CIRCUMSTELLAR HABITABLE ZONES FOR DEEP BIOSPHERES. S. McMahon[1], J. O. James[2] and J. Parnell[3], [1]School of Geosciences, University of Aberdeen, Aberdeen AB24 3UE, UK. sean.mcmahon@abdn.ac.uk, [2]School of Physics & Astronomy, University of St Andrews, North Haugh, St Andrews, Fife, KY16 9SS, [3]School of Geosciences, University of Aberdeen, Aberdeen AB24 3UE, UK.

Introduction: The circumstellar habitable zone (HZ) is traditionally a thin heliocentric shell within which liquid water is thermally stable on the surface of an Earth-like planet [1]. However, subsurface environments in colder rocky and icy bodies are likely to be capable of supporting at least low levels of biological activity while partially or even completely isolated from the frozen surface [e.g. 2, 3, 4, 5].

We used a simple thermal model to calculate "subsurface-habitability zones", or SSHZs, which delimit the heliocentric range of the subsurface habitability of terrestrial planets for a maximum habitable depth (i.e. when this depth is set to 0, the SSHZ is identical to the traditional HZ). We found that SSHZs for biospheres on the order of kilometres below the surface are several times wider than traditional habitable zones (Fig. 1).

Methods: Because subsurface temperature is forced by surface temperature, planets at greater orbital distances are frozen and uninhabitable down to greater depths in the crust. We calculated the variation with heliocentric distance in the thickness and depth of the "habitable layer" where, at depths shallower than the stipulated maximum, temperatures fall between habitable limits. Except where otherwise stated, these limits were set to 0 and 122 °C, respectively the freezing point of pure water and the highest temperature presently known to accommodate life [6].

Surface temperature model. Planetary surface temperature was estimated from the combined solar and geothermal heat fluxes (assuming thermal equilibrium). Geothermal heat production was assumed to scale linearly with planetary mass. Simple temperature-dependent greenhouse gas fluxes were incorporated when including an Earth-like atmosphere. The change in opacity of the atmosphere due to each greenhouse gas was calculated and the heating (or cooling) effect estimated [1, 7].

Subsurface temperature model. Subsurface temperature gradients were found from the heat flux and a temperature-dependent thermal conductivity, $K(T)$. We combined two empirical $K(T)$ relations—one for water ice at low temperatures for which no basalt data are available [8], and one for basalt at higher temperatures [9]—to obtain a smoothly continuous $K(T)$ curve for basalt throughout the desired temperature range. We did not consider other influences on $K(T)$.

Finding the SSHZ. The inner edge of the SSHZ can be placed either where surface temperatures reach a habitable maximum (e.g. 122 °C) or—because a planet too hot to maintain surface water would likely vent and lose subsurface water in a short period—at the traditional HZ inner edge. The outer edge of the SSHZ is placed at the greatest heliocentric distance where the temperature remains higher than the freezing point of water at a shallower depth than the stipulated maximum.

Results: SSHZ outer-edge positions are highly sensitive to the stipulated maximum habitable depth and the planetary radius.

In the simplest case of a planet of Earth's size and heat production with no atmospheric greenhouse, a biosphere at 5 km depth is supportable over 3 AU from the sun; a biosphere at 10 km depth is supportable over 10 AU from the sun, and a biosphere at ~15.5 km depth is supportable even in interstellar space.

Larger radii generate steeper geothermal gradients and proportionally shallower and thinner habitable layers less sensitive to solar radiation. However, if the maximum habitable depth is associated with a minimum porosity or permeability then it must shoal with increasing lithostatic pressure, which is proportional to planetary radius; SSHZ width is then negligibly affected by planetary radius.

Mars. Mars was described by the general (equilibrium) model by substituting empirical values for mass, radius, albedo and orbital distance. The average habitable layer is found to extend from 5.3 km to 14.0 km below the surface. A hypothetical Mars-average-salinity melting point of −10 °C [10] raises the top of the habitable layer to 4.5 km below the surface. These results are similar to other recent estimates [11].

Earth-like atmospheres. Atmospheric gases introduce sharp changes in the depth of the habitable layer as a function of orbital distance (Fig. 1). For Earth itself, we find that the biosphere extends on average 2.8 km below the surface. This is a reasonable figure given the preponderance of relatively thin and hot oceanic crust (known to be inhabited locally down to at least 1.6 km [12]).

We also investigated four low-mass super-earths and their host stars [13, 14]. HD 85512 b is outside the inner edge of the traditional surface HZ, Gliese 667 Cc is well within it, Gliese 581g (unconfirmed) is just beyond the outer edge; and Gliese 581 d is far beyond the outer edge.

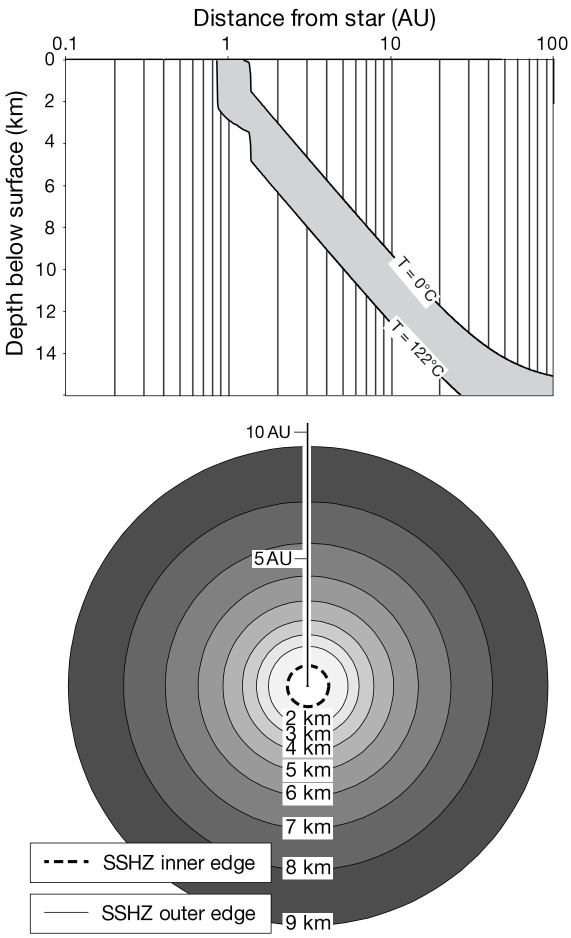

Figure 1. Model results for the Earth. Top: Relationship between habitable layer depth (shaded) and distance from the Sun. Below: Circumstellar SSHZs (AU) as a function of maximum habitable depth (km).

Earth values were assumed for bulk density and heat production per unit mass, and the Earth-like atmosphere model was applied; since these assumptions are only partially valid, the results are best regarded as illustrative. All but HD 85512 b, which cannot support water-based life at any depth, were found to possess temperatures suitable for liquid water less than 2 km below the surface at their current orbital distances.

Discussion: It must be emphasized that the positions of the predicted habitable layers in this model are global averages. Deeper and shallower habitable regions can result from variations in connected pore space, nutrient and energy availability and heat flux, the latter expressing latitude, climate, composition, geodynamic processes, and impact events. On Mars, for example, localised convection cells may also carry liquid water in aquifers several km above the background freezing-point isotherm [15].

SSHZs could be constrained for stars and planets more precisely with information about orbital parameters, planetary atmospheric composition, biogeochemical processes, heat production, heat transport and heat loss due to accretion, radioactive decay, tidal and other gravitational effects.

Temperatures below 0 °C should also be considered habitable in impure water, raising the top of the habitable layer and widening the SSHZ. Besides temperature, subsurface habitability is controlled by pressure, rock rheology, permeability, porosity and fluid flow. Life in any environment also requires long-term nutrient and energy supplies.

The example of our own solar system suggests that most planets and moons in the universe are beyond the outer edge of traditional HZs (although exoplanets closer to their stars are easier to detect) but, as illustrated here, many of these objects may be habitable at depth. Of course, habitable environments are not necessarily inhabited. Moreover, deeper biospheres are less likely to produce planetary biosignatures amenable to remote sensing, although potential search targets include atmospheric chemistry, cryovolcanic plume chemistry [16], and the compositions of hydrothermal and cryovolcanic surface residues.

Conclusion: Our results illustrate the importance of subsurface water for the determination of planetary habitability. Habitable zones for deep biospheres are much wider than traditional surface HZs, suggesting that many more planets can be considered habitable.

References: [1] Kasting J. F., Whitmire D. P. and Reynolds R. T. (1993) *Icarus, 101,* 108–128. [2] Fisk M. R. and Giovannoni S. J. (1999) *JGR*, *104*, 11805–11815. [3] Gaidos E. J., Nealson K. H. and Kirschvink J. L. (1999) *Science*, *284*, 1631–1633. [4] Sleep N. H. (2012) *IJA*, doi:10.1017/S1473550412000122. [5] Lin L. H. et al. (2005) *Geochim. Cosmochim. Acta.*, *69*, 893–903. [6] Takai K. et al. (2008) *PNAS*, *105*, 10949–10954. [7] Caldeira K. and Kasting J. F. (1992) *Nature*, *259*, 226–228. [8] Petrenko V. F. and Whitworth R. W. (1999) *Physics of Ice*. [9] Clauser C. and Huenges E. (1995) *AGU Ref. Shelf*, *3*, 105–126. [10] Jones E. G., Lineweaver C. H. and Clarke J. D. (2011) *Astrobiology*, *11*, 1017–1033. [11] Clifford S. M. et al. (2010) *JGR*, *115*, E07001. [12] Mason O. U. et al. (2010) *PLoS ONE*, *5*, e15399. [13] Schneider J. (2010) *The Extrasolar Planets Encyclopaedia* http://exoplanet.eu [14] Vogt S. S. et al. (2010) *Astrophys. J.* arXiv:1009.5733 [15] Travis B. J., Rosenberg N. D. and Cuzzi J. N. (2003) *JGR*, *108*, 10.1029. [16] McKay C. P. et al. (2008) *Astrobiology*, *8*, 909-919.