Temperatures and stellar evolution

You may recall from intro astronomy that the total energy flux F (energy per area per time) passing through a region can be related to the effective temperature T through the equation

$$F = \sigma_{\rm SB} T^4 \tag{1}$$

where $\sigma_{\rm SB}$ is a constant called the Stefan-Boltzmann constant. You may also remember that if the luminosity (energy per time) of a star is L, then the flux at a distance r from the star is given by

$$F = L/(4\pi r^2) \tag{2}$$

because the area of a sphere of radius r is $A = 4\pi r^2$ and the flux is the luminosity divided by the area.

Computation of the effective temperature at a given radius can proceed by combining these equations:

$$\sigma_{\rm SB} T^4 = F = L/(4\pi r^2)\ . \tag{3}$$

When we consider a single solar system, then not only $\sigma_{\rm SB}$ and 4π, but also the luminosity L, are constants with distance. This tells us that

$$T^4 \propto 1/r^2 \Rightarrow T \propto r^{-1/2}\ . \tag{4}$$

Therefore, if we calculate the effective temperature at any radius (say, 1 AU), we can use this proportionality to calculate the temperature at any other radius. For example, if the temperature is 300 K at 1 AU, then four times farther away the temperature is $4^{-1/2} = 1/2$ times as great, or 150 K. Similarly, the radius where the temperature is 600 K would be given by $(600/300)^{-2} \times 1$ AU$= 0.25$ AU.

The calculation of the expected temperature of a planet involves some subtleties. One is "albedo", which is the degree to which a planet or moon reflects light without absorbing it. Earth reflects about 37% of the light that hits it, whereas the Moon reflects only 12%. More reflection leads to a colder planet. Another issue is the greenhouse effect. If radiation is trapped then the planet heats up beyond the temperature it would normally acquire. An obvious example is that of Venus. Finally, the temperature can vary substantially over the surface of a planet, as is obvious from a comparison between Death Valley and Antarctica. Atmospheres smooth out the difference (compare the Earth with the airless Moon, where the mean daytime temperature is 107°C and the mean nighttime temperature is −153°C). Therefore, a planet such as Earth can have both "habitable" and "uninhabitable" spots on it simultaneously.

With all these caveats, we can nonetheless ask where in the Solar System one would have average temperatures that could allow liquid water to exist. The average temperature of Earth is about 15°C. Note, however, that the temperature T in the equations above has to be measured in a scale that reaches 0 at absolute zero, and Celsius doesn't do that. Thus we represent this in Kelvin: 15°C=288 K. Water freezes at 0°C=273 K and boils at 100°C=373 K, so our scaling indicates that the habitable zone could extend from $(373/288)^{-2} \times 1$ AU= 0.6 AU to $(273/288)^{-1} \times 1$ AU= 1.1 AU. In principle this would include Venus but not Mars. As an indication of how different assumptions can change the range, I have also seen ranges such as 0.95 AU to 1.37 AU for the habitable zone. It's not exact. A large greenhouse effect or small albedo could move the outer boundary of the habitable zone to larger radii; a large albedo could move the inner boundary to smaller radii. One might argue that if such effects could be dialed up or down at will, then plausibly planets from 0.5 AU to maybe 1.5–2 AU from the Sun could be in about the right temperature range. That doesn't seem too restrictive.

There is, however, another effect to consider. The Sun's luminosity has not remained constant over the 4.6 billion years of its existence. Instead, the luminosity has grown slowly with time. Therefore, although a planet might be in the habitable zone for part of the star's evolution, it is a more restrictive constraint to require that it be in the habitable zone for the whole evolution or at least a large part of it. To understand this better let's discuss some aspects of stellar evolution.

Stellar evolution

For most of their lifetimes, on the so-called "main sequence", stars convert hydrogen into helium via nuclear fusion. This process takes many steps and a long time, which is good for life because it means that for a star such as the Sun there is a consistent source of energy for billions of years. Note, though, that since the temperature and density at the core of a star adjusts itself for hydrogen fusion, the helium that is produced cannot itself fuse. The reason is that fusion is a reaction between nuclei, which are positively charged (protons have positive charge, neutrons are electrically neutral). They therefore repel each other, and hence require the high speeds provided by high temperatures to get close enough that the strong nuclear force can bind them together. However, a helium nucleus has two protons and thus bringing helium nuclei together (and you actually need three nuclei!) takes greater temperature and density than bringing together protons. Therefore, as hydrogen fusion proceeds, the helium nuclei act like dead lumps.

The result of all of this is that as the hydrogen supply in the core is gradually converted into helium, the helium sinks to the center where it does not generate energy. The nonparticipation of the helium means that less hydrogen than before has to battle against gravity, implying that the density and temperature in the core has to go up to compensate. Therefore, the luminosity (energy per time) of a star increases gradually as it ages along the main sequence.

This has been important for life on Earth and will be important elsewhere because this change is substantial over time. It is thought that when the Sun started on the main sequence 4.6 billion years ago it had only about 70% of the luminosity it has today. Within a billion years it will become about 10% brighter. This tells us that the very early Earth received much less illumination than it does today. In fact, our simple calculation would suggest that we would have been in danger of freezing. However, the early Earth still had a lot of heat from its formation, and probably a lot more carbon dioxide that could produce a greenhouse effect, so there were compensatory factors.

This change in luminosity with time can lead us to a more restrictive requirement: that a planet with life must be in the *continuously habitable zone*. This is the zone that is favorable for liquid water for many billions of years of a star's existence. Early on the habitable zone is close to the star, but it moves outwards with time, so the overlap is small. For example, some calculations of the continuously habitable zone in the Solar System from birth to now indicate a range of just 0.95 AU to 1.15 AU. That's not much, and it has led some people to propose that we really are in an extremely special situation.

Mass and properties of the host star

Let us thus proceed to a discussion of what we would like from the host star. Our Sun has a mass that is in roughly the top 5% of masses of all stars, but there are plenty that are a lot more massive. Overall, stars at their birth have a mass range between 0.08 $M_\odot$ (where $M_\odot$ is the symbol for the Sun's mass) and at least 150 $M_\odot$. Less massive ones are more common, and the really high-mass ones are rare indeed. For example, only about one star in 1000 has a mass greater than 10 $M_\odot$.

Of special importance to life is that high-mass stars live a short time compared to low-mass stars. Within a factor of a few of the Sun's mass we can estimate the lifetime as:

$$T \approx T_\odot (M/M_\odot)^{-3} . \tag{5}$$

Here $T_\odot$ ∼10 billion years is roughly the lifetime of the Sun. Therefore a star with double the Sun's mass lives a bit over a billion years, whereas a star with half the Sun's mass lives nearly a hundred billion years.

Clearly, this means that very high-mass stars live such a short time that even if you put a planet in that star's habitable zone (which would be farther away because the star would be much more luminous than the Sun), life would be hard-pressed to evolve much even if it managed to originate. As a reminder, the earliest traces of life on Earth go back to something like 800 million years after the formation of the Solar System. Life might have originated before then, but the planets were getting whacked frequently by major collisions, so it wasn't a nice environment. We can probably discount high-mass stars for this reason.

Low-mass stars last plenty of time. However, some people think that a star with too low a mass is a bad candidate to host life. There are two basic reasons. First, low-mass stars have major flares and therefore the illumination from them is not as stable as it is from the Sun. This might still allow microbial life to form, but as complex organisms are less resistant to major environmental changes it could be tough.

Second, if we need to place our planet in the habitable zone then another challenge emerges. Lower-mass stars are much less bright, so the planet would have to be much closer than Earth is to the Sun. When the planet is close enough, the gravity of the host star will force the planet to rotate with the same face always to the star (similarly to the way that the Moon basically always presents the same face to the Earth). The sun side would be very hot, and the night side would be extremely cold. If the temperature isn't distributed well by the atmosphere, the atmosphere might condense out and prevent life from originating. The threshold is that this would likely occur for stars less than half the mass of the Sun.

Note, though, that again a situation like Europa around Jupiter would evade these problems (recally that Europa is one of Jupiter's moons, and that is probably has a liquid water ocean beneath its ice layer). Therefore, once more, I think that this restriction is not necessarily as bad as some people have thought.

Our last restriction related to the host star is that it would be most stable for the star to be single rather than a binary. Roughly two-thirds of stars like our Sun are in binaries (meaning that for every single star there is a binary; the two in the binary versus the one in the single mean two-thirds are in binaries). That's great, but many of the orbits in which you might place planets are therefore unstable. These are the orbits in which the planet is a distance from the binary center that is less than two to three times the binary orbital radius, and is a comparable distance from both stars. Basically, the varying gravitational field the planet would experience would be enough to kick it into empty space. A planet can be in a stable orbit around a binary if it is far enough away (several times the binary orbital radius), or if it is much closer to one star than to the other. Therefore, there are possibilities, but it is tougher than for a single star.