The Coupled Roles of Host Star Age, Exoplanet Radiogenic Heat Budget and Climatic Evolution

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The ideal exoplanets on which to search for life are rocky exoplanets with temperate climates that have been stable for billions of years. Even for a planet orbiting within the host star's habitable zone, its climate is a strong function of its geochemistry and its evolution to date. The primary controls on a rocky exoplanet's climate are the rates of removal of greenhouse gases (in particular, CO_2) by weathering, the rates of release of those greenhouse gases from the planet's interior by volcanic processes, and the balance between these rates. These processes require a sufficient heat budget to power them. As a rocky planet ages, its heat budget --- a combination of heat of formation, gravitational potential energy released during core formation, and heat released by radioactive elements, especially ^{40}K, ^{232}Th, ^{238}U and ^{235}U --- dwindles, slowing the rates of mantle degassing and weathering. Having exhausted their heat budgets, it is possible, then, for certain planets to be too old to support these climate-regulating processes, and thus are more likely to be in the snowball or hot-house climate regimes. Here, we quantify this "timescale of temperateness" by performing Monte Carlo 1-D exoplanet thermal evolution simulations of exoplanets across an observationally-constrained range of stellar abundances for long-lived radionuclides (Th, K) or their proxies (Eu for U). We perform these models under the assumption of stagnant-lid convection. We find the average lifetime of degassing for an Earth-sized stagnant-lid planet is 1.6 ±0.8 Gyr, with longer lifetimes expected for those planets that formed with a higher concentration of ^{40}K. Older exoplanets, such as those in the TRAPPIST-1 (age 8 ±2 Gyr) or Kepler 444 (age 11 ±2 Gyr) systems, are unlikely to be degassing at all and thus very presumably to be in the hothouse or snowball climate regimes. That is unless these planets are additionally heated by tidal dissipation, or undergoing plate tectonics. As plate tectonics may be rare, we assert these results represent a conservative lower-limit for the "timescale of temperateness" for Earth-sized exoplanets. Should an Earth-size exoplanet older this age range be observed to be actively degassing, however, this may be an indirect observation that the planet is undergoing active plate tectonics. We argue, then, that both stellar age and host-star radionuclide abundances are therefore key observables in determining whether an exoplanet is likely to be "Earth-like," temperate and potentially habitable.

Keywords: Exoplanets, Habitability, Geodynamics, Climate

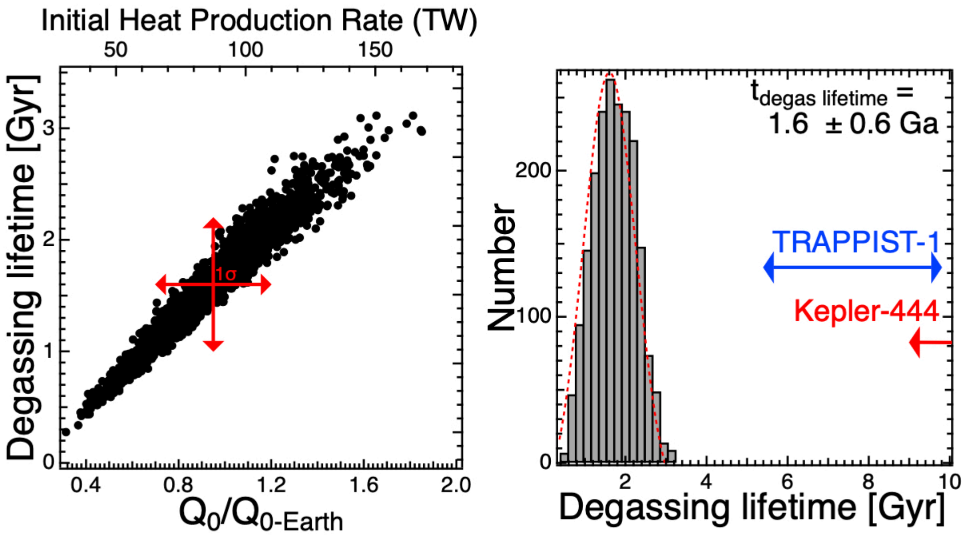

Figure 1:

LEFT: Calculated times when degassing rates fall below 10% of Earth value as function of total initial heat budget (Q_0) relative to model adopting Earth abundances of radionuclides. The one sigma range for each axis are shown as red arrows. Total heat production in TW is shown on top axis.

Right: Histogram of calculated degassing lifetimes for 2000 model runs adopting random radionuclide abundances. The reported ages ± 1σ of the star's TRAPPIST- 1 (Burgasser & Mamajek, 2017) and Kepler-444 (Mack et al., 2018) are shown for reference in blue and red, respectively.