

Extreme Climate Variations from Milankovitch-like Eccentricity Oscillations in Extrasolar Planetary Systems

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Climate Change at the Eve of the Second Decade of the Century

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ABSTRACT

Although our solar system features predominantly circular orbits, the exoplanets discovered so far indicate that this is the exception rather than the rule. This could have crucial consequences for exoplanet climates, both because eccentric terrestrial exoplanets could have extreme seasonal variations, and because giant planets on eccentric orbits could excite Milankovitch-like variations of a potentially habitable terrestrial planets eccentricity, on timescales of thousands-to-millions of years. A particularly interesting implication concerns the fact that the Earth is thought to have gone through at least one globally frozen, “snowball” state in the last billion years that it presumably exited after several million years of buildup of greenhouse gases when the ice-cover shut off the carbonate-silicate cycle. Water-rich extrasolar terrestrial planets with the capacity to host life might be at risk of falling into similar snowball states. Here we show that if a terrestrial planet has a giant companion on a sufficiently eccentric orbit, it can undergo Milankovitch-like oscillations of eccentricity of great enough magnitude to melt out of a snowball state.

Proceeding

Even very mild astronomical forcings can have dramatic influence on the Earth’s climate. Although the orbital eccentricity varies between ~ 0 and only ~ 0.06 , and the axial tilt, or obliquity, between $\sim 22.1^\circ$ and 24.5° , these slight quasi-periodic changes are sufficient to help drive the Earth into ice ages at regular intervals. Milankovitch articulated this possibility in his astronomical theory of climate change. Specifically, Milankovitch posited a causal connection between three astronomical cycles (precession – 23 kyr period, and variation of both obliquity and eccentricity – 41-kyr and 100-kyr periods, respectively) and the onset of glaciation/deglaciation. Though much remains to be discovered about these cycles, often in the literature referred to as “Milankovitch cycles,”¹ they are now generally acknowledged to

¹Or as “Croll-Milankovitch cycles” (1; 2).

have been the dominant factor governing the climate changes of the last several million years (3; 4; 5; 6; 7).

The nonzero (but, at just 0.05, nearly zero) eccentricity of Jupiter’s orbit is the primary driver of the Earth’s eccentricity Milankovitch cycle. Were Jupiter’s eccentricity greater, it would drive larger amplitude variations of the Earth’s eccentricity. This same mechanism might be operating in other solar systems. In the last 15 years, roughly ~ 500 extrasolar planets have been discovered around other stars, where an object is here defined as a “planet” by the condition that it will not burn significant amounts of deuterium, which corresponds approximately to 13 Jupiter masses (8). (This might not be the best way to define exoplanets, but it is probably the most widely used.). Among these ~ 500 , there are many that have masses comparable to Jupiter’s and that are on highly eccentric orbits; $\sim 20\%$ of the known exoplanets have eccentricities greater than 0.4, including such extreme values as 0.93 and 0.97 (HD 20782b; HD 80606). Furthermore, tantalizing evidence suggests that lower mass terrestrial planets might be even more numerous than the giant planets that are easier to detect. Therefore, it seems highly likely that many terrestrial planets in our galaxy experience exaggerated versions of the Earth’s eccentricity Milankovitch cycle.

These kinds of cycles could have dramatic influence on life that requires liquid water. Since the seminal work of Milankovitch several decades ago, a variety of theoretical investigations have examined the possible climatic habitability of terrestrial exoplanets. Kasting and collaborators emphasized that the habitability of an exoplanet depends on the properties of the host star (9). Several authors have considered how a planet’s climatic habitability depends on the properties of the planet, as well. In particular, two recent papers have focused on the climatic effect of orbital eccentricity. Williams & Pollard used a general circulation climate model to address the question of how the Earth’s climate would be affected by a more eccentric orbit (10). Dressing et al. used an energy balance climate model (11) to explore the combined influences of eccentricity and obliquity on the climates of terrestrial exoplanets with generic surface geography (see also (12) and (13; 14) for further description of the model). A more eccentric orbit both accentuates the difference between stellar irradiation at periastron and at apoastron, and increases the annually averaged irradiation. Thus, periodic oscillations of eccentricity will cause concomitant oscillations of both the degree of seasonal extremes and of the total amount of starlight incident on the planet in each annual cycle. Since these oscillations depend on gravitational perturbations from other companion objects, the present paper can be thought of as examining how a terrestrial planet’s climatic habitability depends not just on its star, not just on its own intrinsic properties, but also on the properties of the planetary system in which it resides.

There is evidence that, at some point in the last billion years, Earth went through a “Snowball Earth” state in which it was fully (or almost fully) covered with snow and ice. The high albedo of ice gives rise to a positive feedback loop in which decreasing surface temperatures lead to greater ice-cover and therefore to further net cooling. As a result, the existence of a low-temperature equilibrium climate might be a generic feature of water-rich

terrestrial planets, and such planets might have a tendency to enter snowball states. The ice-albedo feedback makes it quite difficult for a planet to recover from such a state. In temperate conditions, the Earth’s carbonate-silicate weathering cycle acts as a “chemical thermostat” that tends to prevent surface temperatures from straying too far from the freezing point of water. A snowball state would interrupt this cycle. The standard explanation of how the Earth might have exited its snowball state is that this interruption of the weathering cycle would have allowed carbon dioxide to build up to concentrations approaching ~ 1 bar over a million-to-10-million years, at which point the greenhouse effect would have been sufficient to melt the ice-cover and restore temperate conditions.²

However, an exoplanet in a snowball state that is undergoing a large excitation of its eccentricity might be able to melt out of its globally frozen state in significantly less time, depending on the magnitude of the eccentricity variations and on other properties of the planet. Exploring this possibility is the primary focus of (17), in which, using an energy balance climate model, we searched for orbital configurations that would lead to an ice-covered planet melting out of the snowball state. In brief, we found that orbital configurations that are not unlikely could cause a snowball-Earth-analog to melt out by dint of increased eccentricity.

Figure 1 shows the temperature evolution of two cold-start planet models, one of which (on the right) has a crude approximation of a carbonate-silicate cycle incorporated in the infrared cooling term, and the other (on the left) does not. Both model planets have orbital semimajor axis 1 AU, and are initialized to very cold temperatures. The high orbital eccentricity of these models (0.8) causes them to intercept more stellar irradiation over the annual cycle than would a model on a circular orbit. They therefore heat rapidly and, with a crude accounting of the latent heat of melting/freezing water (17), are eventually able to melt through the ice layer. Figure 2 shows two different compressed Milankovitch-like cycles. In each, a cycle that might take 10,000 – 400,000 years is compressed to 25 years, for computational feasibility and visualization purposes. In one (the top row), the planet is at semimajor axis 1 AU and has eccentricity varying sinusoidally between 0 and 0.83. In the other (bottom row), the planet is at semimajor axis 0.8 AU and has eccentricity varying between 0.1 and 0.33. In each case, after several years, a “catastrophic event” dramatically increases the albedo for several years, so as to plunge the model planet into a snowball state. The increasing eccentricity, then, eventually leads the planet to melt out of the snowball state. Finally, see Figures 3 and 4 of (17) for examples of the magnitudes and frequencies of Milankovitch-like eccentricity oscillations that can result from gravitational interactions between an eccentric

²Even an ice-encrusted planet in the habitable zone will eventually melt, due to the post-main sequence red-giant evolution of a Sun-like star, as the star grows larger and brighter. The planet will not enjoy temperate conditions for long, however, as the continued growth in size and luminosity of the giant will eventually sterilize it of any water-based surface life. Whether the Earth will be engulfed by the Sun in its giant phase (either by direct expansion or by tidal decay of its orbit), or will survive through the planetary nebula phase, remains an open question (15; 16).

giant planet and a terrestrial planet. Though these kinds of oscillations might be rare, they are not impossible. Entirely prosaic planetary system architectures can lead to less dramatic, but still highly important, variations of a terrestrial planet’s eccentricity.

In the coming years, as new observatories such as the James Webb Space Telescope come online, exploring the atmospheres and atmospheric dynamics of exoplanets will become an increasingly tractable research problem. Already, planets of the hot Jupiter class have been amenable to investigation with the Spitzer Space Telescope, Kepler, and various ground-based observatories (see, e.g., (18; 19; 20; 21; 22; 23; 24), and more). It might even be possible to probe the atmospheric composition of even extremely distant exoplanets, in the Galactic bulge (25). Increasingly, it is possible to learn about the properties of Neptune-mass exoplanets (26; 27; 28). Discerning the spectral signatures of habitability and of life on terrestrial planets will be the next frontier (29). As the field of exoplanets matures, it will be important to keep in mind that the long-term climatic habitability of a planet might depend not just on the intrinsic properties of the host star and of the planet itself, but also on the detailed architecture of the planetary system in which the planet resides.

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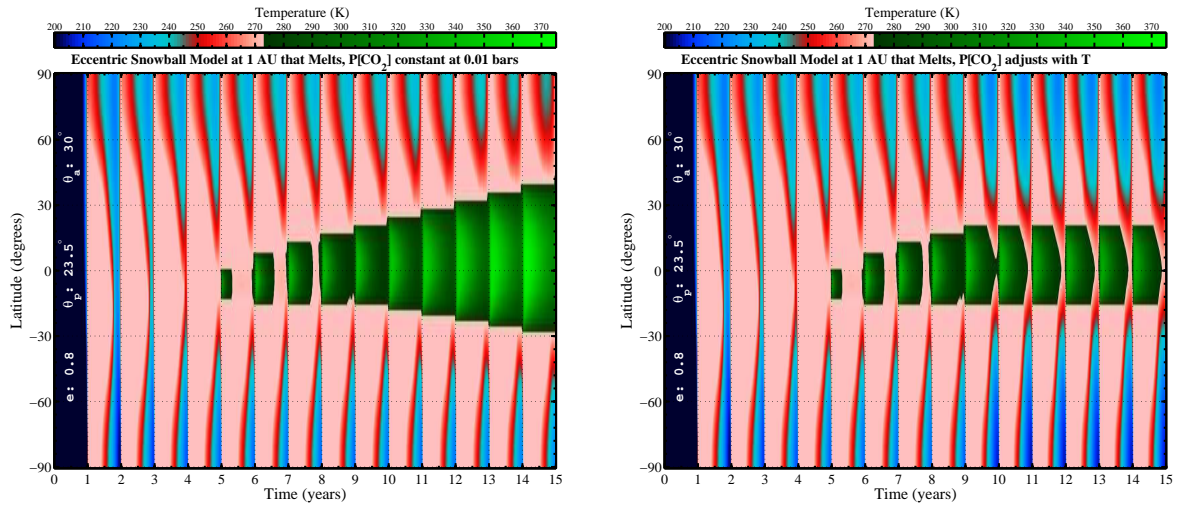


Fig. 1.— Temperature evolution maps for cold-start models at 1 AU. Both models have orbital eccentricity of 0.8 along with Earth-like 23.5° polar obliquity and 1 bar surface pressure. Temperature is initialized to 100 K, and quickly rises to near 273 K. The melting of the ice-cover is handled in accordance with the prescription of (17). **Left:** CO_2 partial pressure is held constant at 0.01 bars. In this model, once the equatorial region melts, the region of surface that has melted ice-cover grows steadily until the entire planet has melted, and temperatures eventually grow to more than 400 K over much of the planet (not shown). **Right:** CO_2 partial pressure varies with temperature, in a crude simulation of a “chemical thermostat”. In this model, the climate reaches a stable state with equatorial melt regions and polar ice-cover.

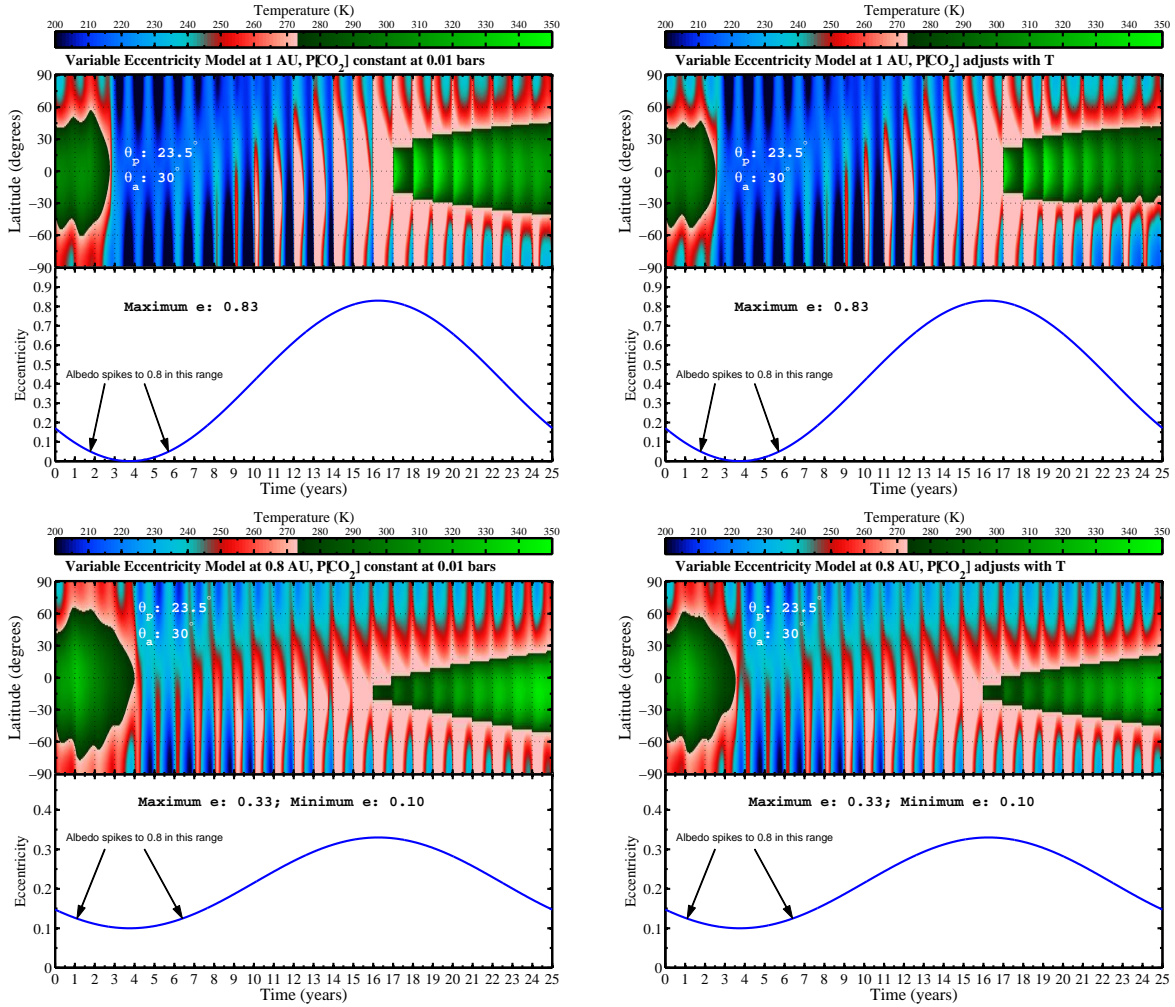


Fig. 2.— Compressed Milankovitch-like evolution of eccentricity and temperature at 1 AU and at 0.8 AU. Planets are initialized with warm equator and cold poles, similar to present-day Earth. In the top row (1 AU), the model planets are the same as in Fig. 1, except the eccentricity varies sinusoidally between 0 and 0.83 with a 25-year period, to simulate a time-acceleration (by a factor of $\sim 10^2$ to $\sim 10^4$) of a Milankovitch-like cycle. When the eccentricity falls below 0.05, the planet’s albedo spikes to 0.8, simulating a catastrophic event that plunges the planet into a snowball state, with the latent heat prescription of (17). In the bottom row (0.8 AU), the eccentricity varies between 0.1 and 0.33, also with a 25-year period. **Left:** CO_2 partial pressure is held fixed at 0.01 bars. As in the left panel of Fig. 1, these planets do not establish a temperate equilibrium. **Right:** CO_2 partial pressure varies with temperature. Here, temperature increases are muted by reduced greenhouse effect once the ice-cover has melted somewhere.