Recipe for a Habitable Planet

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A moment to pause…
Leading effectively during COVID-19

- Employees Need Trust and Compassion: Be Present, Even When You're Distant
- Employees Need Stability: Prioritize Wellbeing Amid Disruption
- Employees Need Hope: Anchor to Your "True North"

Hobbies:
- reading
- movies, shows
- knitting
- mixed media/collage
- violin
- tea
- yoga
- good restaurants
- spa days
- the beach
- hiking
- smelling flowers
- hanging with family
Suppression of the Water Ice and Snow Albedo Feedback on Planets Orbiting Red Dwarf Stars and the Subsequent Widening of the Habitable Zone

Manoj M. Joshi and Robert M. Haberle

Published Online: 23 Jan 2012 | https://doi.org/10.1089/ast.2011.0668
WE’RE LIVING
IN A WHOLE NEW UNIVERSE NOW...
A Jupiter-mass companion to a solar-type star

Michel Mayor & Didier Queloz

Geneva Observatory, 51 Chemin des Maillettes, CH-1290 Sauverny, Switzerland

The presence of a Jupiter-mass companion to the star 51 Pegasi is inferred from observations of periodic variations in the star's radial velocity. The companion lies only about eight million kilometres from the star, which would be well inside the orbit of Mercury in our Solar System. This object might be a gas-giant planet that has migrated to this location through orbital evolution, or from the radiative stripping of a brown dwarf.
As of December 2, 2020

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TESS
Transiting Exoplanet Survey Satellite
Proxima Centauri b
LHS 1140b

Credit: ESO
Which ones do we follow up on?
The Habitable Zone

(Kasting et al. 1993, Kopparapu et al. 2013)

Many factors can affect planetary habitability

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Recipe for a Habitable World
Stellar Effects
Planetary System
Liquid water
Galactic Location
Composition & Structure
Spectral Energy Distribution
Orbits
Stellar Effects
Planetary Properties
Orbital Evolution
Sidereal Planets
Dynamics
Surface
Interior
Atmosphere
Atm. Structure
Visible Structure
Outgassing
UV Shielding
1-D Energy Balance Model (EBM)

- Broadband albedos
- Two-band albedos (for example – Vis/IR)
- Weight by host star spectrum
- EBM needs a separate R-T model to incorporate atmosphere into broadband planetary albedo calculation

Global Climate Model (GCM)

Based on McGuffie and Henderson-Sellers (2005)
Global Climate Model (GCM)
(Ex. CCSM4 (Gent et al. 2011), LMD Generic GCM (Hourdin et al. 2006))
Conservation of momentum
\[ \frac{d\vec{v}}{dt} = -\frac{1}{\rho} \nabla p - \vec{g} + \vec{F}_{fric} - 2\Omega \times \vec{v} \]

Mass continuity
\[ \frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \vec{v}) \]

Conservation of energy (1st law of thermo)
\[ Q = C_p \frac{dT}{dt} - \frac{1}{\rho} \frac{dp}{dt} \]

Equation of state for the atmosphere
\[ p = \rho RT \]
PREDICTING FUTURE CLIMATE ON EARTH
Waterbelt Snowball Earth as refuge for photosynthetic life

Schematic Diagram of Jormungand Global Climate State

- Snowbelt
  - Thick, permanent, snow-covered, sea glacier
  - Narrow strip of open ocean
- Snow belt
  - Thin, seasonal, bare sea ice

Latitude:
- Pole
- ~20°
- Equator
Warming Early Mars

“Eyeball Earth” scenario for Gliese 581 g

Pierrehumbert 2011
Habitable climates on Proxima Centauri b

Turbe et al. 2016
Ice-albedo Feedback
M-dwarf planets

Image credit: ESO/L. Calçada

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M-dwarf planets exhibit more stable climates in simulations

Shields et al. (2013)
Shields et al. (2014)

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Effect holds across multiple possible climate regimes

Wolf, Shields+ (2017)

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Sodium chloride dihydrate ("hydrohalite")
NaCl \cdot 2\text{H}_2\text{O}
Hydrohalite precipitation in sea ice

$T < -23^\circ C$

Carns et al. 2015
Hydrohalite is highly reflective in the IR.
Hydrohalite parameterization matters in the HZ, and climate sensitivity increases as instellation is lowered.
Stronger climate sensitivity to hydrohalite parameterization on synchronously-rotating M-dwarf planets

Shields and Carns 2018
Trenberth diagram

Global Energy Flows W m\(^{-2}\)

Credit: Kevin Trenberth, John Fasullo and Jeff Kiehl
Starlight (% of what Earth gets from the Sun)  
Shields et al. 2019

Instellation (% of Modern Solar Constant)

- M-dwarf planet
- G-dwarf planet
- F-dwarf planet

Global Mean Surface Temperature (K)

- 88%
- 100%
- 108%
G-dwarf planet

Total shortwave reflected to space 111 W/m²
Incoming shortwave 340 W/m²
OLR (longwave) 229 W/m²

27% reflected
19% absorbed
10% reflected

Atmosphere

Surface

165 W/m² Absorbed by surface
184 W/m² Shortwave flux to surface
103 W/m² Latent heat flux
168 W/m² Longwave absorbed by atm.
397 W/m² Longwave emitted by surface
345 W/m² Longwave emitted by atmosphere to surface

Shields et al. 2019
M-dwarf planet

Shields et al. 2019

18% reflected

34% absorbed

7% reflected

Total shortwave reflected to space 63 W/m²

Incoming shortwave 299 W/m²

OLR (longwave) 237 W/m²

Longwave emitted by atmosphere to surface 341 W/m²

134 W/m² Net LW Emitted by surface

134 W/m² Absorbed by surface

Shortwave flux to surface 144 W/m²

Latent heat flux 76 W/m²

Longwave absorbed by atm. 155 W/m²

Longwave emitted by surface 392 W/m²

Sensible heat flux 7 W/m²
Surface Albedo

Ice Fraction

Shields et al. 2019
1-D Energy Balance Model (EBM)

Based on McGuffie and Henderson-Sellers (2005)
\[
Q S(x, t)(1 - \alpha_L) = C_L \frac{dT_L}{dt} - \frac{d}{dx} D(1 - x^2) \frac{dT_L}{dx} + \frac{\nu}{f_L(x)} (T_L - T_W) + (A + BT_L)
\]

\[
Q S(x, t)(1 - \alpha_W) = C_W \frac{dT_W}{dt} - \frac{d}{dx} D(1 - x^2) \frac{dT_W}{dx} + \frac{\nu}{f_W(x)} (T_W - T_L) + (A + BT_W)
\]
\[ QS(x, t)(1 - \alpha_L) = C_L \frac{dT_L}{dt} - \frac{d}{dx} D(1 - x^2) \frac{dT_L}{dx} + \frac{\nu}{f_L(x)} (T_L - T_W) + (A + BT_L) \]

\[ QS(x, t)(1 - \alpha_W) = C_W \frac{dT_W}{dt} - \frac{d}{dx} D(1 - x^2) \frac{dT_W}{dx} + \frac{\nu}{f_W(x)} (T_W - T_L) + (A + BT_W) \]
SMART
(Spectral Mapping Atmospheric Radiative Transfer model)
Meadows & Crisp, 1997; Crisp 1997

\[
\mu \frac{dI(\tau, \mu, \phi, \nu)}{d\tau} = I(\tau, \mu, \phi, \nu) - S(\tau, \mu, \phi, \nu)
\]

\[
S(\tau, \mu, \phi, \nu) = \frac{\omega(\tau, \nu)}{4\pi} \int_0^{2\pi} d\phi' \int_{-1}^{1} d\mu' P(\tau, \mu, \phi, \mu', \phi', \nu) I(\tau, \mu', \phi', \nu)
\]

\[
\quad + [1 - \omega(\tau, \nu)] B[\nu, T(\tau)]
\]

\[
\quad + \frac{\omega(\tau, \nu)}{4\pi} F_\odot P(\tau, \mu, \phi - \mu_\odot, \phi_\odot, \nu) \exp(-\tau/\mu_\odot)
\]
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\[ + [1 - \omega(\tau, \nu)] B[\nu, T(\tau)] \]

\[ + \frac{\omega(\tau, \nu)}{4\pi} F_\odot P(\tau, \mu, \phi - \mu_\odot, \phi_\odot, \nu) \exp(-\tau/\mu_\odot) \]
Land planets orbiting M-dwarf stars

After Shields et al. 2013
Planets dominated by land reflect more starlight and have lower surface temperatures than ocean-covered worlds.

But, land planets orbiting M stars are still warmer than their counterparts orbiting stars with more visible and UV light.
Temporal habitability and water loss on eccentric planets
Planets orbiting cooler stars are thawed for larger fractions of the year.
Different land surfaces will have different albedos and resulting effects on the climate of TRAPPIST-1 planets.

Differences of 50 K across lowest (granite) to highest (calcite) albedo land surface
Surface Temperature

TRAPPIST-1d most capable of supporting life (with low albedo surface (ex. igneous rock))

cross-equatorial energy transport increased for lower-albedo planets
Take –away points

• Surface composition affects planetary climate and habitability

• Important to incorporate spectral dependence of ice, snow, salt, and land albedos into GCMs

• Allows for more realistic assessments of possible climates and habitability of exoplanets
Acknowledgments

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• Allows for more realistic assessments of possible climates and habitability of exoplanets
M-dwarf planet (synchronous)

Shields et al. 2019
Synchronous rotation is possible for Kepler-62f

Shields et al. (2016a)
Surface Temperature

Obliquity = 60°

Obliquity = 23°

Southern hemisphere summer

Shields et al. (2016a)

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Shields et al. (2016a)