The Climates of Other Worlds: Searching for the Next Habitable Planet

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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.
We are in the Earth-sized regime
Exoplanet Discoveries Through the Years
As of May 10, 2016

- 1,284 Newly Validated Planets
- Previous Kepler/K2 Discoveries
- Non-Kepler Discoveries

Discovery Year

Number of New Planets

Credits: NASA Ames / W. Stenzel; Princeton University / T. Morton
NASA’s *Kepler* Mission
Transit Technique
TESS
Transiting Exoplanet Survey Satellite
TESS will identify the best and smallest exoplanet targets for characterization of atmospheres.
James Webb Space Telescope

Starlight filters through the planet’s atmosphere

absorption line spectrum

Credit: Northrop Grumman
• Habitable planet
• hosting life?
Proxima Centauri b

Credit: ESO/M. Kornmesser
Which ones do we follow up on?
New era, new approach

• Observational data AND computer models
Life’s Requirements

A Liquid \((\text{H}_2\text{O})\)

Bioessential Elements (SPONCH)

Energy (Stellar or chemical)
The Habitable Zone

Many factors can affect planetary habitability

Runaway greenhouse

Maximum CO₂ greenhouse

Distance from Star (AU)

Stellar Mass (M☉)

Snowball Earth

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Stellar Effects
Planetary System
Planetary Properties

Liquid water

Orbital Evolution
Galactic Location
Impact Flux
Magnetic Field
Dust
Minor Planets
Eccen. Oscillations
Orbits
Masses
Obliquity
Rotation rate
Oblateness
Orbit

Surface Properties
Surface Temps
Surface Pressures
Liquids
Surface Structure

Atmosphere
Composition
Albedo
Outgassing
Clouds
UV Shielding
Atm. Structure

Composition & Structure
Elem. Abundance
Metallicity
Activity
Rotation
Companions

Spectral Energy Distribution
Luminosity
Magnetic Field
Dust
Minor Planets
Orbit

Credit: Victoria Meadows
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The Climates of Other Worlds
- 1-D line-by-line radiative transfer models
  - 1-D in height
  - Atmospheric gas absorption
- Radiative convective climate models
- Energy Balance Models (EBMs)
  - 0-D or 1-D (in latitude) usually
- 3-D General Circulation Models (GCMs)
  - Sophisticated treatment of atmospheric circulation, ocean-atmosphere processes
PREDICTING FUTURE CLIMATE ON EARTH

IPCC, 2018: Summary for Policymakers

Global warming relative to 1850-1900 (°C)

- Observed monthly global mean surface temperature
- Estimated anthropogenic warming to date and likely range

Likely range of modeled responses to stylized pathways:
- Global CO₂ emissions reach net zero in 2055 while net non-CO₂ radiative forcing is reduced after 2030 (grey in b, c & d)
- Faster CO₂ reductions (blue in b & c) result in a higher probability of limiting warming to 1.5°C
- No reduction of net non-CO₂ radiative forcing (purple in d) results in a lower probability of limiting warming to 1.5°C
Exploring thaw criteria for Snowball Earth

Abbot and Pierrehumbert 2010

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Schematic Diagram of Jormungand Global Climate State

- **Eddies**
- **Net Precipitation**
- **Net Evap.**
- **Hadley Cell**
- **Thick, Permanent, Snow-Covered, Sea Glacier**
- **Thin, Seasonal, Open Ocean**

**Latitude:**
- Pole
- ~20°
- Equator

Abbot et al. 2011

Sea Ice Fraction

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M-dwarf planets

Image credit: ESO/L. Calçada

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All known stars within 10 pc
(= 33 lightyears)
of the Sun:

WD  20
O  0
B  0
A  4
F  6
G  20
K  44
M  246

figure courtesy Todd Henry; RECONS
Small planets are easier to detect around small stars.

Credit: Victoria Meadows
The Habitable Zone

Distance from Star (AU)

Snowball Earth

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Synchronous rotation and surface pressure

(Joshi, Haberle, and Reynolds 1997)
Synchronous rotation can be a benefit for climate and habitability \textsuperscript{(Yang et al. 2013)}
M-dwarf planets could lose oceans during PMS phase

(Luger and Barnes 2015)
The habitability of planets orbiting M-dwarf stars

Aomawa L. Shields, Sarah Ballard, John Asher Johnson

http://dx.doi.org/10.1016/j.physrep.2016.10.003
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
Ice-albedo Feedback
Ice absorbs where M-dwarfs emit strongly.

Shields et al. (2013)
Warren et al. (2002)
Grenfell et al. (1994)
M-dwarf planets less susceptible to snowball

Snowball!

No ice!

F-dwarf planets more susceptible to snowball

PAL ("present atm level") CO₂

Instellation (% of what Earth receives)

Shields et al. (2013)

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M-dwarf planet is more stable against convection

Shields et al. (2013)
Albedo

G-dwarf planet (100%)

M-dwarf planet (90%)

Surface Temperature

Shields et al. (2013)
Climate Stability

M-dwarf planets have more stable climates

Shorter jump in ice line  \rightarrow  Higher jump in ice line

Better for life?

Shields et al. (2014)

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HADLEY CIRCULATION CELL

Transports heat from equator to higher latitudes

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Weaker Hadley circulation helps M-dwarf planet thaw more easily

Shields et al. (2014)
Identifying Multiple Possible Climate Regimes

Wolf, Shields+ (2017)

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Sodium chloride dihydrate ("hydrohalite")
NaCl · 2H₂O
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
Targeted planet studies
"Eyeball Earth" scenario for Gliese 581 g
Pierrehumbert 2011
Multiple-planet systems

First place to look for a habitable, Earth-like planet?

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Too hot?
Kepler-62f

Needs CO₂
Stable eccentricities

$e_{f_{\text{max}}} = 0.32$

Stable ecc for Kepler-62f
$0.00 \leq e \leq 0.32$

Shields et al. (2016a)
Surface Temperature

High CO₂
Earth-like axial tilt
Circular orbit

Global mean surface temps similar to Earth!

Shields et al. 2016a

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Insolation

PAL CO₂

Shields et al. 2016a

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Surface Temperature

Obliquity = 60°

Obliquity = 23°

Freezing point

Southern hemisphere summer

Shields et al. (2016a)

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Summer solstice at closest approach

Winter solstice (southern hem) farthest approach

Shields et al. (2016a)
Surface Temperature 3 bar CO$_2$

Shields et al. (2016a)

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Take away point

Combining observations AND theory = How we will most accurately assess planetary habitability
More than the eye can see

IRAS

Axel Mellinger
"NSF Fellow Pairs Art, Astronomy to Hook Girls on Science"

Education Week, March 18, 2015

We encourage girls of all colors and backgrounds to bring their whole selves to the learning, exploration, and discovery of the universe.

By integrating creative strategies such as free writing, visual art, and theater exercises, we've created a new, innovative astronomy curriculum that addresses each girl as a whole by providing an avenue for individual self-expression and personal exploration that is intertwined with scientific engagement and

www.risingstargirls.org
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Thank you!

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Minimum land fraction for glaciations increases with redder host star SED

Rushby et al. in prep

Rushby et al. in prep
Planets orbiting cooler stars are thawed for larger fractions of the year for lower eccentricities.

Igor Palubski

Palubski et al. in prep
NEW WORK (Here at KITP)
Synchronous rotation is possible

Shields et al. (2016a)

e=0.00

e=0.32