The current limits on life are bounded by physical and chemical extremes such as temperature, water availability, pH, pressure, and radiation. These limits define Earth's biospace, though do these limits change or remain the same beyond Earth? The Earth hosts a vast range for each of the environmental parameters listed above and life has been found to survive in almost all of them. Because these microorganisms can exist at these extremes, I believe this provides support that life is likely able to exist beyond the limits that have currently been observed on Earth. There are universal limits to life based on the fundamental laws of physics and biochemistry, though I do not believe the current known extremes are the absolute universal extremes at which life can exist. I will describe the known limits to life for each environmental parameter, then explore the possibility of life existing beyond such known limits.

From extreme-cold East Antarctica to scorching hot deep-sea hydrothermal vents, Earth's natural temperatures range from -98.6 to 495°C (technically, the max temperatures are much higher if one includes subsurface magma)[1]. In 2017, the bacteria *Deinococcus geothermalis* was cultured under Mars-like conditions with a temperature range of -25 to 60°C and neither the "culturability nor membrane integrity" were affected[2]. Thus, this sets a possible lower temperature limit which microbial life can exist. On the other side of the spectrum an archea, *Geogmma barossi* (also called "Strain 121") has been found to be capable of reproduction at 121°C and tolerates 130°C[3]. One can clearly see that the temperatures life has been found to survive is only a small portion of Earth's entire temperature range. Because Earth has such a large range of available temperatures, if life could thrive much further beyond what we observe, I believe there would be more clear evidence of it. That is not to say that life cannot exist beyond what has been observed (-25 - 130°C), in fact I believe it is very likely that there is some life beyond these limits – however I do not expect life to be able to thrive at the very extremes of Earth's -98.6°C and 495°C or far beyond what we currently observe. Thus, I believe a universal temperature limit can be set between -98.6 to -25°C (lower) and 130 to 495°C (upper). More specifically, I would restrain the limits to ~ -40°C (due to "thermodynamic considerations") and 150°C (due to "instability of macromolecules")[1]. Next I will talk about how current life requires some amount of water to survive – the environment's water availability.

Water availability can be described by the term 'water activity' (a_w). Water activity, as defined in the textbook, is 'the ratio of the vapor pressure of a substance to the vapor pressure of pure water. Distilled water therefore has a water activity of 1'"[4]. Water activity can be reduced by the inclusion of materials in the water solution. With regards to life and Earth, the most common material in reducing natural water activity is salt (NaCl). The amount of salt dissolved in a solution is called its 'salinity' and organisms that live in high salinity environments are called halophiles. The minimum theoretical water activity level for halophilic archaea and bacteria is $0.611a_w$ and $0.635a_w$ for fungi[1], though this theoretical limit has been passed by microbial communities with water activities as low as $0.4a_w$, however these environments contain high concentrations of $MgCl_2$ or $CaCl_2$[1]. More extreme conditions, such as Don Juan Pond in

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[1] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6476344/

[2] https://www.liebertpub.com/doi/pdf/10.1089/ast.2015.1431

[3] https://www.researchgate.net/publication/10612642_Kashefi_K_Lovley_DR_Extending_the_upper_temperature_limit_for_life_Science_301_934

[4] Astrobiology – *Charles Cockell*

Antarctica (T ~ -36 to 20°C, pH = 4.6, a_w likely below $0.45a_w$) has been found to not contain life, though this could be due to the multiple extreme conditions it harbors[1]. Earth hosts environments across the whole range of water activity levels and life can be found in many of them, but not necessarily all of them. I believe, like temperature, that life likely can exist beyond the current extremes of $0.611a_w$ (theoretical) and $0.4a_w$ ($MgCl_2$ or $CaCl_2$). These current limits that have been observed are not the universal limits. Life as we know it requires water in some way or another to survive, so I do not believe the universal limit to water availability is all the way down at $0a_w$ - so, it must be somewhere between $0\text{-}0.4a_w$. Somewhat related to water availability is pH – how acidic or basic the environment is.

pH, which stands for 'power of hydrogen,' is a measure of the hydrogen-ion (proton) concentration of a solution[5]. The higher the concentration of hydrogen-ions, the more acidic the solution is (< 7 on pH scale). The lower the concentration, the more basic the solution is (> 7 on scale). Organisms must maintain homeostasis with its environment to survive (*Because of 2nd law of thermodynamics?), but if the environment is too extreme, it may not be able to survive. For example, "All microorganisms must maintain a near neutral cytoplasmic pH to enable cellular functions for survival and metabolism… The cytoplasmic pH of acidophilic bacteria is ~6.0 while alkaliphilic [basic-loving] bacteria have a cytoplasmic pH around 7.2–8.7,[1]" but if the environment has a pH below 6.0 or above 8.7, it could be detrimental to the organism. Though this is the case, many organisms have become well adapted to significantly changing their immediate environment's pH through metabolic reactions[1]. This ability has allowed life to be found on both sides of the pH spectrum: "Currently, the most extreme acidophile and alkaliphile can survive at pH 0 and pH 12.5, respectively," though microbial communities have been found at Iron mountain in Shasta County, California which has a pH of -3.6 (some of these microorganisms from Iron Mountain have been isolated, but have not been shown to grow when exposed to these conditions)[1]. Because life on Earth has become well adapted to maintain its own pH and its immediate environment's pH, I believe that the current observed extremes are very close to the universal limits. The universal limits may extend slightly beyond what is currently observed, but because life has been found to exist on opposite sides of the pH spectrum, I believe the universal limits have nearly been reached by life on Earth.

There are other factors that bound Earth's biospace, such as pressure and radiation, though they will follow a similar trend to the topics covered here. Life has been found at extremes, though those extremes are not the absolute limits experienced by the Earth. Life as we know it is extremely capable of adapting and surviving in hostile environments, especially simple microorganisms. As time progresses, microorganisms will continue to adapt to their environments and figure out new ways to survive and even thrive. The current limits of Earth's biospace is not permanently static – they will expand. Likewise, life that may exist elsewhere in the universe will continue to expand their biospace. How far can they expand however? They will be able to expand until they reach the universal limits bounded by physics and biochemistry – until their chemical bonds begin to break apart from heat or until massive pressures literally crush them. There are universal limits to life, but life has not yet reached these limits.

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[5] http://hyperphysics.phy-astr.gsu.edu/hbase/Chemical/ph.html