Astrophysics Community View of CCMC web-based simulations services and benefits and opportunities of exoplanetary systems modeling support

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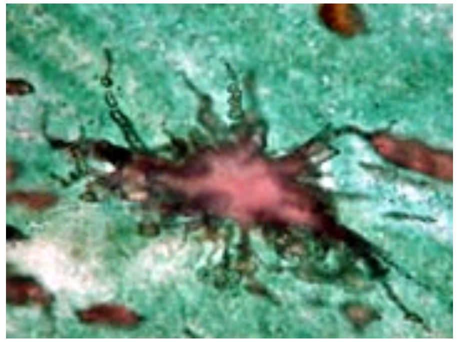


Earth' formation
-4.550 Gyrs

-3.600 Gyrs

-3.500 Gyrs, Archean pillow lavas,
Furnes et al. 2004.

No trace of fossils

Finding of fossils and dating of isotope ratios can hardly be made

Oldest fossils known (cyanobacteries)
-3.550 Gyrs

Résidus carbonés
-3.850 Gyrs

18 C. F. CHYBA ET AL.

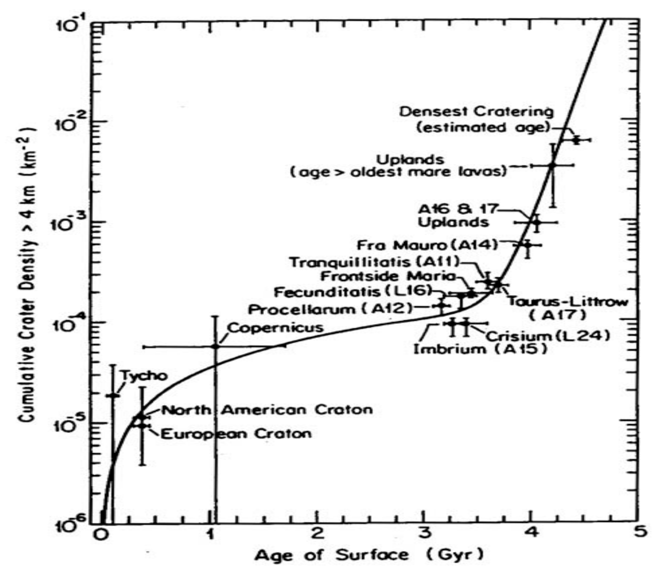
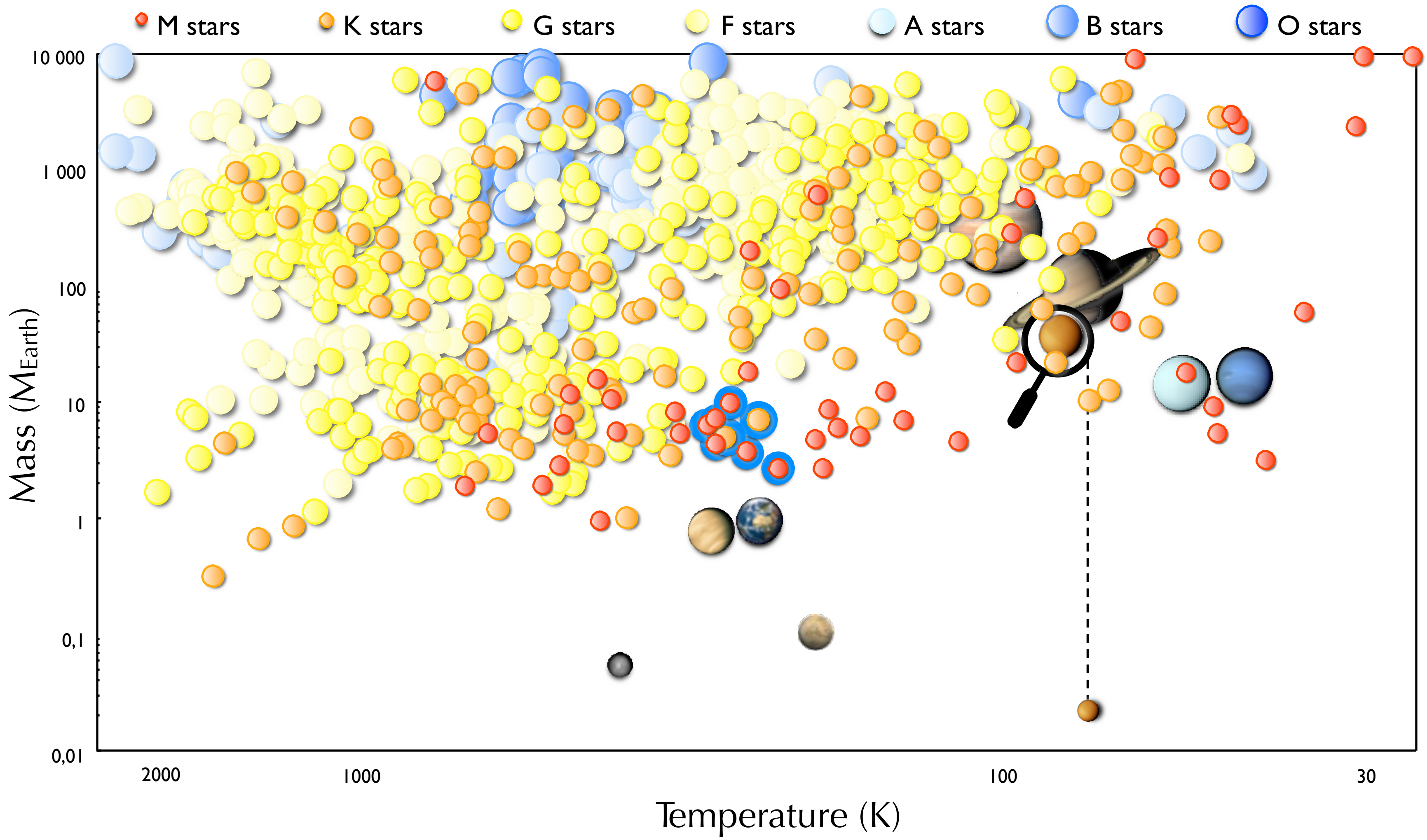
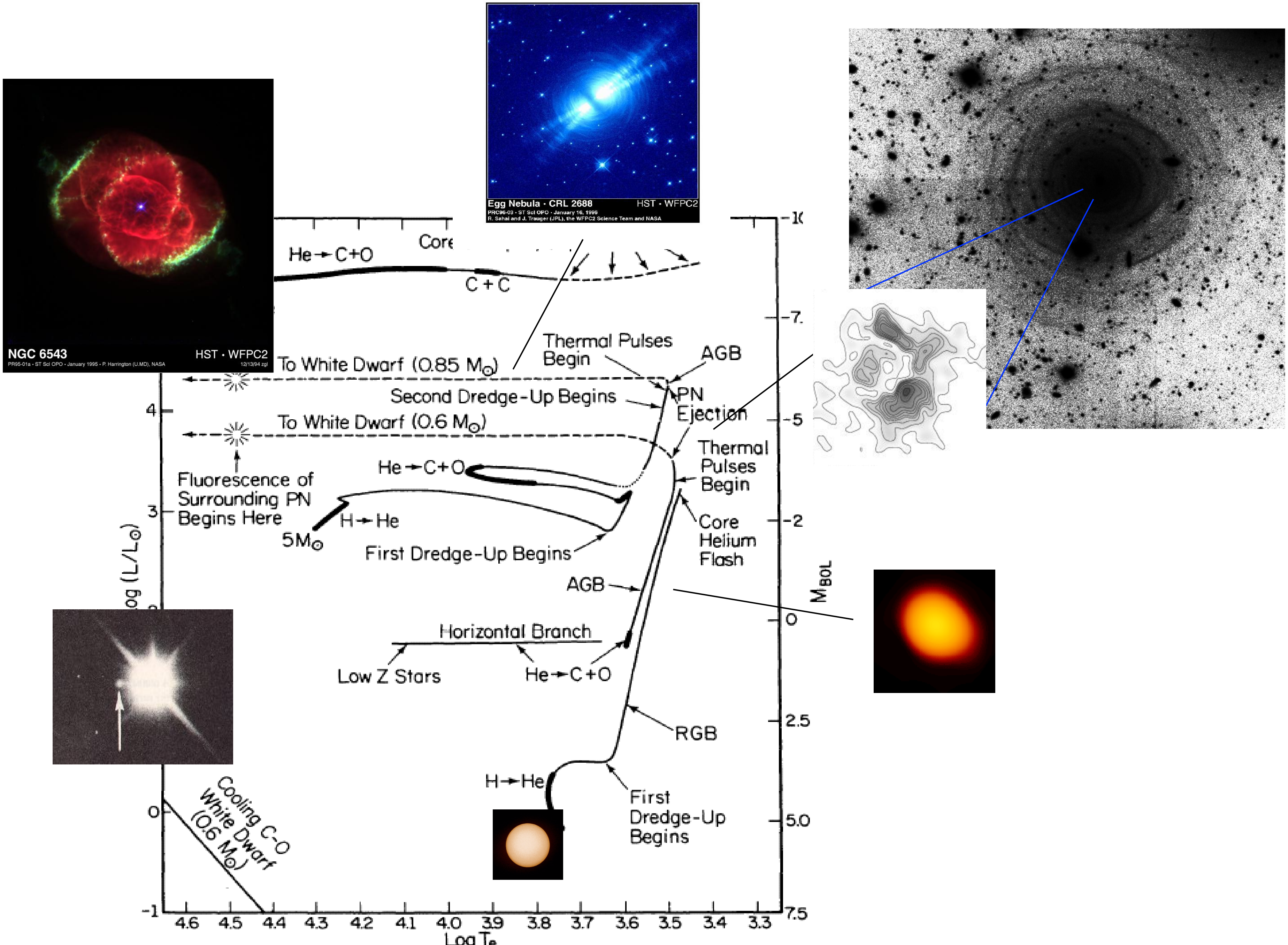


Figure 2. Cumulative lunar crater density as a function of surface age, with analytical fit (Eq. 1), using a 100 Myr half-life decay constant (figure from Chyba 1991*a*).

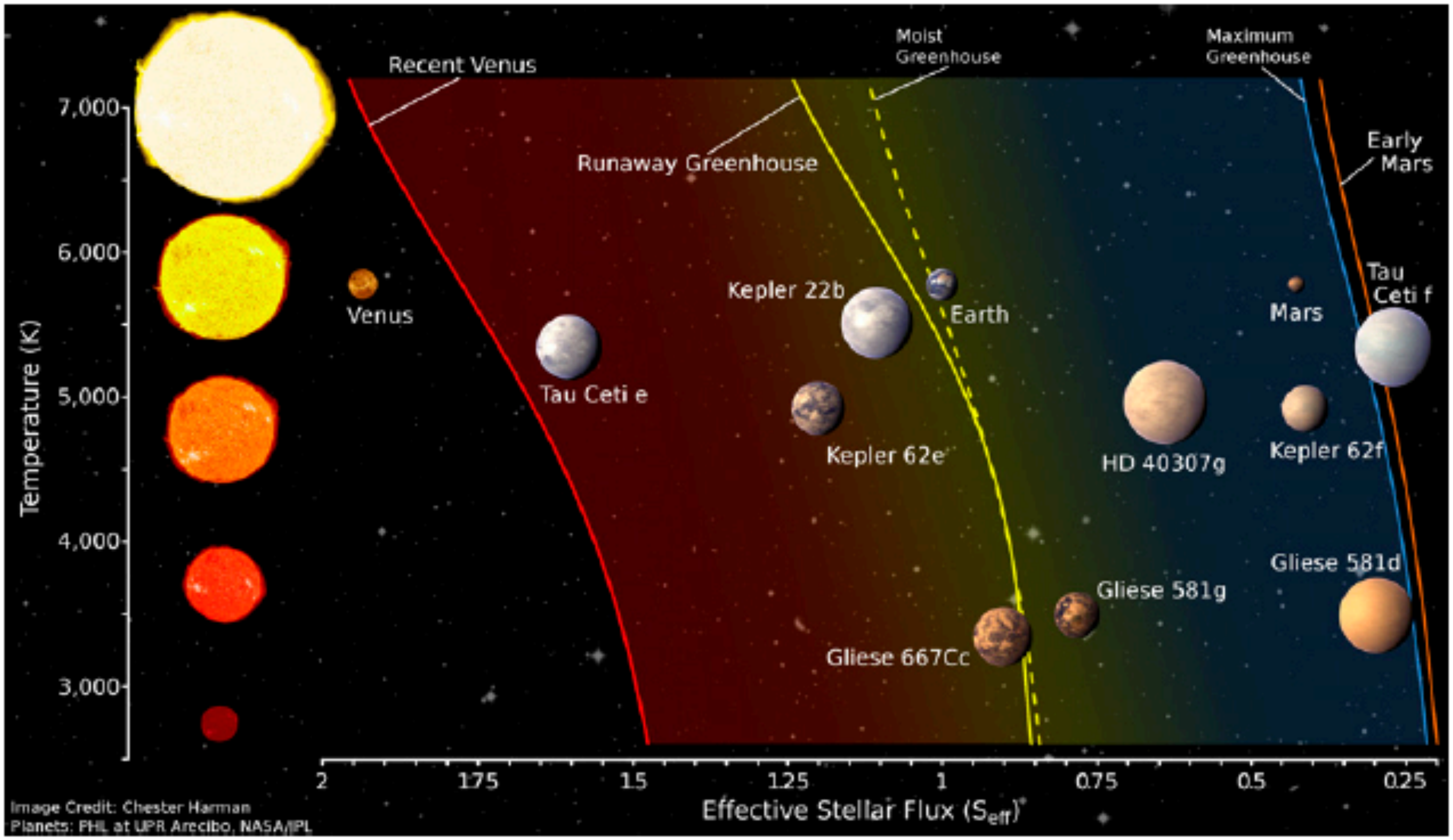
Heavy meterotic bombardement
during the first Gyr

A LARGE DIVERSITY OF (EXO)PLANETS and THEIR ATMOSPHERES AROUND A LARGE DIVERSITY OF STARS




NGC 6543
HST • WFPC2
Egg Nebula • CRL 2688
HST • WFPC2
He → C+O
Core
C + C
Thermal Pulses Begin
AGB
To White Dwarf (0.85 $M_{\odot}$)
Second Dredge-Up Begins
PN Ejection
To White Dwarf (0.6 $M_{\odot}$)
Thermal Pulses Begin
Fluorescence of Surrounding PN Begins Here
He → C+O
H → He
$5M_{\odot}$
First Dredge-Up Begins
Core Helium Flash
AGB
Horizontal Branch
Low Z Stars
He → C+O
RGB
H → He
First Dredge-Up Begins
Cooling C-O White Dwarf (0.6 $M_{\odot}$)
log (L/$L_{\odot}$)
M_{BOL}
Log T_e
4.6
4.5
4.4
4.3
4.2
4.1
4.0
3.9
3.8
3.7
3.6
3.5
3.4
3.3
4
3
0
-1
-5
-2
0
2.5
5.0
7.5

Habitable zone boundaries including recent Venus

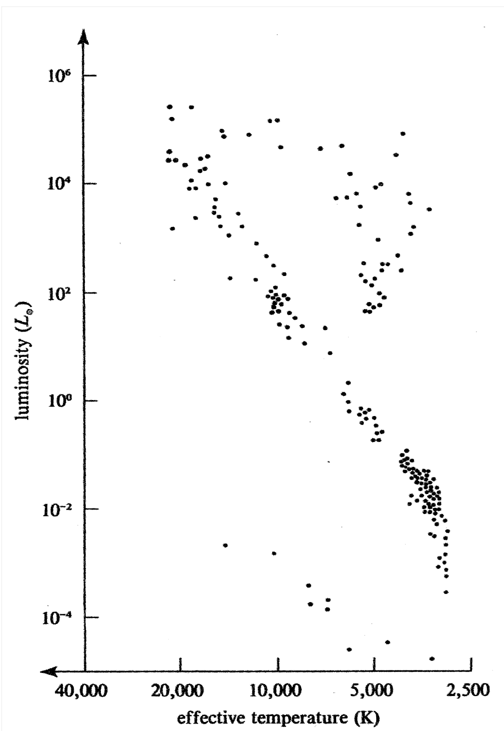


From Kasting et al. 2014 PNAS paper

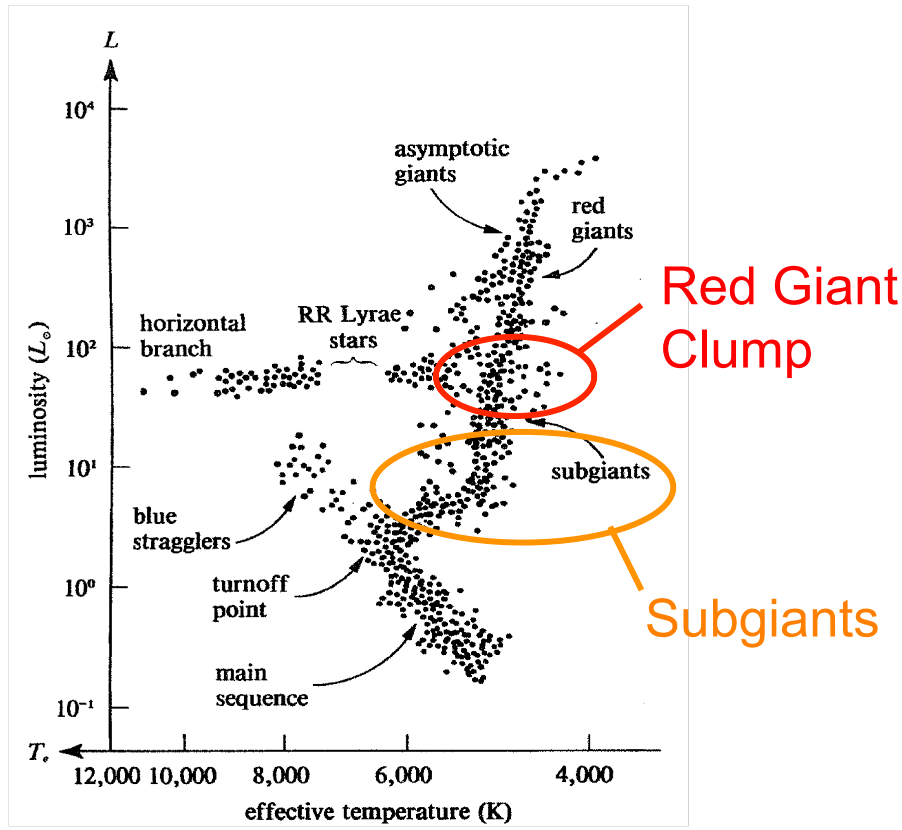
Other definitions of Habitable Zone

- *Conservative* limits are (Forget 1998):
  - Inner HZ = 0.95 AU
  - Outer HZ = 1.67 AU
- *Inner limit* set by water loss in stratosphere of planet (Kasting et al. 1993)
- *Outer limit* set by temperature at which water freezes. Depends on greenhouse gases, CO_2 , and H_2O (Kasting et al. 1993)
- *Less conservative* definition for Outer HZ is 2.4 AU. Depends on radiative properties of CO_2 ice clouds, particularly with particles > 6-8 um in size (Forget & Pierrehumbert 1997, Mischna et al. 2000)

H-R Diagrams

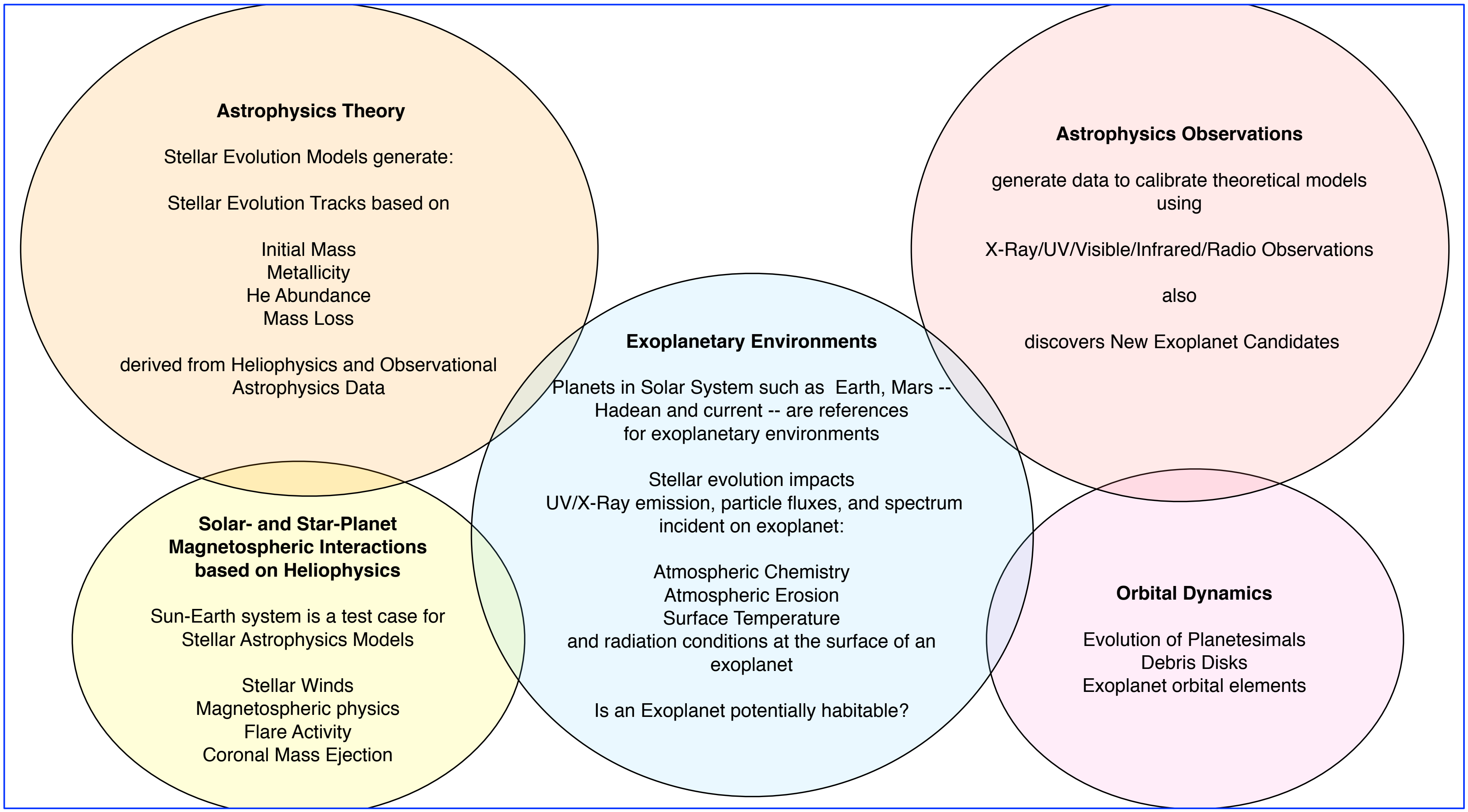


HR Diagram of Nearby Stars

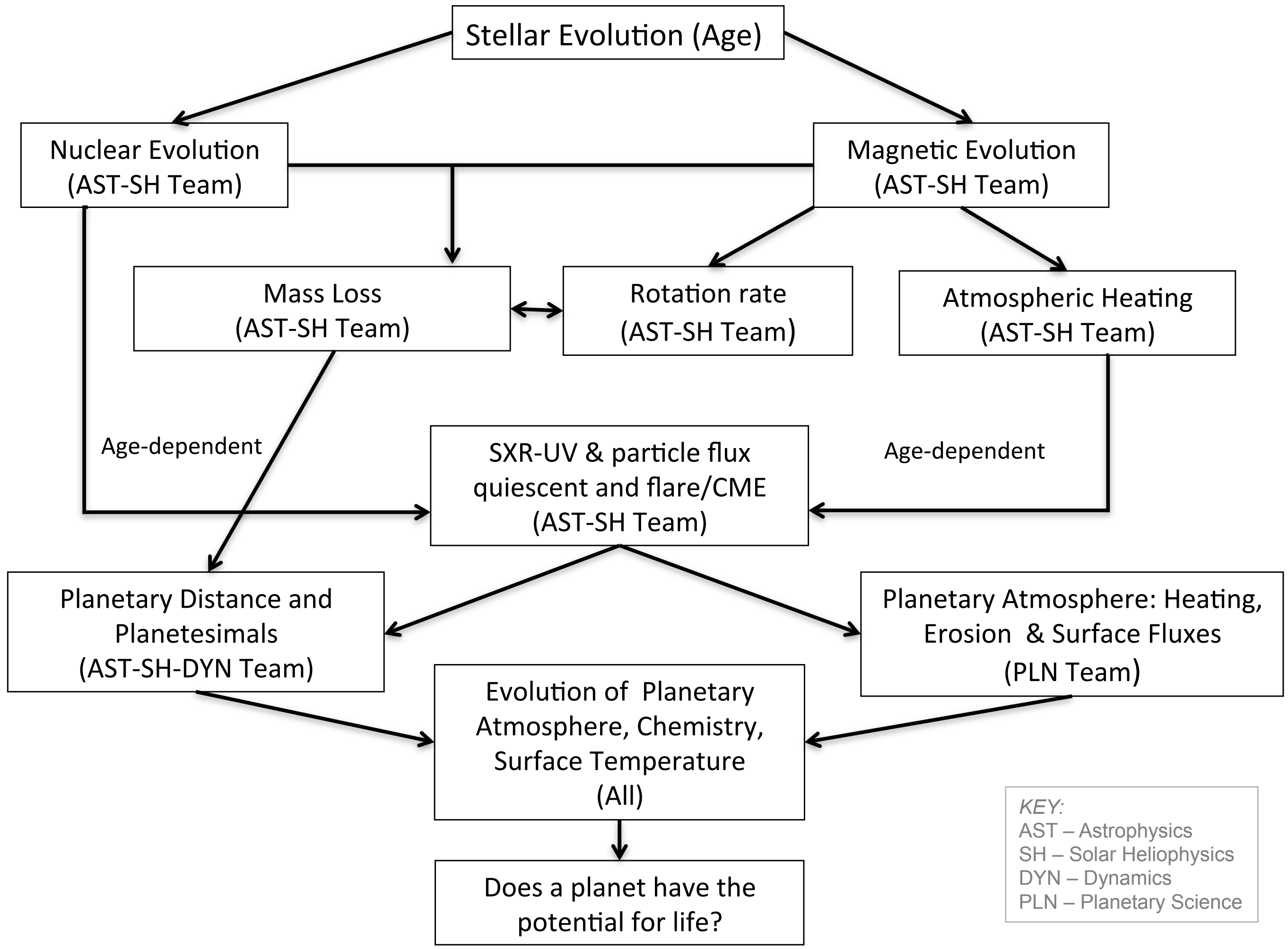


Empirical HR Diagram

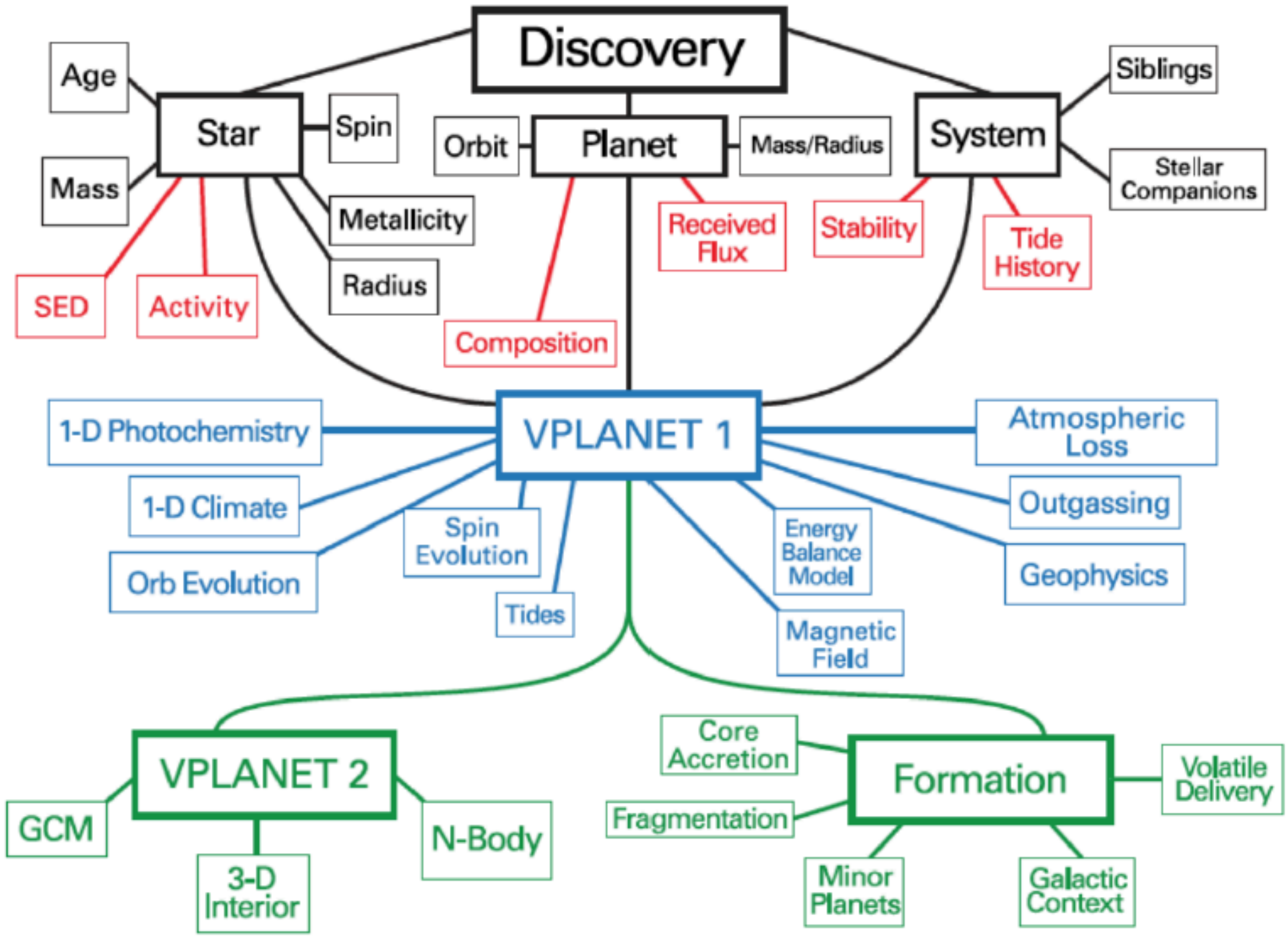
Understanding Exoplanetary Environments is an Intrinsically Interdisciplinary Exercise



Many phenomena are associated with stellar evolution and to understand the chance of life for an exoplanet requires these linkages between disciplines



More on the interconnectedness disciplines needed for exoplanetary science …



Next few slides are an example of what can be achieved …

Some recent results from our interdisciplinary effort

Paper accepted to *Nature Geosciences*: Will soon have a joint press release with Heliophysics and Astrophysics

Prebiotic Chemistry and Atmospheric Warming at Early Earth by an Active Sun

Authors: V. S. Airapetian[1], A. Glocer[1], G. Gronoff[2], E. Hébrard[1] W. Danchi[1]

Abstract. Understanding how the simple molecules present on the early Earth and possibly Mars may have set a path for complex biological molecules, the building blocks of life, represents one of greatest unsolved questions. Here we study the chemical impacts on the early terrestrial atmosphere due to energetic protons accelerated in shock waves driven by frequent and powerful coronal mass ejection events from the young Sun. Magnetic clouds ejected from the young Sun produce shocks which accelerate energetic particles and cause the compression of the early Earth's magnetosphere, which produce extended polar caps. These polar caps provide pathways for energetic particles associated with magnetic clouds to penetrate into the nitrogen-rich weakly reducing atmosphere and initiate the reactive chemistry by breaking molecular nitrogen, carbon dioxide, methane and producing nitrous oxide, the potent greenhouse gas, and hydrogen cyanide, the essential compound for life. This picture challenges the current models of warming of early Earth, by major atmospheric constituents, because CO_2 and CH_4 are destroyed due to collisional dissociation with energetic particles. Instead, we predict efficient formation of nitrous oxide as a by-product of these processes. This mechanism can consistently explain the Faint Young Sun's paradox for the early terrestrial atmosphere. Our new model provides insight into how life may have initiated on Earth and Mars and suggests an alternative for the Habitability Zone in terms of the Biogenic Zone. It also predicts the spectral signatures of prebiotic molecules in atmospheres of planets "pregnant" with the potential for life.

Findings (from paper)

What CMEs do to the early Earth's magnetic field

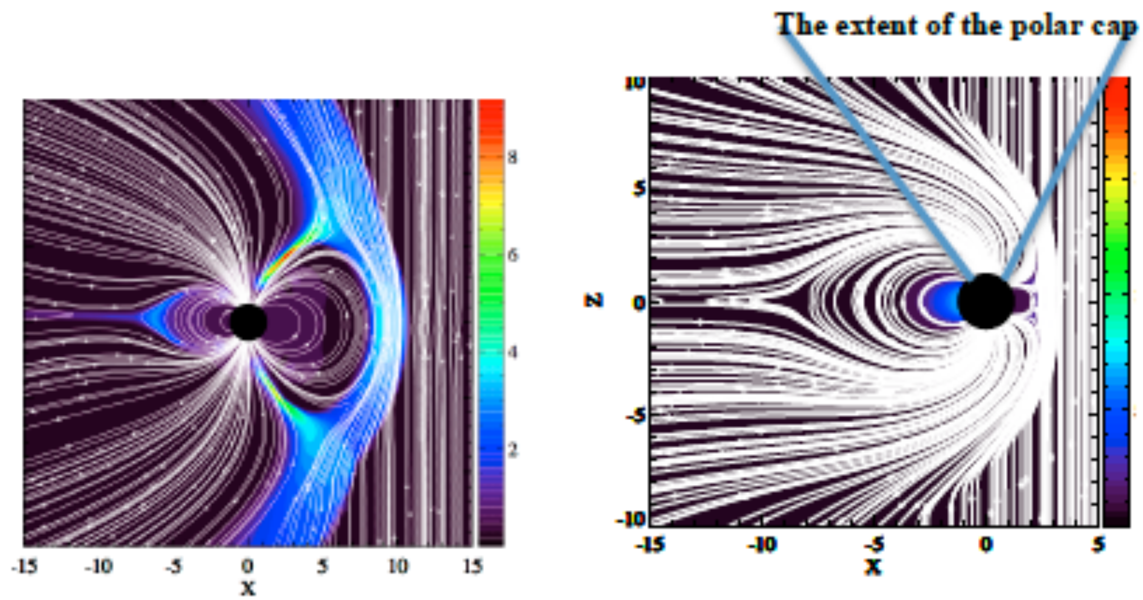


Figure 1. The initial (left panel) and the final state (right panel) magnetic field lines in white) and the plasma pressure (in color) of the Earth's magnetosphere due to the CME event with energy of ~3 x 10^{33} erg (Airapetian et al. 2015)

Findings (from paper)
Chemical pathways are important

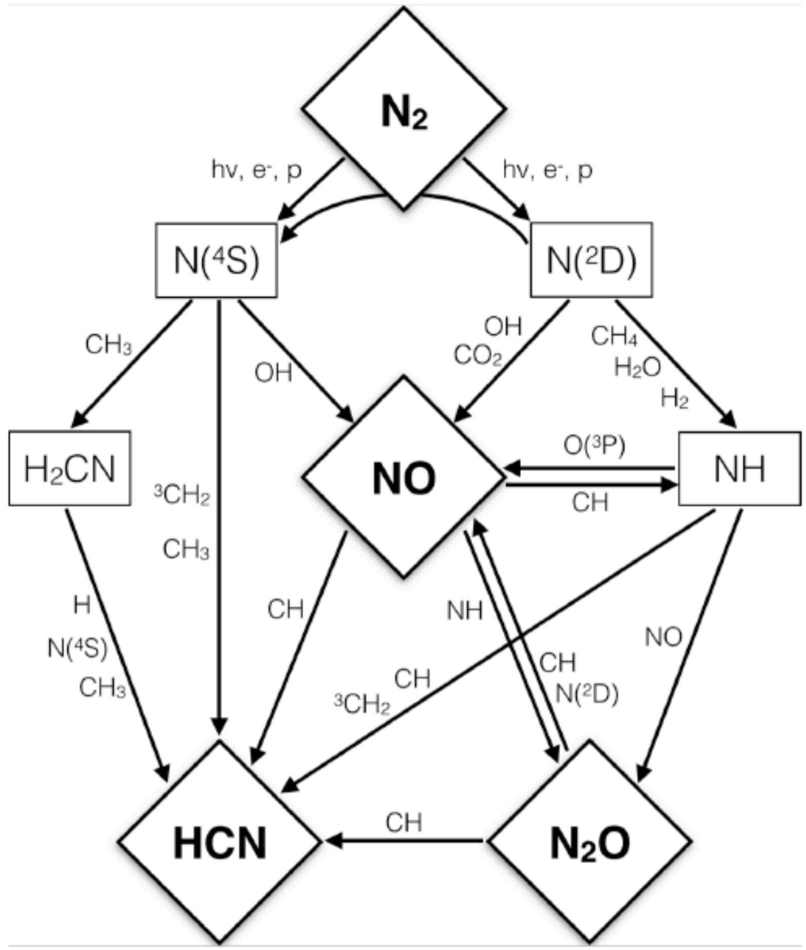


Figure 3. The pathway diagram of abiotic production of odd nitrogen and nitrogen-bearing compounds including nitrous oxide and hydrogen cyanide due to photo and collisional dissociation and ionizations caused by EUV solar flux and SEP particle flux.

Findings (from paper)

Increased abundance of important molecules, particularly nitrous oxide that can warm the early Earth and are precursors to molecules necessary for life

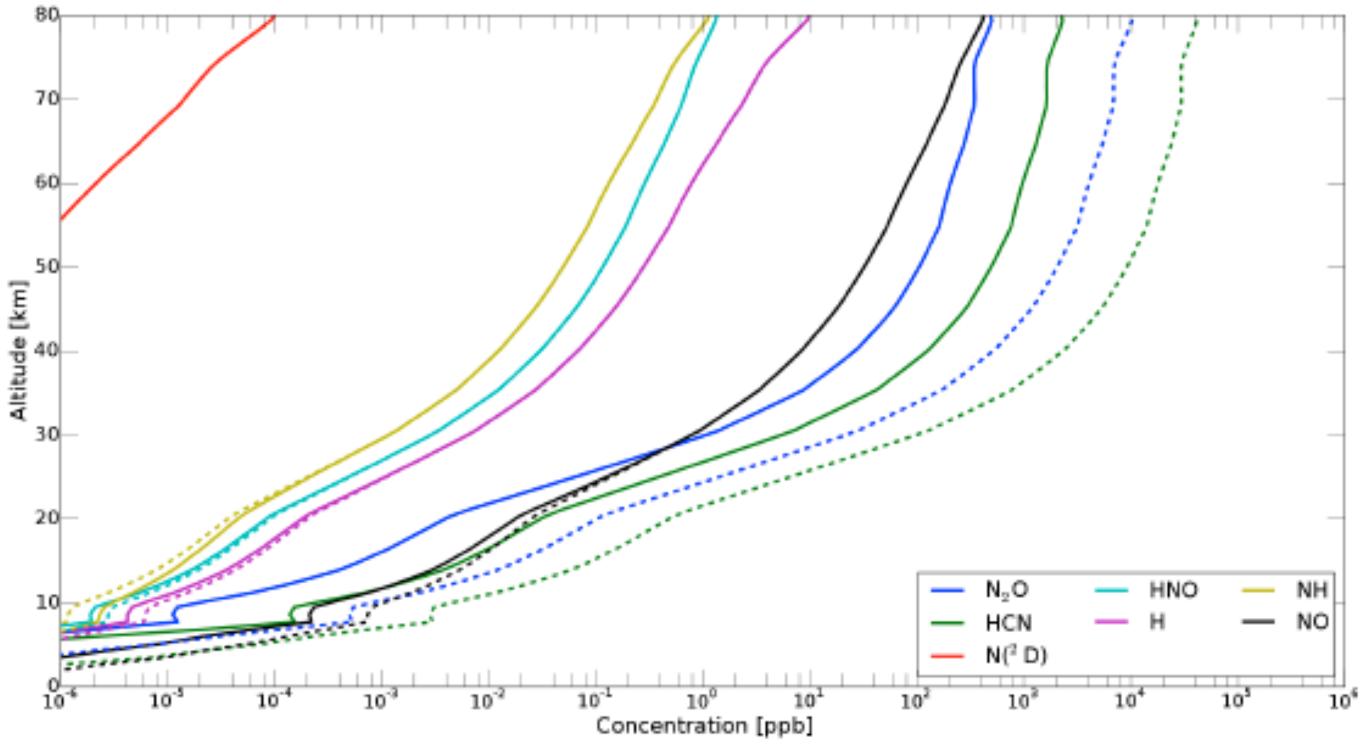


Figure 4. Radial profiles of the steady-state mixing ratios of various species produced by incoming flux of primary protons and secondary electrons at 1 PAL for 10% (dotted lines) and 100% (solid lines) of the maximum photo-destruction rate.

What we used, where we're headed

- This work required several codes, in particular the 3-D MHD code BATS-R-US, and the Aeroplanet code, with over 100 reactions included to find the steady state value of the molecules at each pressure.
- Work is in progress to calculate the temperature at the surface of the Earth using the VPLANET code.
- We can evolve stars with the open source MESA code …
- We can use the PWOM to study atmospheric escape ...
- These codes are complicated and a "scenario" type of framework would make studies of exoplanet atmospheres and habitability much more accessible to a broader set of researchers.
- The CCMC provides the type of services that can ease this task ...

Summary

- Exoplanet habitability is not a well-defined concept within the exoplanet community. Knowing whether or not liquid water can exist on the surface of a planet is insufficient to predict whether or not a planet has life on it or the potential for life.
- Life evolved on the Earth over hundreds of millions of years, during which the Earth was bombarded by super-Coronal Mass Ejection events (SCMEs) and intense UV. Solar energetic particles (protons, neutrons, gamma rays, electrons) penetrated the Earth's atmosphere, splitting nitrogen molecules into odd nitrogen, creating the greenhouse gas nitrous oxide, and chemical pathways to HCN, Tholins, and other life-precursor molecules.
- We use an integrated (see previous slides), interdisciplinary (Astrophysics, Heliophysics, Planetary Science), and numerical approach to determine the physical, thermal, and chemical equilibrium over geologically significant times.
- We will determine if an exoplanet is habitable over long time periods and whether its atmosphere contains life-precursor molecules that could be observed with JWST, and future direct imaging missions such as LUVOIR and HabEx.