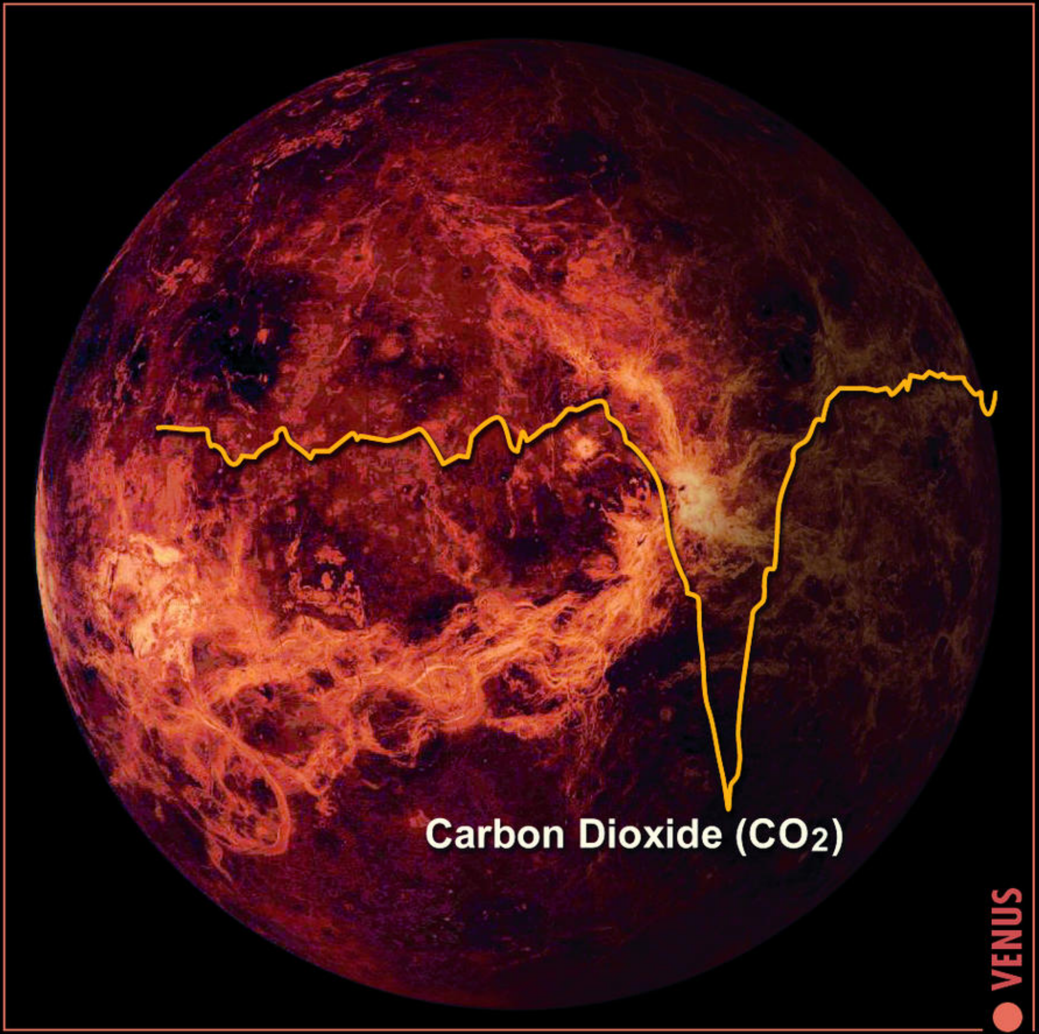
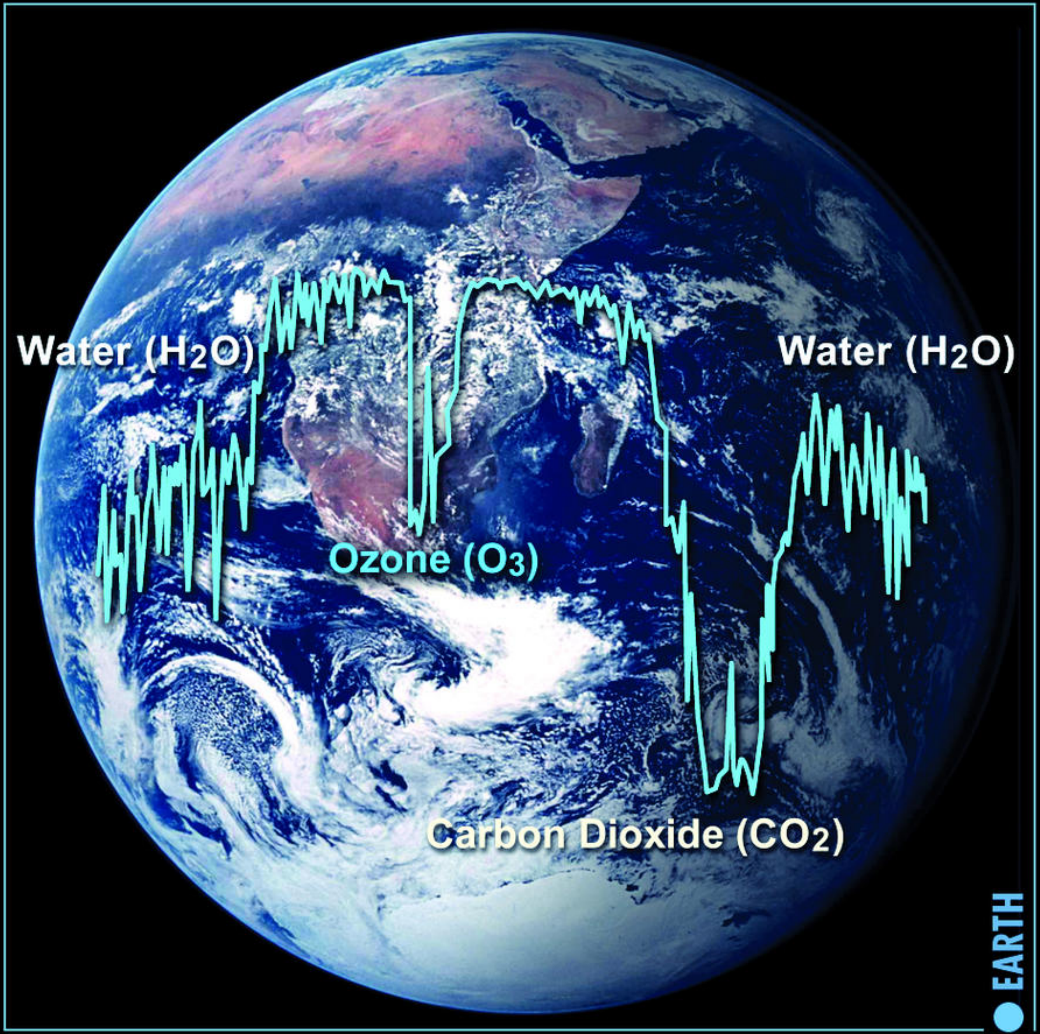
Planetary Habitability



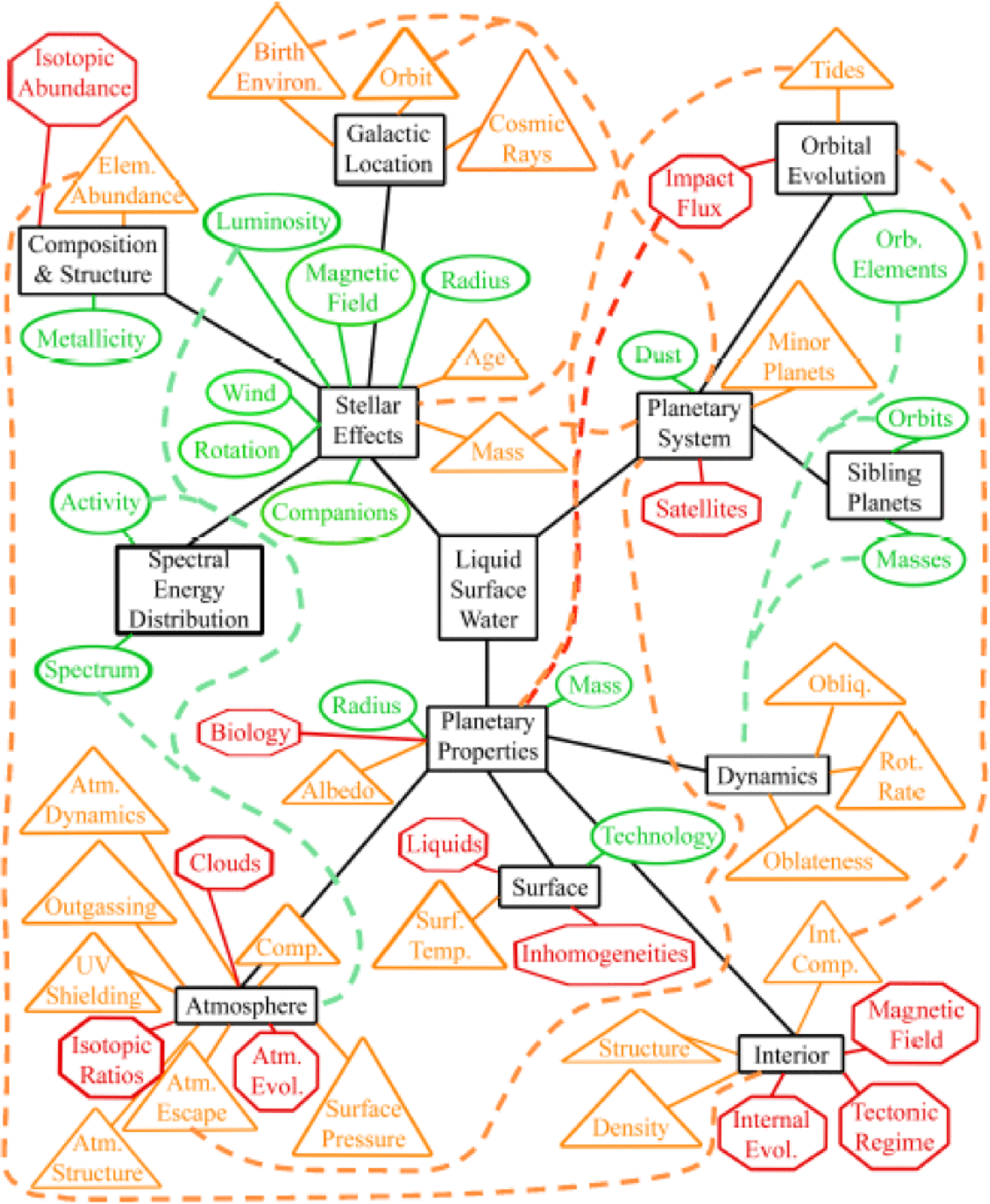


Stephen Kane

UNIVERSITY OF CALIFORNIA
UC RIVERSIDE

Topics

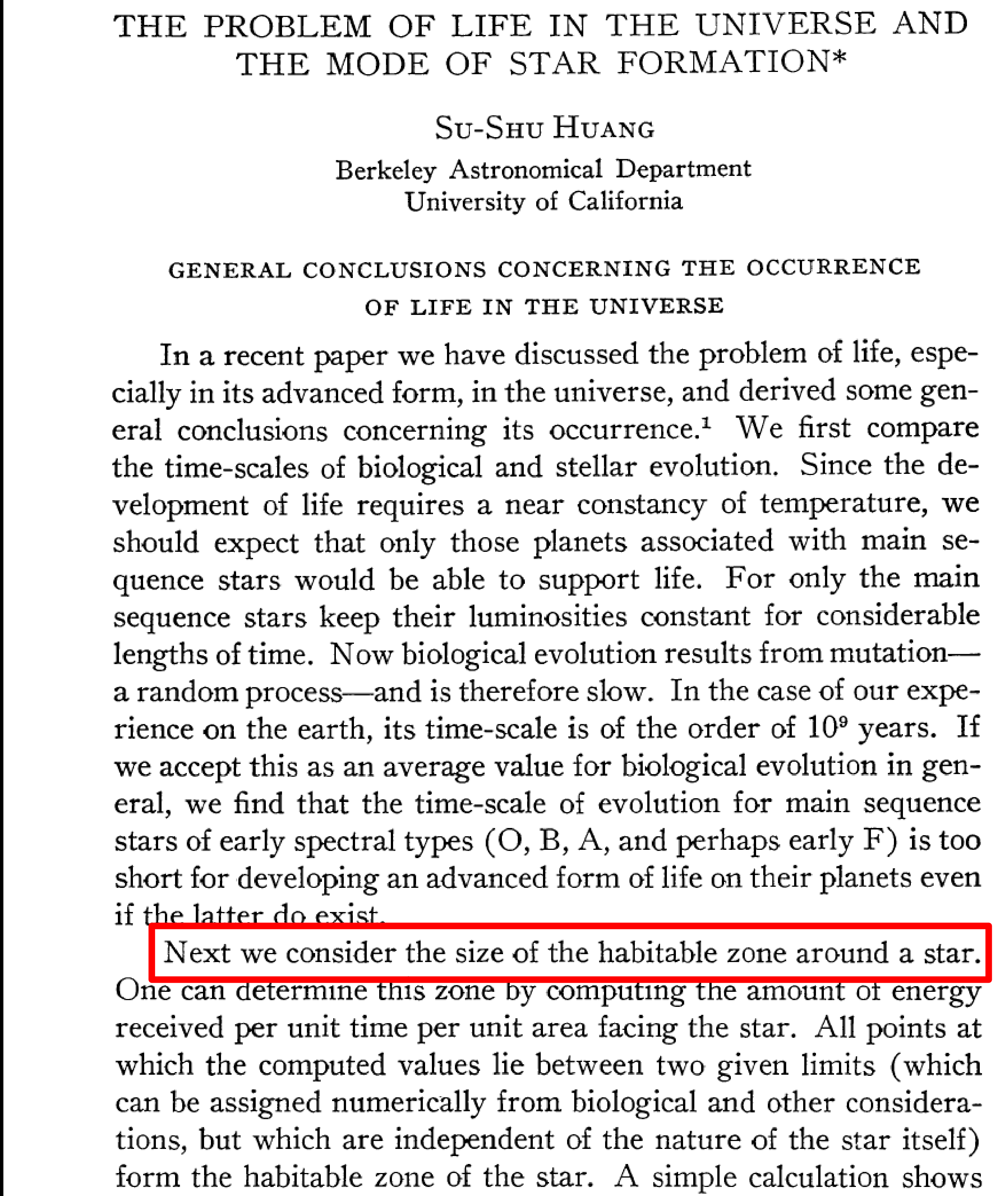
- Lecture 1 – Introduction
- Lecture 2 – Habitability Factors
- Lecture 3 - Stars
- Lecture 4 – Planetary Atmospheres
- Lecture 5 – Planetary Interiors
- Lecture 6 – Planetary Energy Balance
- Lecture 7 – Habitable Zone I
- Lecture 8 – Habitable Zone II
- Lecture 9 – Earth as a Living Planet
- Lecture 10 – Mars
- Lecture 11 – Icy Moons
- Lecture 12 – Venus
- Lecture 13 – Mercury & the Moon
- Lecture 14 – The Role of Giant Planets
- Lecture 15 – Stellar Influences
- Lecture 16 – Magnetic Fields
- Lecture 17 – Milankovitch Cycles
- Lecture 18 – Geological Cycles
- Lecture 19 – The Next Steps
- Lecture 20 – Summary/Discussion


Isotopic Abundance
Birth Environ.
Orbit
Cosmic Rays
Tides
Galactic Location
Orbital Evolution
Impact Flux
Elem. Abundance
Composition & Structure
Luminosity
Magnetic Field
Radius
Orb. Elements
Metallicity
Age
Dust
Minor Planets
Wind
Stellar Effects
Planetary System
Orbits
Rotation
Mass
Sibling Planets
Activity
Companions
Satellites
Spectral Energy Distribution
Liquid Surface Water
Masses
Spectrum
Mass
Radius
Obliq.
Biology
Planetary Properties
Dynamics
Rot. Rate
Albedo
Atm. Dynamics
Liquids
Technology
Oblateness
Clouds
Outgassing
Surface
Comp.
Surf. Temp.
Inhomogeneities
Int. Comp.
UV Shielding
Atmosphere
Magnetic Field
Isotopic Ratios
Atm. Evol.
Structure
Interior
Atm. Escape
Surface Pressure
Density
Internal Evol.
Tectonic Regime
Atm. Structure

An Incomplete List of Habitability Caveats

- **How is water delivered?**
- **When did Mars have surface water?**
- **When did Venus have surface water?**
- **Did Venus and Earth have near identical starting conditions?**
- **How small can a planet be and remain habitable?**
- **Why don’t we have a super-Earth?**
- **What does the T-P profile of a super-Earth look like?**
- **Does a giant planet beyond the snow line matter?**
- **Can life survive extreme eccentric orbits?**
- **How do terrestrial atmospheres respond to flux variations?**
- **Are circumbinary planets habitable?**
- **How does atmospheric erosion depend on magnetic field?**
- **Does a substantial moon create a more habitable world?**
- **How well do we need to understand the star?**
- ***What observations/measurements do we need to make to test the Habitable Zone hypothesis?***

Huang, S-S., 1959, PASP, 71, 421



THE PROBLEM OF LIFE IN THE UNIVERSE AND THE MODE OF STAR FORMATION*

SU-SHU HUANG
Berkeley Astronomical Department
University of California

GENERAL CONCLUSIONS CONCERNING THE OCCURRENCE OF LIFE IN THE UNIVERSE

In a recent paper we have discussed the problem of life, especially in its advanced form, in the universe, and derived some general conclusions concerning its occurrence.[1] We first compare the time-scales of biological and stellar evolution. Since the development of life requires a near constancy of temperature, we should expect that only those planets associated with main sequence stars would be able to support life. For only the main sequence stars keep their luminosities constant for considerable lengths of time. Now biological evolution results from mutation—a random process—and is therefore slow. In the case of our experience on the earth, its time-scale is of the order of 10^9 years. If we accept this as an average value for biological evolution in general, we find that the time-scale of evolution for main sequence stars of early spectral types (O, B, A, and perhaps early F) is too short for developing an advanced form of life on their planets even if the latter do exist.

Next we consider the size of the habitable zone around a star. One can determine this zone by computing the amount of energy received per unit time per unit area facing the star. All points at which the computed values lie between two given limits (which can be assigned numerically from biological and other considerations, but which are independent of the nature of the star itself) form the habitable zone of the star. A simple calculation shows

What is the “Habitable Zone”?

- The “Habitable Zone” is the region around a star where water **COULD** exist in a liquid state on the surface of a planet **IF** it has sufficient atmospheric pressure
- It does NOT comment on the presence of water
- It does NOT comment on habitability
- It does NOT comment on the presence of life
- Based on ~~one~~ several data points (size/mass of planet also matters)

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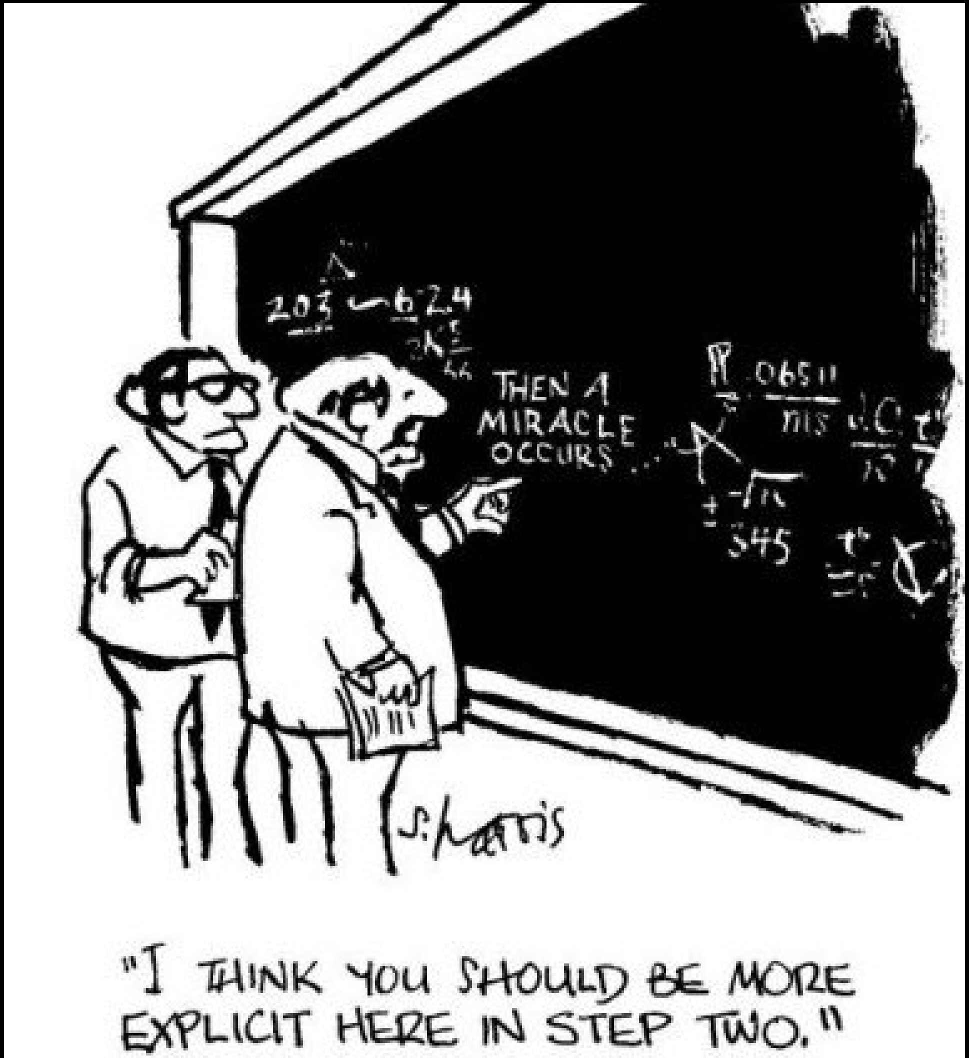
TARGET SELECTION!

What is the “Habitable Zone”?

Planet in the Habitable Zone ≠ Habitable Planet



Habitable Zone Models

- **The “Habitable Zone” is the region around a star where water could exist in a liquid state on the surface of a planet if it has sufficient atmospheric pressure**

- **“Dry Habitable Zone” (Abe et al. 2011, Astrobiology, 443, 460)**

- **Wider inner edge for Habitable Zones (Zsom et al. 2013, ApJ, 778, 109)**

- **Wider Habitable Zones for tidally-locked planets (Yang et al. 2013, ApJ, 771, L45)**

- **Petigura et al. 2013, PNAS, 110, 19273**

- **Kopparapu et al. 2013, ApJ, 765, 131**

- **Kasting et al. 2013, Nature, 504, 221**

Habitable Zones around Main Sequence Stars

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A one-dimensional climate model is used to estimate the width of the habitable zone (HZ) around our Sun and around other main sequence stars. Our basic premise is that we are dealing with Earth-like planets with $CO_2/H_2O/N_2$ atmospheres and that habitability requires the presence of liquid water on the planet's surface. The inner edge of the HZ is determined in our model by loss of water via photolysis and hydrogen escape. The outer edge of the HZ is determined by the formation of CO_2 clouds, which cool a planet's surface by increasing its albedo and by lowering the convective lapse rate. Conservative estimates for these distances in our own Solar System are 0.95 and 1.37 AU, respectively; the actual width of the present HZ could be much greater. Between these two limits, climate stability is ensured by a feedback mechanism in which atmospheric CO_2 concentrations vary inversely with planetary surface temperature. The width of the HZ is slightly greater for planets that are larger than Earth and for planets which have higher N_2 partial pressures. The HZ evolves outward in time because the Sun increases in luminosity as it ages. A conservative estimate for the width of the 4.6-Gyr continuously habitable zone (CHZ) is 0.95 to 1.15 AU. CHZs around K and M stars are wider (in log distance) than for our Sun because these stars evolve more slowly. Planets orbiting late K stars and M stars may not be habitable, however, because they can become trapped in synchronous rotation as a consequence of tidal damping. F stars have narrower (log distance) CHZ's than our Sun because they evolve more rapidly. Our results suggest that mid-to-early K stars should be considered along with G stars as optimal candidates in the search for extraterrestrial life.

I. INTRODUCTION

Astronomers have been interested for many years in the possibility of life on other planets in our own Solar System and in other planetary systems. The region around a star in which life-supporting planets can exist has been termed the "habitable zone" (Huang 1959, 1960), or the "ecosphere" (Dole 1964, Shklovski and Sagan 1966). Its limits are defined by assumed climatic constraints which

The HITRAN Database

Introduction

HITRAN is an acronym for *hi*gh-resolution *tran*smission molecular absorption database. HITRAN is a compilation of spectroscopic parameters that a variety of computer codes use to predict and simulate the transmission and emission of light in the atmosphere. The database is a long-running project started by the Air Force Cambridge Research Laboratories (AFCRL) in the late 1960s in response to the need for detailed knowledge of the infrared properties of the atmosphere.

The HITRAN compilation, and its associated database HITEMP (high-temperature spectroscopic absorption parameters), are developed and maintained at the Atomic and Molecular Physics Division, Harvard-Smithsonian Center for Astrophysics under the continued direction of Dr Laurence S. Rothman.

HITRAN*online* provides access to the latest version of the HITRAN molecular spectroscopic database.

Scientific Objectives

The simultaneous developments of high-resolution laboratory instrumentation (such as the Fourier transform spectrometer), the digital computer and storage, and sensitive detectors and the means to carry them on board high-altitude balloons and space craft provided the stimulus to create a machine-readable archive of the fundamental properties of molecular transitions. It was then possible to simulate transmission and radiance in the terrestrial atmosphere by applying known radiative-transfer equations. Thus was born the original HITRAN molecular absorption line parameters database.

The initial HITRAN was limited to the seven main telluric atmospheric absorbers in the infrared: H_2O, CO_2, O_3, N_2O, CO, CH_4, and O_2. The most significant of the isotopologues of these molecular species was also included. The initial HITRAN database included only the basic parameters necessary to solve the Lambert-Beers law of transmission, namely the line center of a transition, the intensity of the transition, and the lower-state energy. In addition, the air-broadened Lorentz width was included as well as the unique quantum identifications of the upper and lower states of each transition.

HABITABLE ZONES AROUND MAIN-SEQUENCE STARS: NEW ESTIMATES

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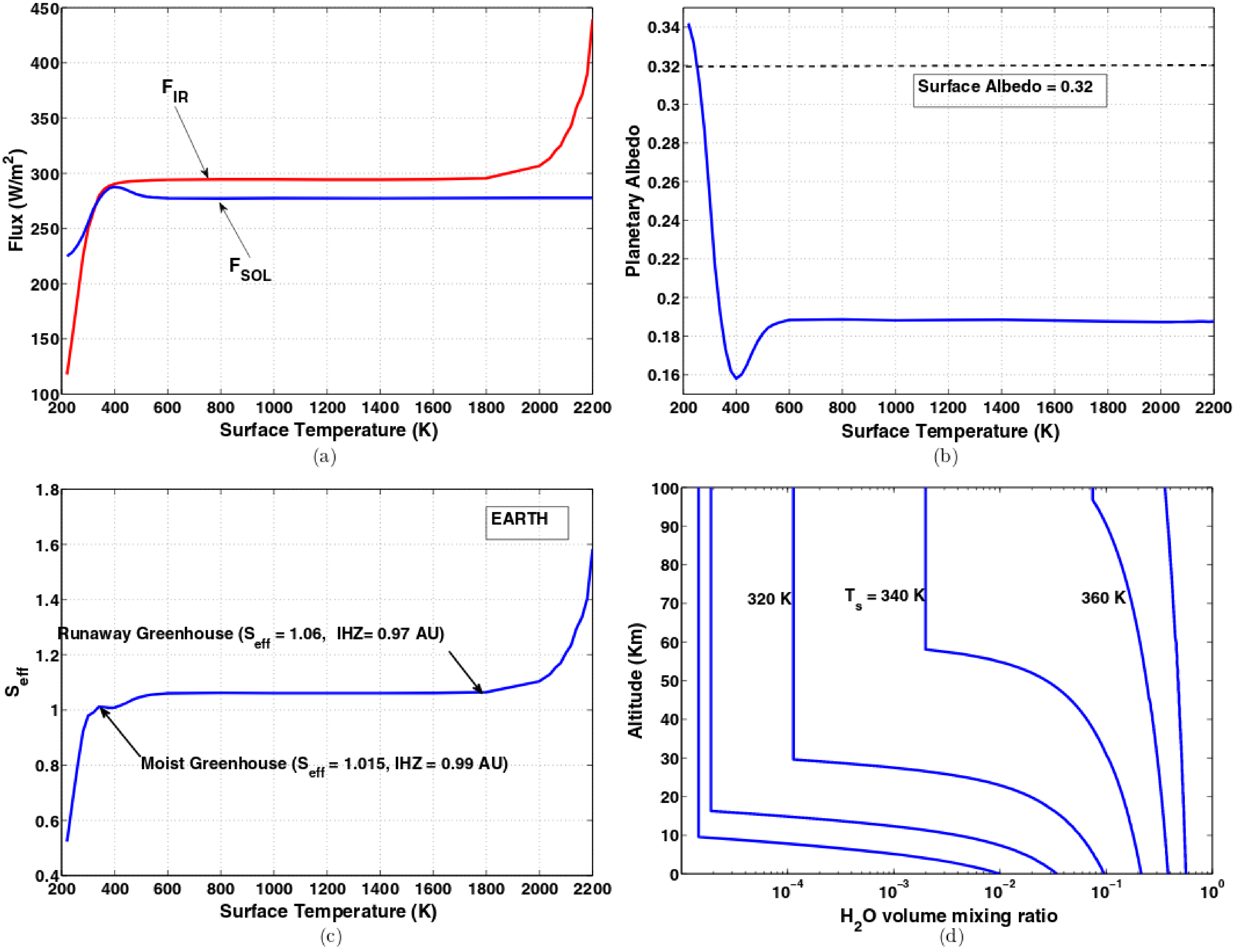
ABSTRACT

Identifying terrestrial planets in the habitable zones (HZs) of other stars is one of the primary goals of ongoing radial velocity (RV) and transit exoplanet surveys and proposed future space missions. Most current estimates of the boundaries of the HZ are based on one-dimensional (1D), cloud-free, climate model calculations by Kasting et al. However, this model used band models that were based on older HITRAN and HITEMP line-by-line databases. The inner edge of the HZ in the Kasting et al. model was determined by loss of water, and the outer edge was determined by the maximum greenhouse provided by a CO_2 atmosphere. A conservative estimate for the width of the HZ from this model in our solar system is 0.95–1.67 AU. Here an updated 1D radiative–convective, cloud-free climate model is used to obtain new estimates for HZ widths around F, G, K, and M stars. New H_2O and CO_2 absorption coefficients, derived from the HITRAN 2008 and HITEMP 2010 line-by-line databases, are important improvements to the climate model. According to the new model, the water-loss (inner HZ) and maximum greenhouse (outer HZ) limits for our solar system are at 0.99 and 1.70 AU, respectively, suggesting that the present Earth lies near the inner edge. Additional calculations are performed for stars with effective temperatures between 2600 and 7200 K, and the results are presented in parametric form, making them easy to apply to actual stars. The new model indicates that, near the inner edge of the HZ, there is no clear distinction between runaway greenhouse and water-loss limits for stars with $T_{\rm eff} \lesssim 5000$ K, which has implications for ongoing planet searches around K and M stars. To assess the potential habitability of extrasolar terrestrial planets, we propose using stellar flux incident on a planet rather than equilibrium temperature. This removes the dependence on planetary (Bond) albedo, which varies depending on the host star's spectral type. We suggest that conservative estimates of the HZ (water-loss and maximum greenhouse limits) should be used for current RV surveys and *Kepler* mission to obtain a lower limit on $\eta_{\oplus}$, so that future flagship missions like *TPF-C* and *Darwin* are not undersized. Our model does not include the radiative effects of clouds; thus, the actual HZ boundaries may extend further in both directions than the estimates just given.


Flux (W/m^2)
450
400
350
300
250
200
150
100
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
Surface Temperature (K)
F_{IR}
F_{SOL}
Planetary Albedo
0.34
0.32
0.3
0.28
0.26
0.24
0.22
0.2
0.18
0.16
Surface Albedo = 0.32
S_{eff}
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
EARTH
Runaway Greenhouse (S_{eff} = 1.06, IHZ= 0.97 AU)
Moist Greenhouse (S_{eff} = 1.015, IHZ = 0.99 AU)
Altitude (Km)
100
90
80
70
60
50
40
30
20
10
0
320 K
T_s = 340 K
360 K
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
H_2O volume mixing ratio

(a)

(b)

(c)

(d)

is dependent on the type of star considered. Therefore, we have derived relationships between HZ stellar fluxes (S_{eff}) reaching the top of the atmosphere of an Earth-like planet and stellar effective temperatures (T_{eff}) applicable in the range $2600\ \mathrm{K} \leqslant T_{\mathrm{eff}} \leqslant 7200\ \mathrm{K}$:

$$S_{\mathrm{eff}} = S_{\mathrm{eff}\odot} + aT_\star + bT_\star^2 + cT_\star^3 + dT_\star^4, \tag{2}$$

where $T_\star = T_{\mathrm{eff}} - 5780\ \mathrm{K}$ and the coefficients are listed in Table 3 for various habitability limits.[19] The corresponding HZ distances can be calculated using the relation

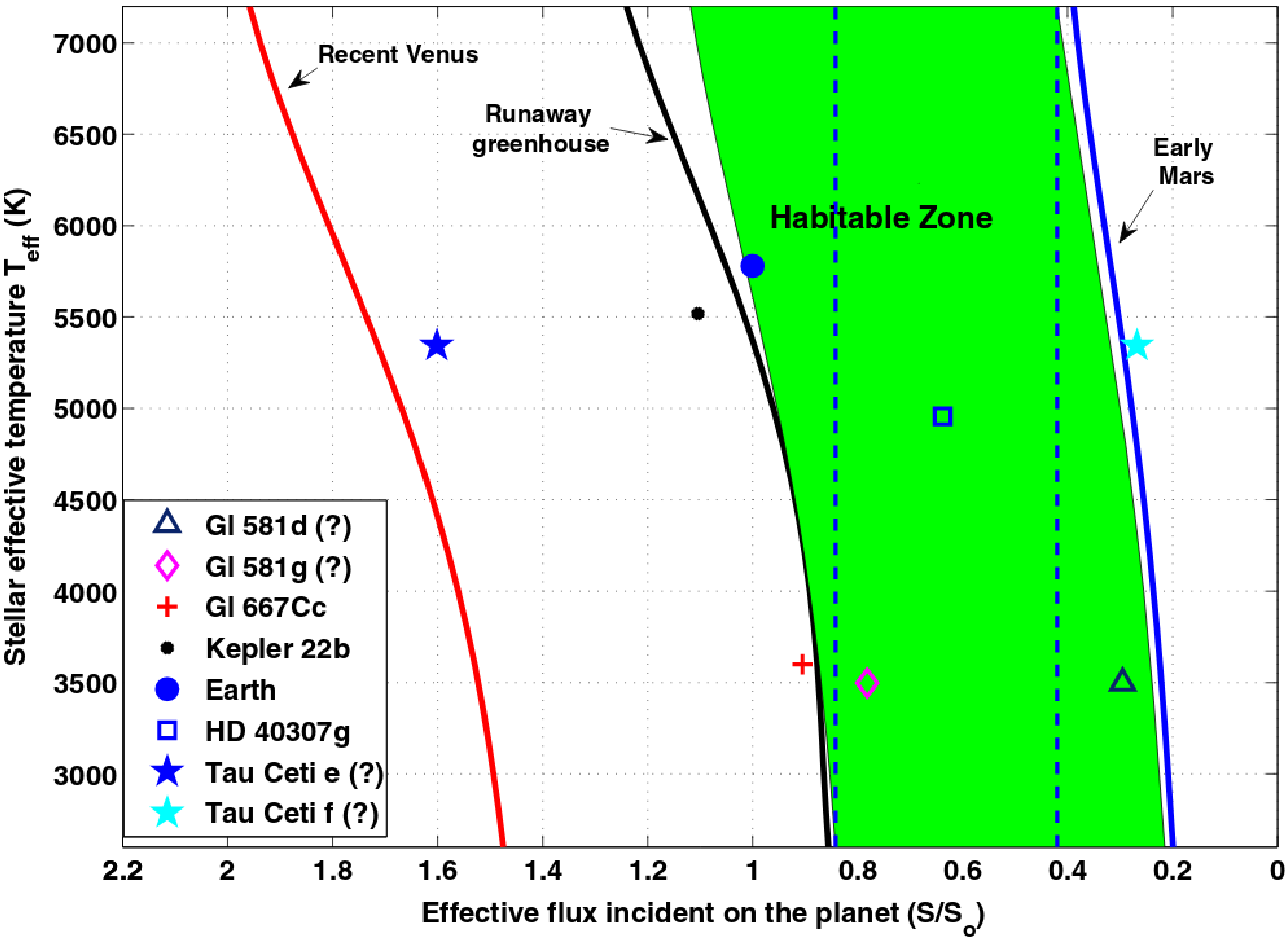
$$d = \left(\frac{L/L_\odot}{S_{\mathrm{eff}}}\right)^{0.5} \mathrm{AU}, \tag{3}$$

where $L/L_\odot$ is the luminosity of the star compared to the Sun.

Table 3

Coefficients to Be Used in Equation (2) to Calculate Habitable Stellar Fluxes, and Corresponding Habitable Zones (Equation (3)), for Stars with $2600\,\mathrm{K} \leqslant T_{\mathrm{eff}} \leqslant 7200\,\mathrm{K}$

Constant	Recent Venus	Runaway Greenhouse	Moist Greenhouse	Maximum Greenhouse	Early Mars
$S_{\mathrm{eff}\odot}$	1.7753	1.0512	1.0140	0.3438	0.3179
a	1.4316×10^{-4}	1.3242×10^{-4}	8.1774×10^{-5}	5.8942×10^{-5}	5.4513×10^{-5}
b	2.9875×10^{-9}	1.5418×10^{-8}	1.7063×10^{-9}	1.6558×10^{-9}	1.5313×10^{-9}
c	-7.5702×10^{-12}	-7.9895×10^{-12}	-4.3241×10^{-12}	-3.0045×10^{-12}	-2.7786×10^{-12}
d	-1.1635×10^{-15}	-1.8328×10^{-15}	-6.6462×10^{-16}	-5.2983×10^{-16}	-4.8997×10^{-16}



Recent Venus
Runaway greenhouse
Habitable Zone
Early Mars
Stellar effective temperature T_{eff} (K)
7000
6500
6000
5500
5000
4500
4000
3500
3000
Effective flux incident on the planet (S/S_o)
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
△ Gl 581d (?)
◇ Gl 581g (?)
+ Gl 667Cc
● Kepler 22b
● Earth
□ HD 40307g
★ Tau Ceti e (?)
★ Tau Ceti f (?)

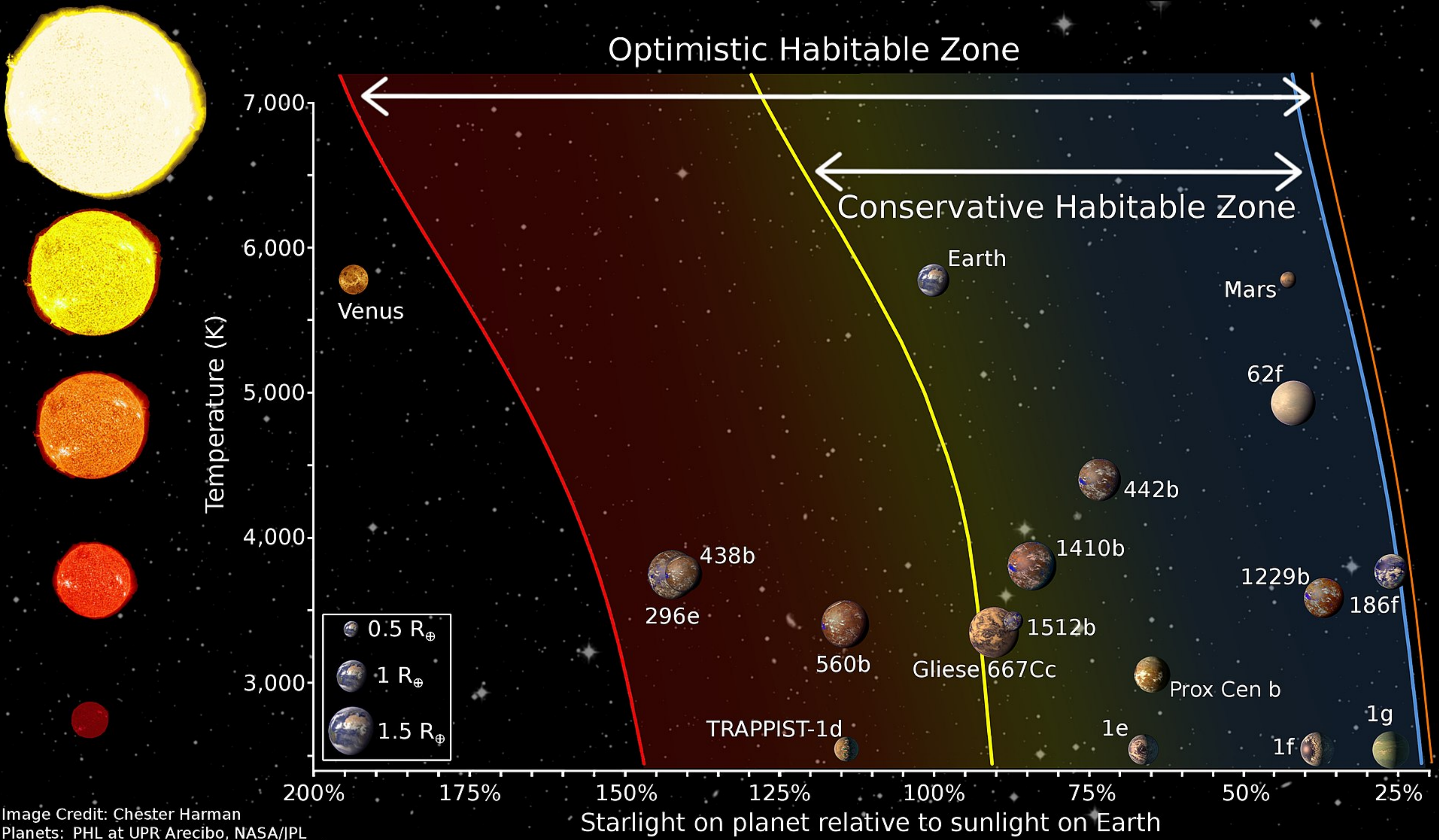


Image Credit: Chester Harman
Planets: PHL at UPR Arecibo, NASA/JPL

HABITABLE ZONES AROUND MAIN-SEQUENCE STARS: DEPENDENCE ON PLANETARY MASS

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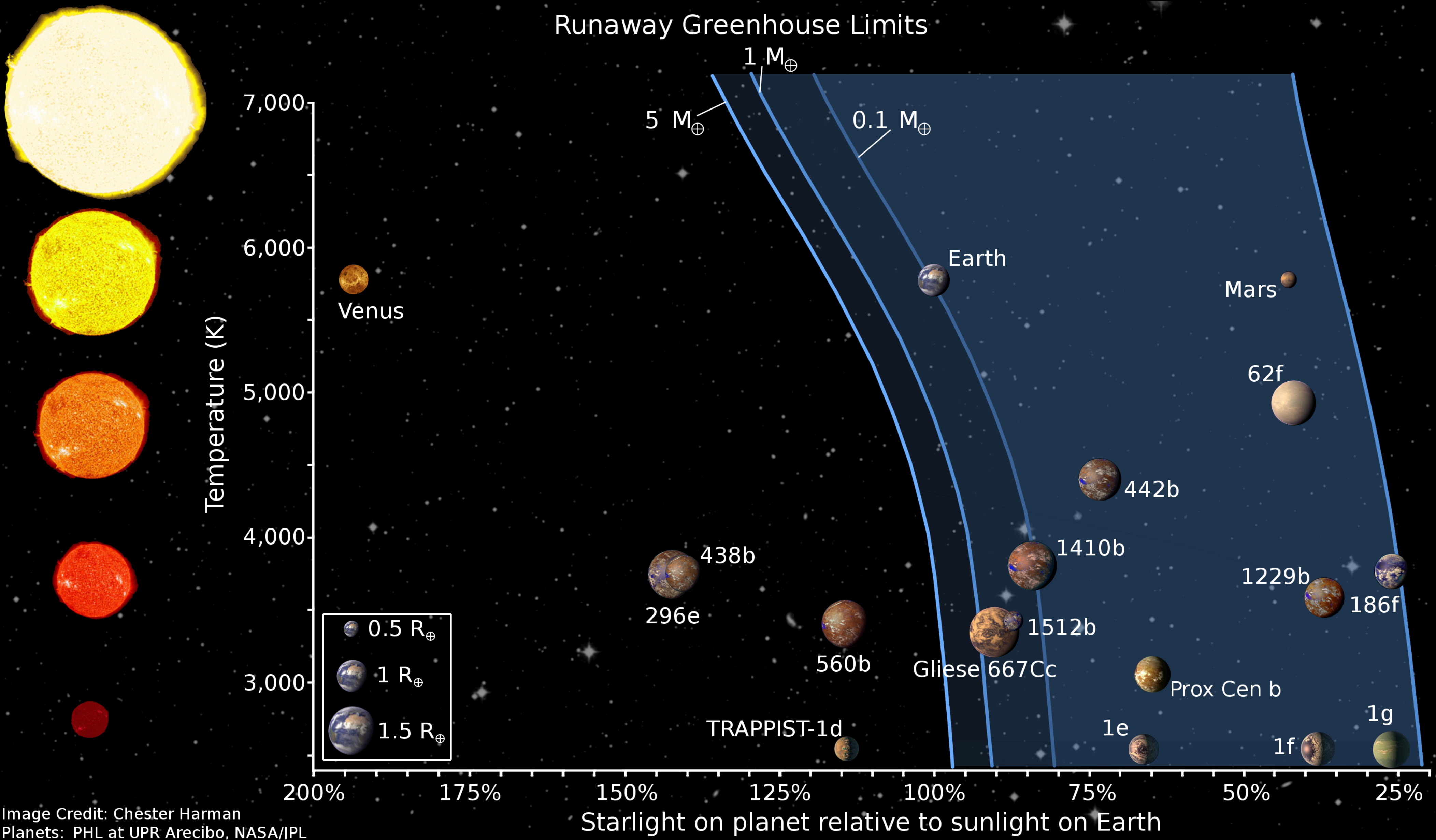
ABSTRACT

The ongoing discoveries of extra-solar planets are unveiling a wide range of terrestrial mass (size) planets around their host stars. In this Letter, we present estimates of habitable zones (HZs) around stars with stellar effective temperatures in the range 2600 K–7200 K, for planetary masses between 0.1 $M_\oplus$ and 5 $M_\oplus$. Assuming H_2O-(inner HZ) and CO_2-(outer HZ) dominated atmospheres, and scaling the background N_2 atmospheric pressure with the radius of the planet, our results indicate that larger planets have wider HZs than do smaller ones. Specifically, with the assumption that smaller planets will have less dense atmospheres, the inner edge of the HZ (runaway greenhouse limit) moves outward ($\sim$10% lower than Earth flux) for low mass planets due to larger greenhouse effect arising from the increased H_2O column depth. For larger planets, the H_2O column depth is smaller, and higher temperatures are needed before water vapor completely dominates the outgoing longwave radiation. Hence the inner edge moves inward ($\sim$7% higher than Earth's flux). The outer HZ changes little due to the competing effects of the greenhouse effect and an increase in albedo. New, three-dimensional climate model results from other groups are also summarized, and we argue that further, independent studies are needed to verify their predictions. Combined with our previous work, the results presented here provide refined estimates of HZs around main-sequence stars and provide a step toward a more comprehensive analysis of HZs.

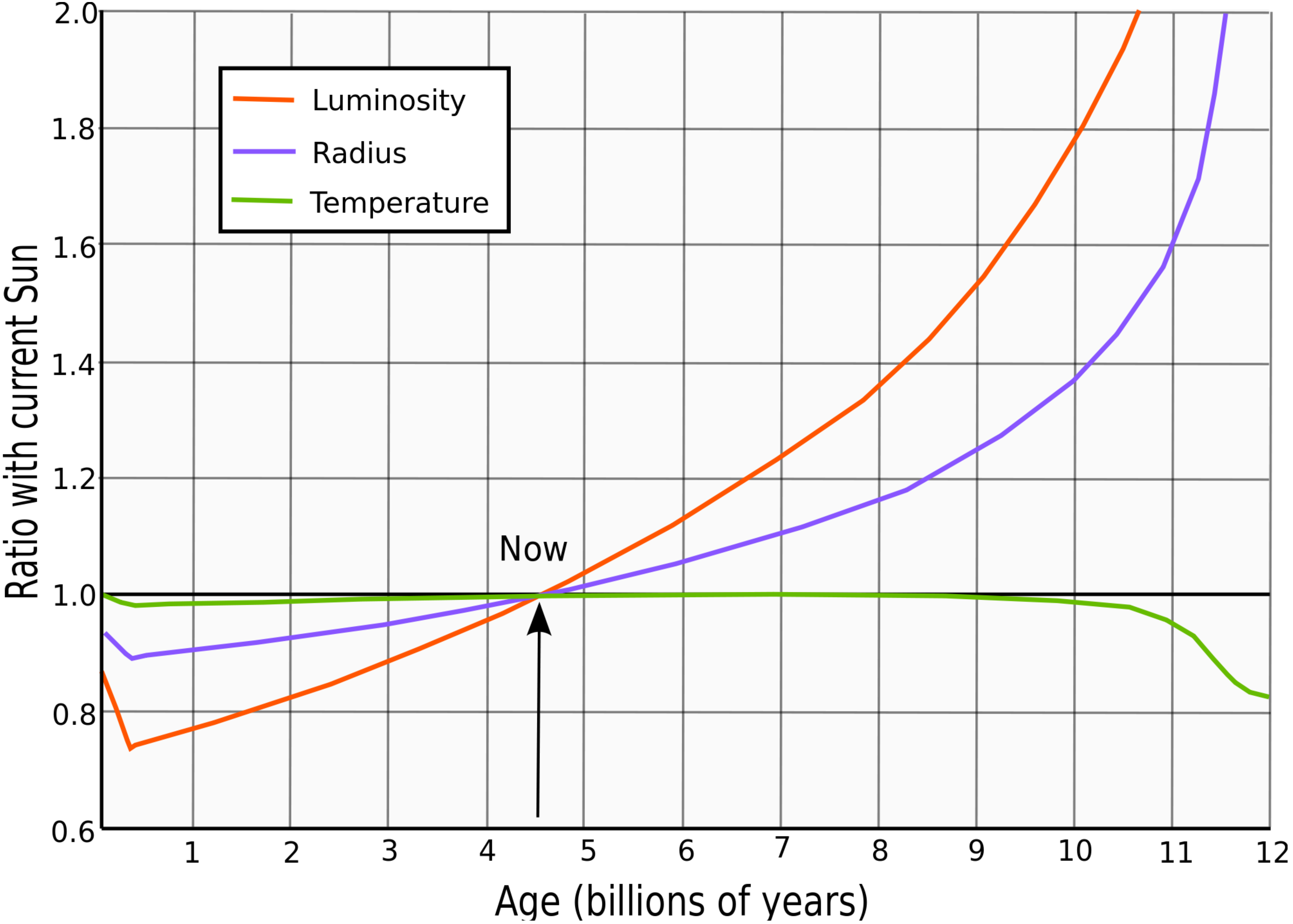
Table 1
Coefficients to be Used in Equation (4)

Constant	Recent Venus	Runaway Greenhouse	Maximum Greenhouse	Early Mars
$S_{\mathrm{eff}\odot}$ ($1\,M_\oplus$)	1.776	1.107	0.356	0.32
$S_{\mathrm{eff}\odot}$ ($5\,M_\oplus$)	...	1.188	...	...
$S_{\mathrm{eff}\odot}$ ($0.1\,M_\oplus$)	...	0.99	...	...
a ($1\,M_\oplus$)	2.136×10^{-4}	1.332×10^{-4}	6.171×10^{-5}	5.547×10^{-5}
a ($5\,M_\oplus$)	...	1.433×10^{-4}	...	...
a ($0.1\,M_\oplus$)	...	1.209×10^{-4}	...	...
b ($1\,M_\oplus$)	2.533×10^{-8}	1.58×10^{-8}	1.698×10^{-9}	1.526×10^{-9}
b ($5\,M_\oplus$)	...	1.707×10^{-8}	...	...
b ($0.1\,M_\oplus$)	...	1.404×10^{-8}	...	...
c ($1\,M_\oplus$)	-1.332×10^{-11}	-8.308×10^{-12}	-3.198×10^{-12}	-2.874×10^{-12}
c ($5\,M_\oplus$)	...	-8.968×10^{-12}	...	...
c ($0.1\,M_\oplus$)	...	-7.418×10^{-12}	...	...
d ($1\,M_\oplus$)	-3.097×10^{-15}	-1.931×10^{-15}	-5.575×10^{-16}	-5.011×10^{-16}
d ($5\,M_\oplus$)	...	-2.084×10^{-15}	...	...
d ($0.1\,M_\oplus$)	...	-1.713×10^{-15}	...	...



Runaway Greenhouse Limits

Image Credit: Chester Harman
Planets: PHL at UPR Arecibo, NASA/JPL


Luminosity
Radius
Temperature
Now
Ratio with current Sun
Age (billions of years)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
1
2
3
4
5
6
7
8
9
10
11
12