**On the role of the carbon cycle and plate tectonics in the development of habitable climates on Extrasolar worlds around M Dwarf stars. Earth as an analog.**

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ABSTRACT

1. Introduction

The Solar System is home to the only known inhabited planet: Earth. Our Solar System's history has driven the earliest notions of a "habitable zone" (HZ) that have traditionally been applied to evaluate the potential for life on planets discovered orbiting other stars in the Milky Way. Water is thought to be critical for the development of life, so habitability, defined in simplest terms, refers to the extent of a planet's ability to sustain liquid water oceans (Kasting and Catling 2003). To first order, to be habitable, a planet must lie within a habitable zone or the range of orbital distances where water can exist in stable phase on a rocky planet’s surface and it must have accreted enough water to produce an ocean. However, lying within the HZ alone does not guarantee suitability for the rise of life, the abundance of greenhouse gases in a planet’s atmosphere is also critical.

The long-term carbon cycle is vital for maintaining liquid water oceans on rocky planets due to the negative climate feedbacks involved in carbonate-silicate weathering. Plate tectonics plays a crucial role in driving the long-term carbon cycle via its input and output of CO2 to the atmospheric reservoir through CO2 degassing at ridges and arcs, the return of CO2 through subduction of oceanic crust bearing carbonate-rich biogenic sediment at continental margins and carbonate-silicate weathering by the supply of fresh weatherable substrate to the surface via uplift and orogenic events. Recent advances in theoretical research have revealed a host of factors that contribute to determining a planet's habitability beyond orbital distance from its host star. Particularly, the interaction between a star and orbiting planets can bring about both radiative and gravitational effects on planetary climate (Budyko et al 1969, Barnes et al, 2008). These effects are now contributing to a larger discussion of habitability. Subsequently, an understanding of how these processes might change for different host stars and planetary system architectures has expanded and deepened.

Interest in M-dwarf stars as hosts for habitable planets has increased considerably over the last twenty years as the field of exoplanet discovery and characterization has grown. Since M dwarfs comprise ~75% of all stars in the galaxy (Bochanski et al., 2010), they offer the best chance of finding habitable planets through the sheer population size but also proximity to the local solar neighborhood (~15 ly). They also offer distinct observational advantages. Small planets are easier to detect orbiting smaller stars via the radial velocity and transit techniques as spectroscopic Doppler shifts and photometric transit depths are larger owed to the smaller star-to-planet mass and size ratios. In addition, their relatively low stellar temperatures and luminosities determine that the HZ around these stars are much closer in than their Sun-like counterparts, increasing the geometric probability of observing a transit, therein a possible planetary detection, (Gould et al., 2003) as well as the frequency of transits of potential HZ planets during a discrete observational time period. Small rocky planets with atmospheres located around low-mass stars such as M Dwarfs are also better suited for investigations using transmission spectroscopy to characterize their atmospheres (Kreidberg et al., 2014).

Furthermore, the extended stellar lifetimes of M-dwarf stars are a special benefit in the discussion of the potential for life on an orbiting planet. The "dwarf" designation is assigned to stars that are in the main sequence phase of stellar evolution and also markedly means they are fusing hydrogen to helium in their cores. Every M star that has ever formed is still on the Main Sequence. This is because M-dwarfs, with their low masses, burn their nuclear fuel at significantly slower rates as compared to Sun-like or brighter and more massive stars (Tartar et al., 2007). Consequently, they are extremely long lived with main sequence lifetimes of trillions of years for the lowest mass M-dwarfs (Laughlin et al., 1997). They would therefor offer appropriate timescales subject to biological development and evolution on their planetary companions.

In this work, I investigate the stability that the carbon cycle can provide to the climate system of an Earth analog around a young M Dwarf star. This will be done chiefly by examining a model parameterization of land fraction on atmospheric CO2 concentrations for modern Earth conditions to assess how the climate might respond to the effects of insolation over a range of habitable zone limits around M-dwarf stars.

* 1. Spectroscopy of the M-dwarf class.

The advent of optical spectroscopy revolutionized astrophysics in the mid-nineteenth century. For the first time, Astronomers could examine the nature of stellar material and theorize the mechanisms behind associated radiative processes. With such an advancement, the spectral energy distribution (or black body radiation curve) of stars became an important tool in finely resolving the radiative output as well as atomic/molecular content of stars via increases . Early attempts at developing classification schemes were based on the shape of the spectral energy distribution as well as colors of their emissions in the optical region of the electromagnetic spectrum. Novel classification systems for stellar populations converged on an ordering of stars from blue to red, reflecting suspicions that this represented a scale of decreasing temperature and perhaps and evolutionary sequence. In summary

Questions in stellar astrophysics often begin with reference to what is known as the Hertzprung-Russel diagram

Should I include a description about the M spectral class -> explanation for the motivation of using early M3 in the model... ->Stellar flares, UV output, Magnetic activity...not sure what section it belongs in.

2. Model Setup

Global Carbon Cycle models of varying intricacy have been used to investigate the long-term evolution of Earth and other planets (Walker et al, 1981; Takija and Matsui 1990,1992) as well for more in-depth studies of Neoproterozoic and Phanerozoic climate evolution. In this work, a simple model is used to focus on the first order effects of land area on climate stabilization via the global carbon cycle for a terrestrial analog around an early spectral type M dwarf star. To relate atmospheric CO2 to surface temperature, a simple parameterization from (Walker et al 1981) is used:

where = 285 K is the present day surface temperature, is the effective temperature, and =254 K is the present day effective temperature. It should be noted that this parameterization also includes the contribution of water vapor to greenhouse warming, assuming that H20 is always saturated in the atmosphere. The effective temperature is related to the absorbed solar radiation following

Where S is the solar irradiance, A is the Albedo, and is the Stefan Boltzmann constant. In this work, albedo will be held constant for simplicity so that ice-albedo feedbacks, or the currently poorly understood feedbacks involving clouds (e.g Leconte et al. 2013; Wolf and Toon 2014) are not included. This parameterization provides a good first order approximation to the results of more complex radiative-convective models for an Earth-like planet (Kasting & Ackerman 1986).

Although temperatures reach ~600 k at pco2 ~ 107 Pa, liquid water is still stable at the surface. A true runaway greenhouse, where liquid water cannot exist in stable phase on the planetary surface, is thought only to be possible through increases in insolation rather than through the increase in atmospheric opacity via elevated levels CO2 levels (Nakajima et al. 1992). However above 350 K the atmosphere would be in a moist greenhouse state, where although surface liquid water is stable, high mixing ratios H20 in the stratosphere lead to rapid water loss to space. (Abbot et al. 2012). These are distinctions, however, for Earth around the sun. For an M dwarf star the orbital distance for runaway greenhouse temperatures much too close for an early M dwarf star. At distances of 0.07 AU, the coupling of tidal locking and large irradiation in the Xray and UV bands present other issues for habitable atmospheres and climate. Water loss, or other potential complications are not modeled in this study, rather i look at the expected climate for a terrestrial analog while varying land area(atm CO2 content) and incoming stellar fluxes.