The Effect of Host Star Spectral Energy Distribution on Ice Line Latitude in Terrestrial Exoplanetary Systems

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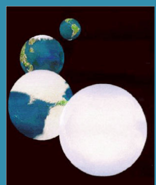
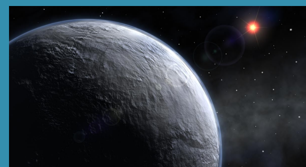
Motivation





Figs. 1 and 2 –The Earth is believed to have experienced multiple climate changes over its 4.5 billion year lifetime, including glacial episodes. Three of these glacial periods extended to low-latitudes, termed "Snowball Earth" events.

The outer edge of the habitable zone is defined as the distance from its host star at which a planet's surface freezes over, and depends on the luminosity of the star. Because of the spectral dependence of ice albedo, the ice-albedo feedback mechanism is sensitive to the wavelength of light coming from the host star, and complicates the calculation of the outer edge of the habitable zone for different stars. Recent models have suggested that the transition to a snowball state for planets is dependent on multiple factors. Here we examine the affect of stellar spectral type, given the spectral dependence of planetary surfaces, particularly ice.

Abstract

The ice-albedo feedback mechanism is a positive feedback process in which a change in ice cover, due to a warming or cooling trend, alters the albedo of a planet and reinforces the original climate perturbation. Because of the spectral dependence of ice albedo, the behavior of this mechanism is sensitive to the type of stellar radiation incident on a planetary surface. Previous work has implied that planets around M stars would demonstrate a suppression in ice-albedo feedback due to ice absorbing strongly at infrared wavelengths, where M stars emit a significant fraction of their radiation [1]. Using a 1-D, line-by-line radiative transfer model, the Spectral Mapping and Atmospheric Radiative Transfer model (SMART) , we quantify the effect of stellar spectral energy distribution on the broadband albedo of snow and ice of varying grain size and porosity [2]. We demonstrate that terrestrial planets orbiting stars with higher near-UV radiation output than the Sun would exhibit a stronger ice-albedo feedback, and could become ice-covered . Using a seasonal energy balance model, we examine the degree to which ice line latitude is affected by ice albedo and explore how changes to land distribution and planetary obliquity affect this result.

Results

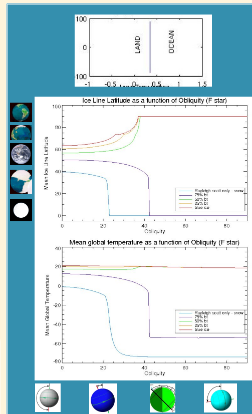


Fig. 7 – F star, symmetric land/ocean

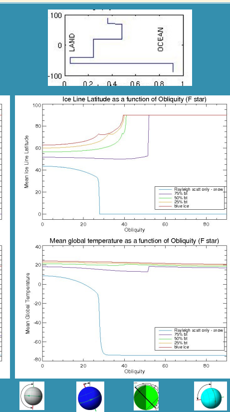


Fig. 8 – F star, modern land/ocean

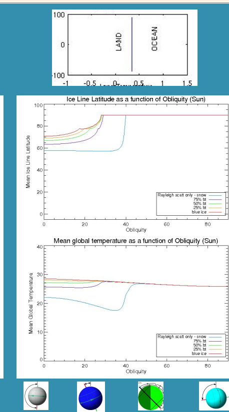


Fig. 9 – Sun (G star), symmetric land/ocean

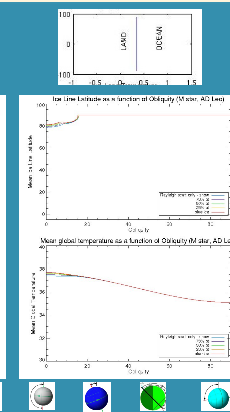


Fig. 10 – M star, symmetric land/ocean

Fig. 7-10 - Here ice line latitude is calculated for planets orbiting different stars at the distance at which they receive the equivalent flux from their star that Earth receives from the Sun. No atmospheric constituents are included in these simulations, but the effect of Rayleigh scattering within an Earth-like air composition is incorporated. We use ice surfaces of varying density as input for below-freezing surfaces in the seasonal EBM. The higher the albedo of ice, the farther towards the equator the ice extends.

For low obliquities, seasonal variability is low, leading to colder summer temperatures and warmer winter temperatures (which may allow greater snow accumulation during cold seasons, since warmer-than-average air can hold more moisture). Decreasing snowmelt and increasing winter snow accumulation, coupled with ice-albedo feedback, can lead to ice volume growth. At high obliquities, the summer hemisphere insolation is high, leading to warmer summers, increased melting of ice at high latitudes in the summer hemisphere, and colder winters. This may lead to the ice retreating, and eventually melting entirely. For fresh snow and high albedo ice surfaces, ice-covered states are possible for a symmetric land/ocean configuration on planets orbiting F stars. For certain obliquities and relatively high ice albedos, multiple stable states are possible. For a modern land/ocean configuration, the ice-albedo feedback mechanism is weakened in the northern hemisphere, due to the greater percentage of ice-free land.

The spectral dependence of ice

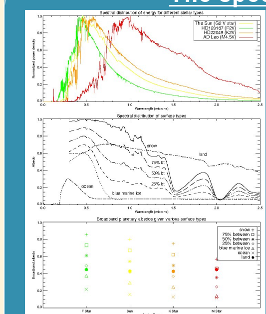


Fig. 3 – Spectra of F, G, K, and M stars (top), spectral albedo of ice of varying density compared with ocean and land spectra (middle), and broadband albedos of a planet covered in different surface types as a function of host star spectral energy distribution, using SMART (bottom).

Fig. 4 – Ice albedo is a critical parameter in climate models. Fresh snow has a high albedo (~0.9). Bubble-free marine ice has a low albedo (~0.4). Ice may exit between these two states, and has been modeled in Fig. 2 (Photo courtesy of Stephen Warren).

In the near-UV and visible parts of the spectrum, both ice and snow albedos are high, while in the IR, ice and snow become extremely absorptive, due to molecular vibrations involving various combinations of the water molecule's three fundamental vibrational modes. The ice-albedo feedback mechanism may be enhanced on planets orbiting F stars, which emit strongly in the visible and near-UV.

Conclusions:

- Ice-covered states are possible for planets orbiting in the habitable zones of F stars, due to ice reflecting strongly at visible and near-ultraviolet wavelengths, where F stars emit a large fraction of their light. However the presence of greenhouse gases could ameliorate this result.
- M stars are more stable to ice-albedo feedback than F stars, confirming the supposition of Joshi and Haberle (2012) that snowball states may be less likely on planets orbiting red dwarf stars.
- Incorporation of atmospheric constituents with a full-scale General Circulation Model (GCM) will address the affect of gas absorption on ice line latitude as a function of host star spectral type.

The Model

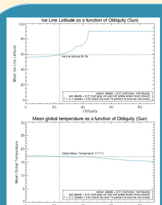


Fig.5 – The Earth's ice line latitude at its present obliquity is validated.

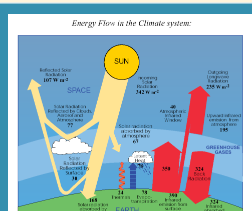


Fig. 6 – Energy Flow in the climate system

Energy balance climate models (EBMs) estimate the change in a climate system from an analysis of the energy budget of the planet. Here we use a seasonally varying one-dimensional energy balance model based on the work of North and Coakley (1979) to evaluate how ice line latitude changes as a function of obliquity, given broadband planetary albedos for land, ocean, and ice-covered areas, calculated with SMART using different stellar spectral energy distributions as input [3]. We have validated this method by calculating the Earth's current ice line to within a degree in latitude, and global mean surface temperature to within two degrees Celsius. Earth's present atmospheric composition was used in our SMART runs.

Acknowledgments:

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References:

[1] Joshi, M. and Haberle, R.M., (2012) Astrobiology, 12(1), 3-8.

[2] Meadows, V.S. and Crisp, D., (1996) Journal of Geophysical Research, 101, 4595– 4622.

[3] North, G.R. and Coakley, J.A., (1979) Journal of Atmospheric Sciences, 36, 1189-1204.