10^{-8} W $m^{-2}K^{-4}$. The total number of photons emitted is

$$B_P = \frac{4\zeta(3)k^3}{h^3c^2}T^3$$

Here, ζ(3) is a mathematical constant, the Riemann zeta function of 3, with a value of about 1.202 as a simple (pure) number.

These are "nice results," but we want the number of photons emitted over an interval that starts at a lower limit that is not zero in frequency, rather being the frequency corresponding to a wavelength of 850 nm. This calculation is presented nicely on one website put up by a commercial corporation, GATS, Inc., of Newport News, VA. They start by converting from wavelength to a new variable, called wavenumber, the number of wavelengths in a meter, 1/λ, given the symbol σ (not the same as the Stefan-Boltzmann constant!). They actually use σ in older units of wavelengths per cm, not per m, but I'll stay really metric here (really "SI").

We want to do the integration (this is calculus) over all wavenumbers from a minimum value of σ, which is 1/(850 nm) = $1/(8.5\text{x}10^{-7}$ m) = $1.176\text{x}10^{6}$ m^{-1}, to infinity. Well, that's too far, but the number of photons of very high energy (very high wavenumber, very short wavelength) is so small that doing the integral to infinity makes very little difference. After all, we are making a guess about the lower limit that bacteria can use, anyway. The math is shown nicely one of the company's deeper webpages. The result is

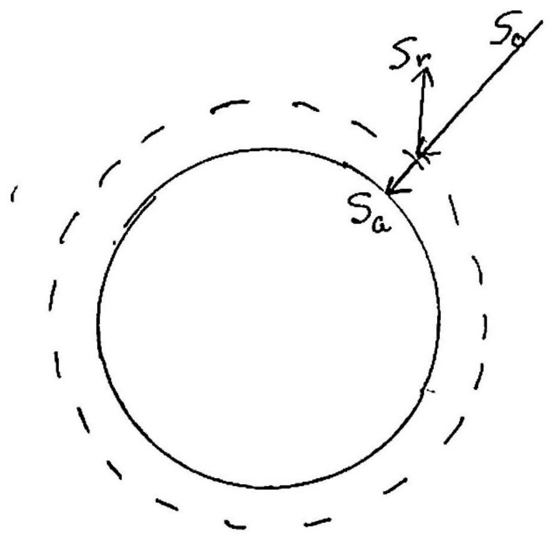
$$B_P(\sigma) = 2\frac{k^3T^3}{h^3c^2}\sum_{n=1}^{\infty}\left(\frac{x^2}{n}+\frac{2x}{n^2}+\frac{2}{n^3}\right), x=\frac{hc\sigma}{kT}=\frac{hc}{\lambda kT}$$

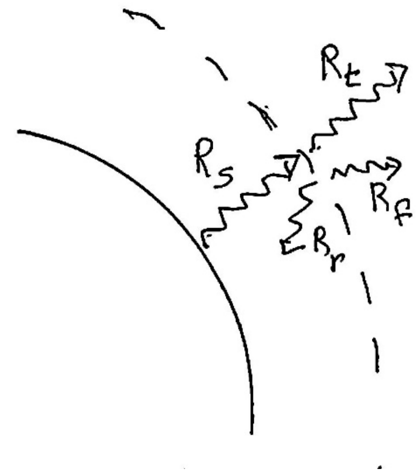
We can do this sum because only the first several terms are big enough to matter. I did this in the spreadsheet.

The result is interesting. I have to multiply it by a factor of π to account for emission into all directions (all solid angles). Deflating it, as it were, for the falloff at the planet's surface by the factor $(r_{star}/r_{orbit})^2$, I find a photon flux density of $7.5\text{x}10^{20}$ photons per square meter. That sounds like a huge number, and, of course, it is. However, a more common measure, used in studies of photosynthesis on Earth, is in moles of photons, not photons themselves. A mole is Avogadro's number of anything, including photons, and that number is N = $6.024\text{x}10^{23}$. This jibes better with tracking chemical reactions such as photosynthesis. Dividing our result by *N*, we get a photon flux density of $1.25\text{x}10^{-3}$ mol $m^{-2}s^{-1}$ for "overhead sun" above the atmosphere, or 1250 micromol $m^{-2}s^{-1}$. On Earth under clear skies, we get up to 2200 micromol $m^{-2}s^{-1}$ in a range of wavelengths from 700 nm to 400 nm, and that is more than plants and bacteria can use – the rate of photosynthesis is saturated, with some interesting exceptions. So, we're in the ballpark. There are a couple of corrections to apply. First, a fraction of the photons is lost in passing through the planet's atmosphere – it had better have an atmosphere to support life chemically and with a greenhouse effect. Second, if the planet is tidally locked, as noted in the introductory essay, then only regions of the planet with glancing incidence of light are habitable (see a later section here). The photon flux density is reduced by a factor between 0.17 and 0.43. So, the usable photon flux density is no more than about 430 micromol $m^{-2}s^{-1}$, assuming an atmospheric transmission of 80%. That puts any bacterial life on Proxima Centauri b in a slow lane, though one that could sustain life as long as star flares don't blow away the atmosphere or directly kill bacteria.

The greenhouse effect:
what keeps us warm (and we hope, not too warm in the future!)

In the long term (years, or many years), a planet or moon without a big source of energy internally balances out the radiant energy coming in from its sun with the energy it radiates more or less as a black body. Our Earth absorbs energy from the Sun primarily as short wavelength or shortwave radiation, which is visible light and infrared with a touch of ultraviolet and of very longwave radiation. The energy absorbed is balanced by the thermal infrared radiation that it emits. From space, above the atmosphere, the Earth looks cold, at a mean temperature of -18°C or near 0°F. At the surface, beneath the atmosphere, however, the average temperature is a relatively toasty +15°C. This happens because the Earth's atmosphere absorbs a lot of outgoing thermal infrared radiation; a major fraction is radiated back to the surface, helping to warm the surface. A simplified view is given below:





The figure to the left just shows the average interception of sunlight. Using data for the Earth, the incoming radiation, S_0, averaged over the whole surface is ¼ of the solar constant, or about 342 watts per square meter (W m^{-2}). About 30% is reflected, much of it by clouds and some by surface features that absorb less than 100% of sunlight – some, much less than 100%, such as ice fields. That leaves about 240 W m^{-2} to heat the average area of the Earth's surface.

The figure to the right, an enlargement, shows how the thermal radiation ultimately leaves at the top of the atmosphere. The surface emits thermal infrared (R_s) at an effective blackbody temperature of +15°C or about 288K. That's a rate of 390 W m^{-2}, more than 62% higher than the solar energy absorption rate! Only about 23% (R_t) escapes directly through the air (in this very simplified model), or 90 W m^{-2}. The other 300 W m^{-2} are absorbed. Half of this, 150 W m^{-2}, radiates back to the surface (R_r). This makes the surface the recipient of 240 W m^{-2} from the Sun and 150 W m^{-2} from back-propagating thermal infrared originally emitted by the surface, for a total of 390 W m^{-2}; the budget is balanced. Half of the thermal radiation absorbed by the atmosphere, another 150 W m^{-2}, radiates to space (R_f), joining the 90 W m^{-2} that got through the atmosphere directly. That gives a total emission of thermal radiation of 90 + 150 = 240 W m^{-2}, balancing the budget also at the top of the atmosphere.

This picture is very simplified. The detailed physics of the greenhouse effect is a rich, intriguing field…and controversial as a real effect only among non-scientists with an agenda of their own. There are scientific debates about details, of course, which is the way that science progresses. I note that the major absorbers of thermal radiation in the atmosphere are water (as vapor and as clouds), carbon dioxide, methane, nitrous oxide, and some suspended particles called aerosols. Water accounts for the greatest part of the absorption, but it "follows" the effects of the other absorbers. Add more of them and the temperature rises; this evaporates more water; decrease the other absorbers and the water content of the atmosphere goes down. With none of the other absorbers, the amount of water vapor would be much smaller and the greenhouse effect would be much smaller. Of great interest are episodes in the earlier history of the Earth, about 2.2 billion years ago, when photosynthetic cyanobacteria evolved and liberated oxygen gas. This reacted with the methane in the atmosphere, creating carbon dioxide, a much weaker greenhouse gas. However, the Sun had much weaker energy output then. The lower energy input and the weaker greenhouse effect led to the Earth freezing over almost completely, ending all life of Earth; so much for the Gaia hypothesis that life as a system helps maintain Earth in a favorable condition for itself! The Earth recovered when volcanoes,, over about 50 million years, emitted enough carbon dioxide to make a strong greenhouse effect. The Earth warmed up and overshot – liquid water absorbed much more solar radiation. The temperature of the Earth rose, perhaps to +50^oC. Life barely made it through this episode of Snowball Earth, and a second one a bit later.

No one knows if planet Proxima Centauri b has a decent atmosphere and greenhouse effect. There is some promise in new methods to detect the atmospheric composition around a distant planet by the light absorbed at the edges of the planet, where there is a long path for light through the atmosphere.

In the discussion above, I assumed that a planet, Earth or Proxima Centauri b, had no significant internal source of heat that has to be counted in the surface energy balance. Of course, almost everyone knows that Earth has an internal heat source, called geothermal energy when it emerges at the surface. It's driven by the decay of radioactive elements, continuing solidification of the core, condensing of metals to deeper levels, and the original heat of accretion. It's not a large source, averaging only 0.06 W m^{-2}. This is far below solar energy levels. Tapping geothermal energy for heating and electric power is not really using it renewably. One "mines" the energy stored in considerable depths of rock, over a few years' time. That energy will not be replenished by slow flow from the deeper layers of Earth for thousands or perhaps millions of Earth. So, oddly, geothermal energy is another "fossil" energy source.

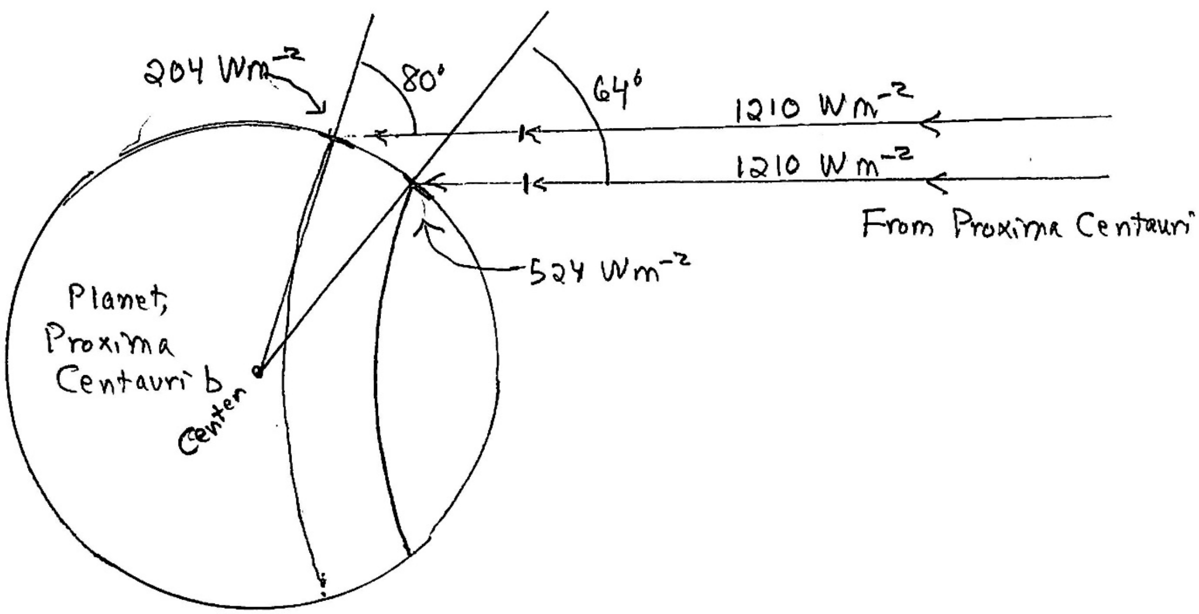
Only a modest area is habitable

It's very likely that Proxima Centauri b is tidally locked, with one face of the planet constantly facing the star. The surface of the planet with the star (sun) directly overhead gets baked. The surface facing away from the star cools off to about the temperature of interstellar space, not that far above absolute zero! Are there any places temperate enough for life to exist, even if only as bacteria? We should figure out two things: (1) what is the range of temperatures that bacteria can thrive at, and (2) where these temperatures might be found on the planet.

For the first item, let's take the range as just above the freezing point of water, near 0^oC, to the highest temperature on the surface of the Earth where bacteria live, in hot springs such as are found at Yellowstone National Park, say, 70^oC. I'm discounting very high temperatures, above the boiling point of water (at an atmospheric pressure assumed to be similar to ours, though this is iffy). These temperatures occur only at great depths in oceans. Of course, we don't even know if this planet has water!

For the second item, I'll make some simplifying assumptions. For one, I'll assume that the temperature of a location on the planet depends upon the amount of stellar radiation at that point, plus an increase from a greenhouse effect. This means not accounting for heat being transported to or from this spot by an atmosphere or ocean such as happens on Earth (which is why the poles are not even colder and the equator even hotter than they are). Now, the amount of radiation will depend on the angle between the direction to the star and the normal or perpendicular to the surface (for flat areas). Thus, we're going to calculate a range of angles that make the radiation not too low, not too high, just right, a Goldilocks story.

Let's start with the higher temperature, 70°C or 343K. How much absorbed radiation will support this as a steady temperature? First, assume that there is *no* significant greenhouse effect. Oops, that's not possible. If there's water, there's a strong greenhouse effect. I'll use an Earth-like greenhouse effect that raises temperatures by 33°C . So, the radiative temperature of a location should be 33°C lower than the surface temperature. Our higher surface temperature of 70°C corresponds to a radiative temperature of 37°C or 310K. We'll use the blackbody equation again, $I = \sigma T^4$. We obtain I = 524 W m^{-2}, which is 43% of the direct starlight intensity. This occurs at an angle away from the "sun" of 64°.



That's over 2/3 of the way, in angle, to the "terminator," or permanent shadow zone that starts at what we might call the equator. Let's proceed to the lower temperature. I'll take this as 5°C. Yes, I know that bacteria on Earth are found in areas that get seasonally much colder. However, on a tidally locked planet we don't expect changeable weather; each location stays around its own constant temperature (except when the star flares!). At a surface temperature of 5°C, the radiative temperature will be 33°C lower, or -28°C, which his or 245K, we need I = 204 W m^{-2}, which is 17% of the full starlight. This occurs at an angle of about 80° from overhead, almost to the planet's terminator or equator. Overall then, my first estimate is that there's a narrow band of angles on the starlit side that's habitable, from 64° to 80°. By geometry, we can figure out that this covers a fraction (0.43-0.17)/2 = 13% of the planet's surface.

For intelligent life to have evolved, more moderate conditions would be needed. That's a long story that I cover in a book I'm writing. There's not much room on this planet! Many other conditions are needed for life, intelligent or not, which I won't detail, such as the ready availability at the surface of certain chemical elements – something we have on Earth because the Earth cooled just right and had the right elements in the planetary nebula from which our solar system formed.

BUT…there's a major problem with this – condensation of all the atmosphere on the cold side of the planet

Shielding from star flares and cosmic rays

Earth is in a region of space to get some heavy-duty impacts of charged particles, damaging to living beings, from the Sun's occasional flares and from cosmic rays. Fortunately, Earth has two protective items, an atmosphere and a magnetic field. The atmosphere provides lots of atoms with which these particles can collide, losing energy and becoming less harmful, even to innocuous. Our magnetic field also deflects charged particles, making some of them miss the Earth and some others to skim into radiation belts or into oblique paths where they lose even more energy.

Is Proxima Centauri shielded by an atmosphere and by a magnetic field? Well, if it's to have life, it has to have an atmosphere, if only because water vapor will be there (not a lot; it's only about 1% of our own atmosphere, on average), but also so that certain chemical elements can recycle as they do on Earth (nitrogen and carbon, for example). What about a magnetic field? In the simple essay that started all this, I noted some scientists' speculations that its rotation during an orbit can help keep a dynamo going, moving conductive liquid such as iron in the core moving. One may ask how critical a magnetic field is, as well. Our earthly magnetic field does reverse about every 50,000 years, and, during the reversal, we have intervals of time with little or no magnetic field. We've all survived, nonetheless. You may draw some conclusions, or get interested in some fascinating ideas about evolution, radiation effects on organisms, tracers (isotopes of chemical elements) that indicate when we've been hit more heavily by cosmic rays, how the magnetic reversals were found in the first place (in magnetization patterns of rocks formed as the ocean basins spread), etc. One notable aspect of scientific research is that studying other bodies in the Universe can give us a wider perspective on our own planet!