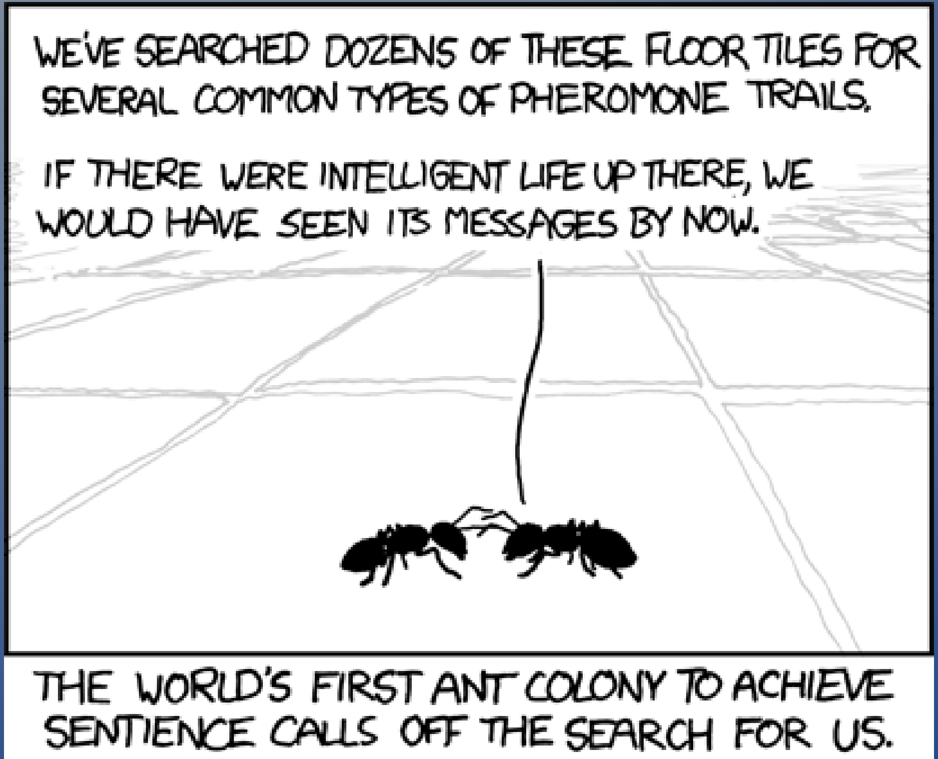
Coronal Mass Ejection and Its Influnce on the Potential for Terrestrial Exoplanets

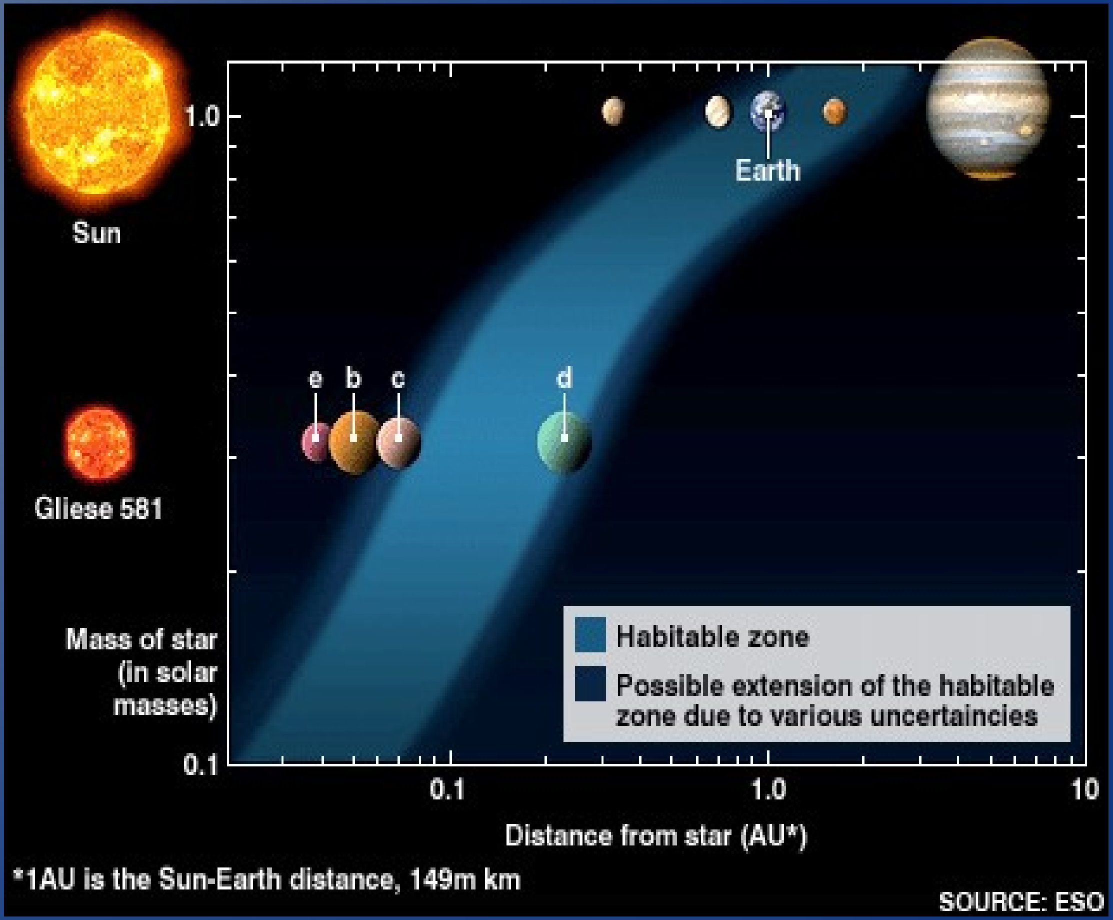
CME and Terran Exoplanets



- The search for Spock... er... Earth2?
- X-Rays and EUV
- Exospheric density
- Ion pickup
- CME and erosion from ion pickup
- What can we predict?
- Q&A

Searching for our Summer-Home Planet

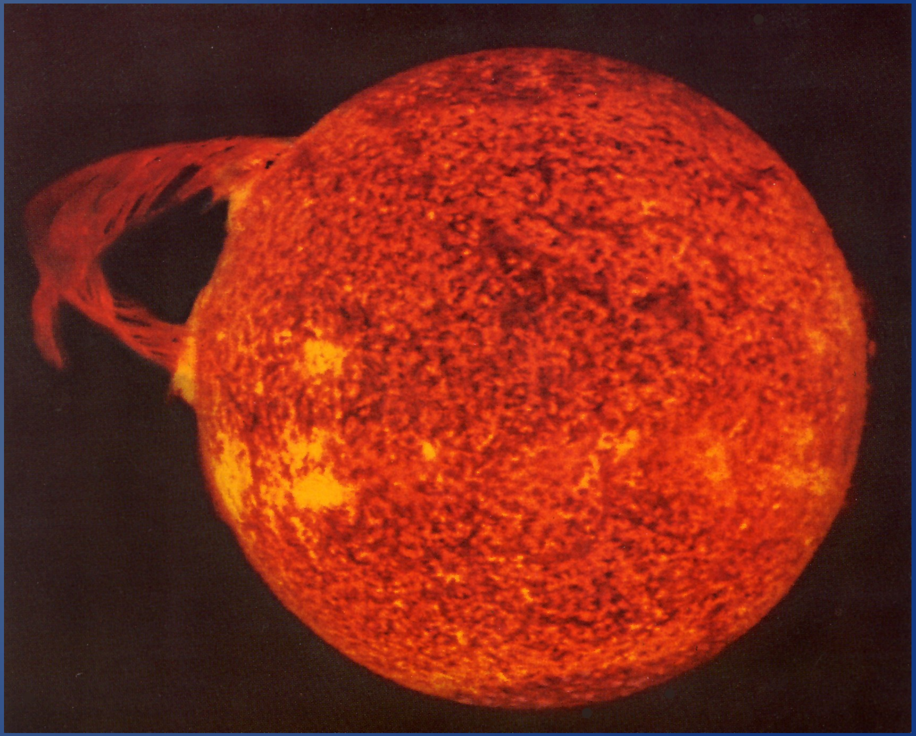
- Gliese 876
- M stars over G
  - Tidal locking
  - EUV and XUV
  - CME
    - ASPERA-3
- Need... Water...
- The model
  - Like an onion



*1AU is the Sun-Earth distance, 149m km

SOURCE: ESO

Heating from Stellar Radiation



- Photoionization by XUV
  - N2, O2, O
- Photodissociation by UV
  - O2, O3
- Exothermic reactions
  - Chemical
  - O, O3
- Neutral Gas Conduction
- Thermospheric Fluctuations
- Turbulent Energy Dissipation

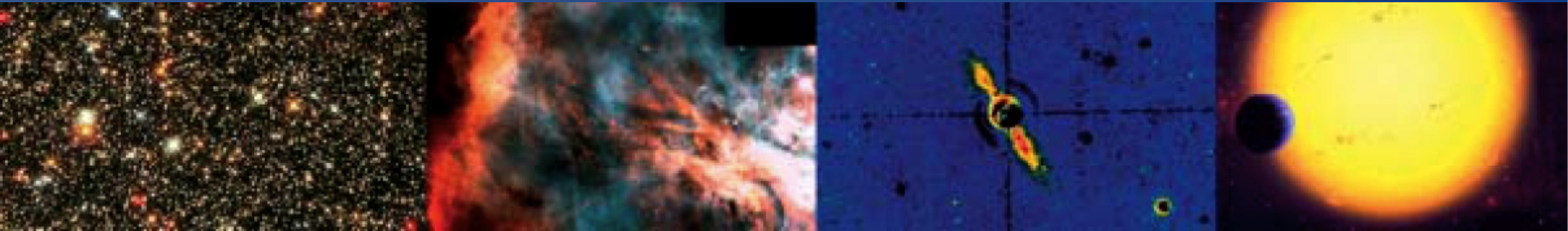
Heating from Stellar Radiation

- Numerical model applied to Earth found primary heat source is XUV (Gordiets, et al.)
  - Photoionization and photodissociation of O2.
  - Balanced by IR radiative cooling and molecular conduction
  - Yields 1000-1200 K (Jacchia, Crowley)
    - Venus: 270-290 K, despite its proximity to Sol
    - Higher CO2 have less expansion from XUV
- Class M stars are more active
  - 100 times the XUV of Sol (Haisch, Schmitt, Audard, Ciaravella, Smith, Ribas, Khodachenko, Scallo)

Modeling Thermospheric Heat Budgets

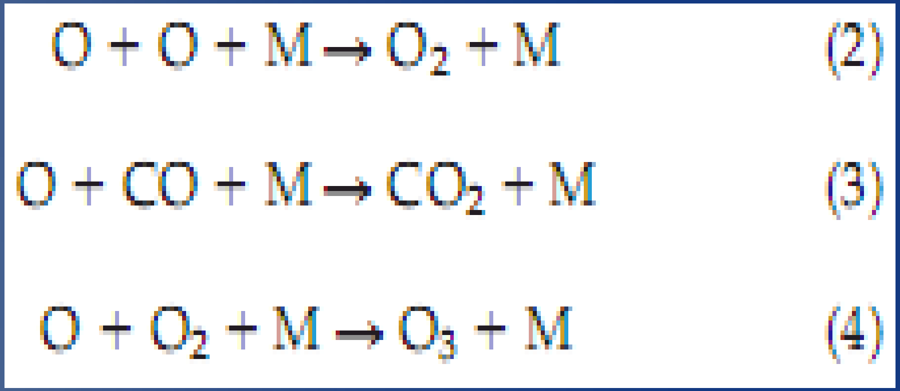
- Heat from XUV is balanced by
  - IR radiation
  - Contraction and Expansion (CE)
- Adapted for Earth -size and -mass, with Venus-like atmosphere

$$\rho c_v\left[\frac{\partial T}{\partial t} + \vec{v}_n \cdot \vec{\nabla} T\right] + p\vec{\nabla} \cdot \vec{v}_n - \vec{\nabla} \cdot (K_n \vec{\nabla} T) = Q_{XUV} - L_{IR} - L_{ce} \quad (1)$$



Thermal Modeling cont'd

- Solves one-dimensional time dependent factors
  - Continuity
  - Diffusion
  - Hydrostatic Equilibrium
  - Heat balance
  - Vibrational Kinetics



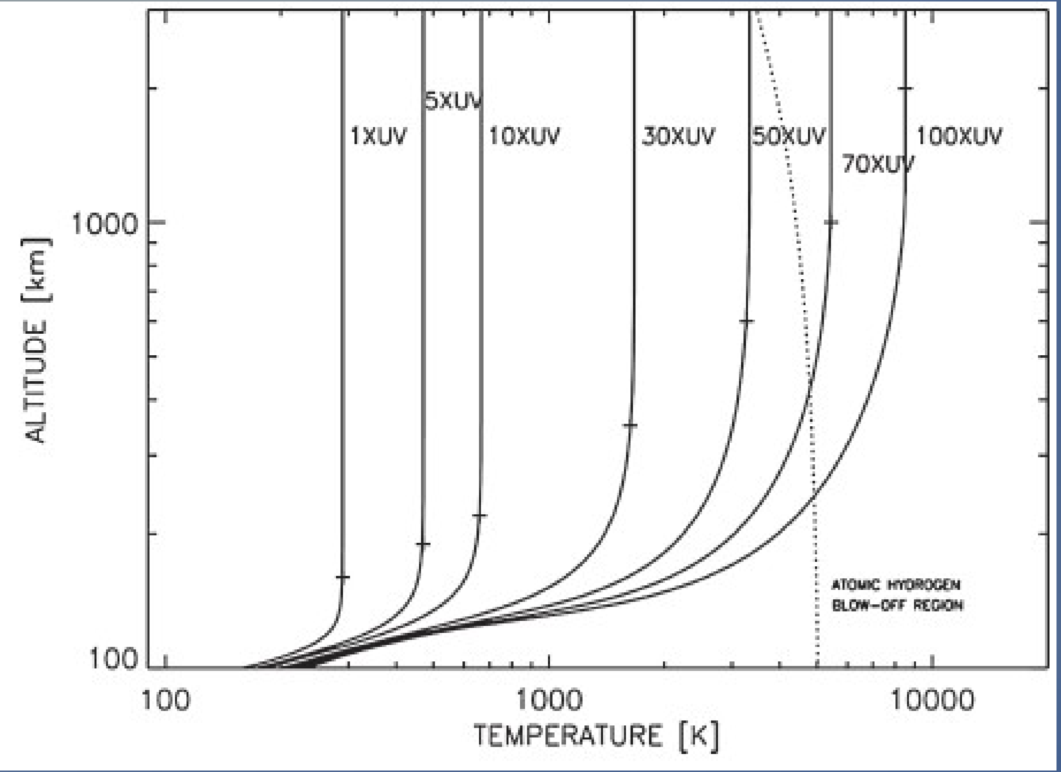
$$O + O + M \rightarrow O_2 + M \qquad (2)$$

$$O + CO + M \rightarrow CO_2 + M \qquad (3)$$

$$O + O_2 + M \rightarrow O_3 + M \qquad (4)$$

- Model is self-consistent with IR species, accounting for:
  - CO2, N2, CO, O2, & O photoionization from XUV
  - O2 & O3 photodissociation by UV
  - Chemical heating

Thermal Modeling cont'd

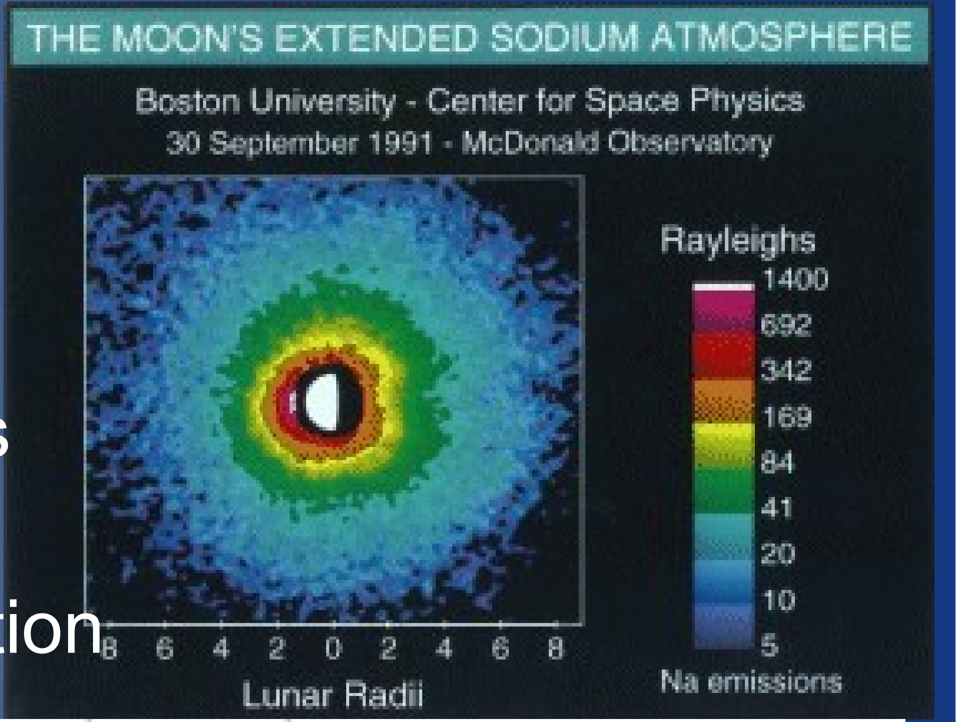


- Modeled temperature profiles in a Venus-like CO2-rich thermosphere of an Earth-size and -mass planet as a function of altitude for different XUV flux values. The short horizontal lines mark the exobase altitudes, and the dotted line shows the blow-off temperature for atomic hydrogen.

- In a “dry” atmosphere with lower CO2 and higher N2 mixing ratios during 70–100 times higher XUV periods, exospheric temperatures of more than 20,000 K can be obtained,causing expansive upper atmospheres and high Jeans loss rates for heavy species like oxygen, nitrogen, and carbon.

Exospheric Number Density

- O2+
  - Produces “hot” atoms
  - Reaches higher alititudes
  - Density determined via ionospheric recombination
  - Four channels:



$$O_2^+ + e \rightarrow O(^3P) + O(^3P) \qquad \Delta E = 6.96\ \text{eV} \qquad (5)$$

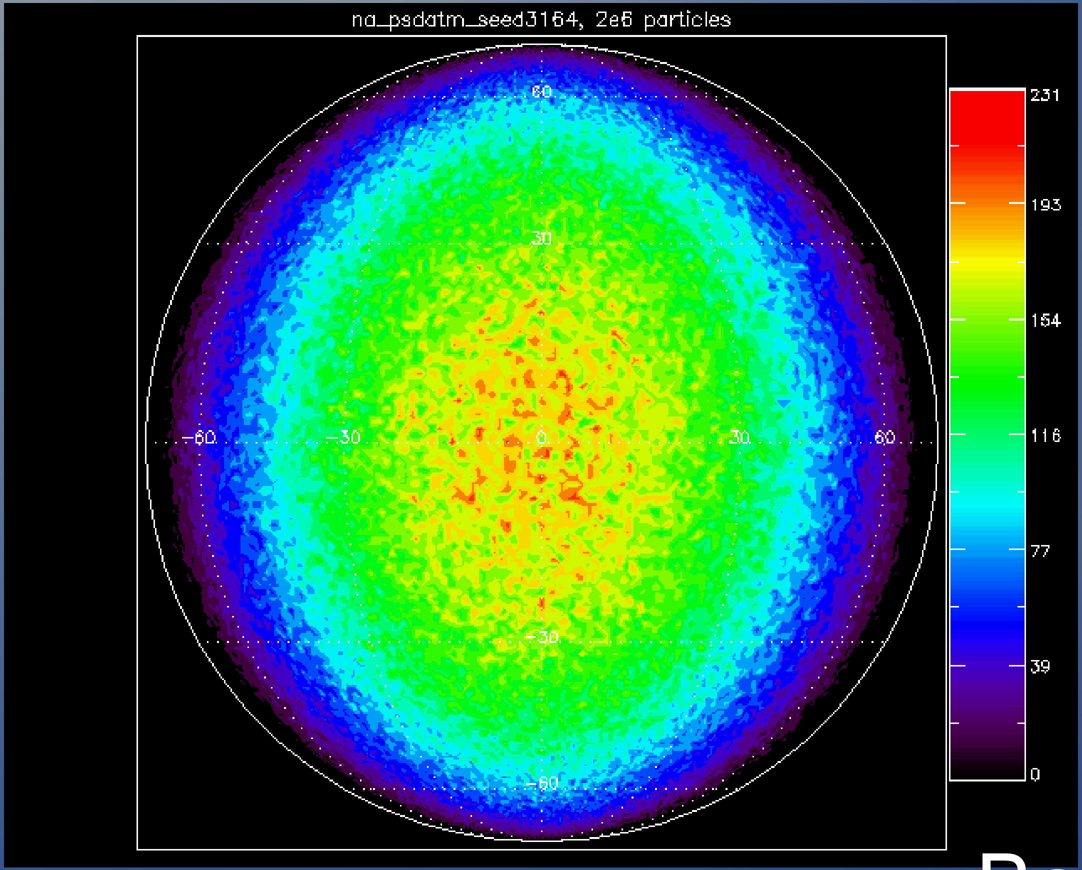
$$O_2^+ + e \rightarrow O(^3P) + O(^1D) \qquad \Delta E = 5.00\ \text{eV} \qquad (6)$$

$$O_2^+ + e \rightarrow O(^1D) + O(^1D) \qquad \Delta E = 3.02\ \text{eV} \qquad (7)$$

$$O_2^+ + e \rightarrow O(^1D) + O(^1S) \qquad \Delta E = 0.80\ \text{eV} \qquad (8)$$

- Shinagawa Model
  - Finds O2+ density

Exospheric Number Density cont'd

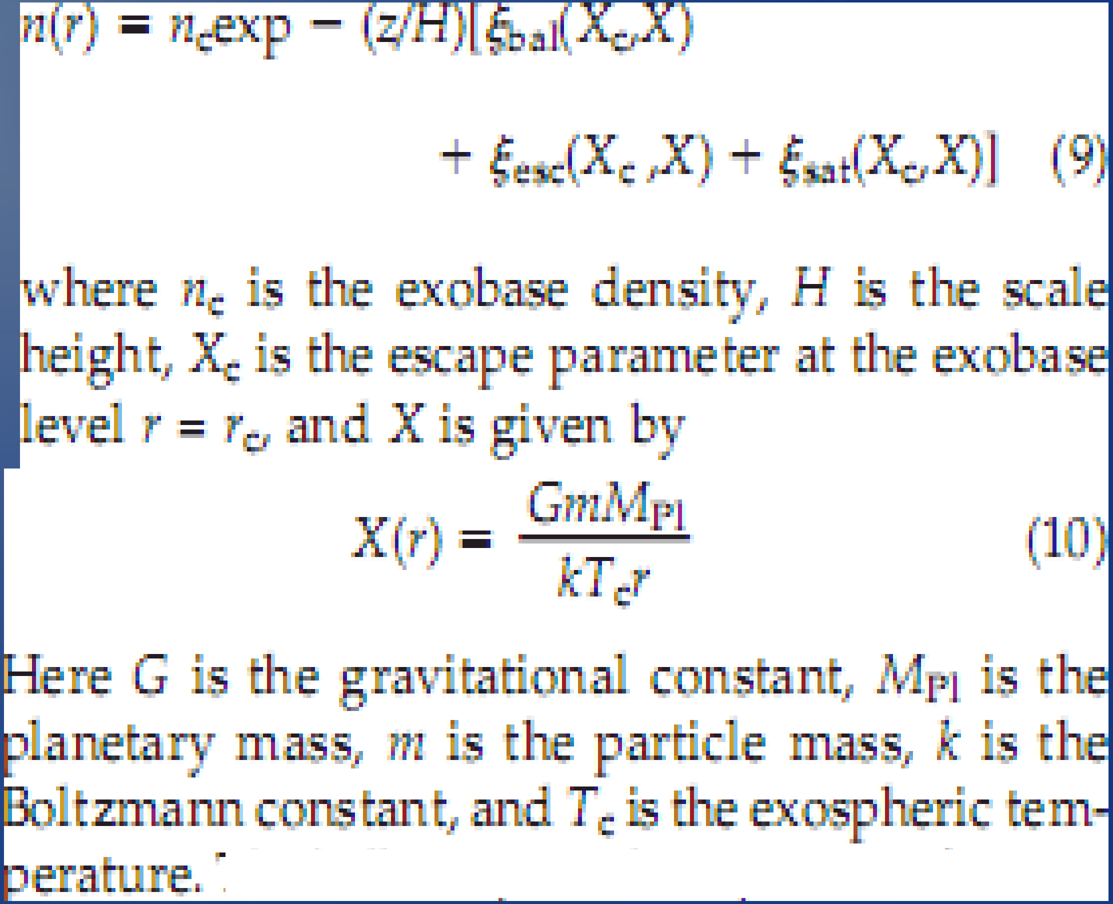


Monte Carlo Model of Mercury's Exosphere

- Monte Carlo Model
  - Uses O2+ density
  - Tracks O*. Might:
    - Lose energy
    - Collide with gases
    - Change direction
    - Drift peacefully
    - Inelastic UNLIKELY
- Barometric Law fails
  - Liouville's Equation

Exospheric Number Density cont'd

- Liouville's equation
  - Used to write out exospheric number density
- Density of O* most critical for XUV flux values <50 times Sol
- Exobase rises with XUV fluxes
  - More O* collisions
  - Incorporate into background gas



$$n(r) = n_c \exp - (z/H)[\xi_{bal}(X_c,X) + \xi_{esc}(X_c,X) + \xi_{sat}(X_c,X)] \quad (9)$$

where n_c is the exobase density, H is the scale height, X_c is the escape parameter at the exobase level $r = r_c$, and X is given by

$$X(r) = \frac{GmM_{Pl}}{kT_c r} \quad (10)$$

Here G is the gravitational constant, M_{Pl} is the planetary mass, m is the particle mass, k is the Boltzmann constant, and T_c is the exospheric temperature.

Ion Pick Up

- Three types of obstacles for solar wind
  - Earth-like
  - Venus-like
  - Titan-like
- Earth Like
  - Strongly magnetized
  - Magnetosphere balances solar wind plasma flux.
  - Magnetopause

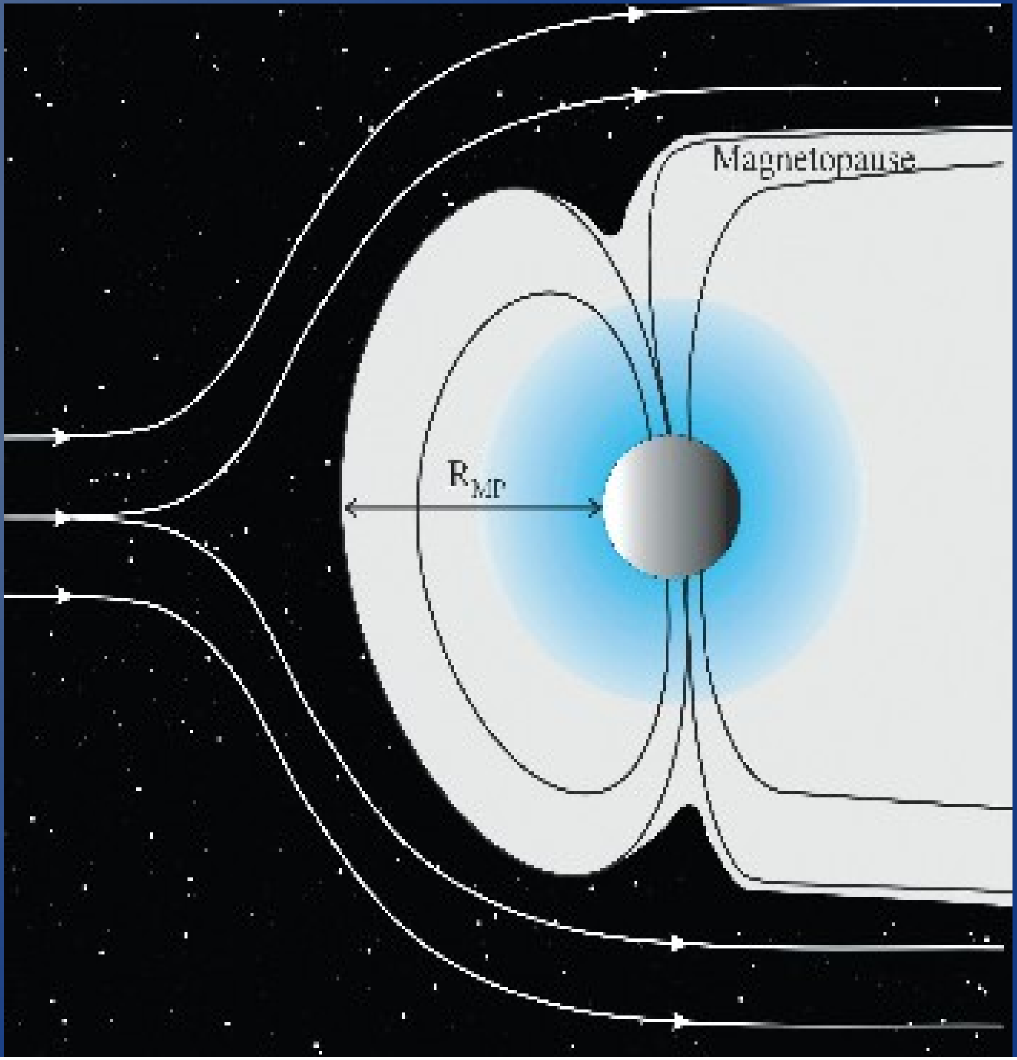
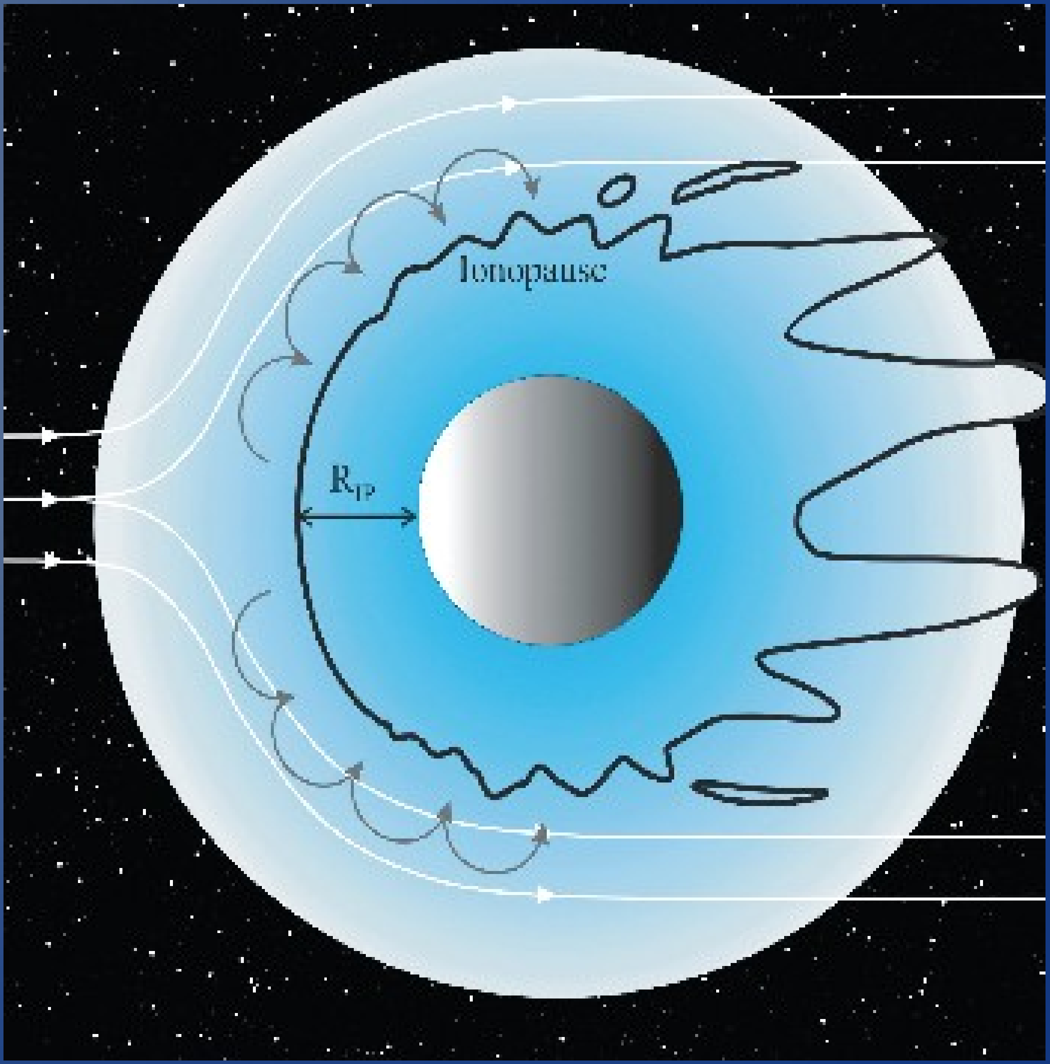


Illustration of the CME plasma interaction with a strongly magnetized planet (Earth-like).

Ion Pick Up cont'd

- Venus like
  - Weakly magnetized
  - Eroded by CME
  - Solar wind balanced by ionospheric pressure.
  - Ionopause
    - Near exobase
  -



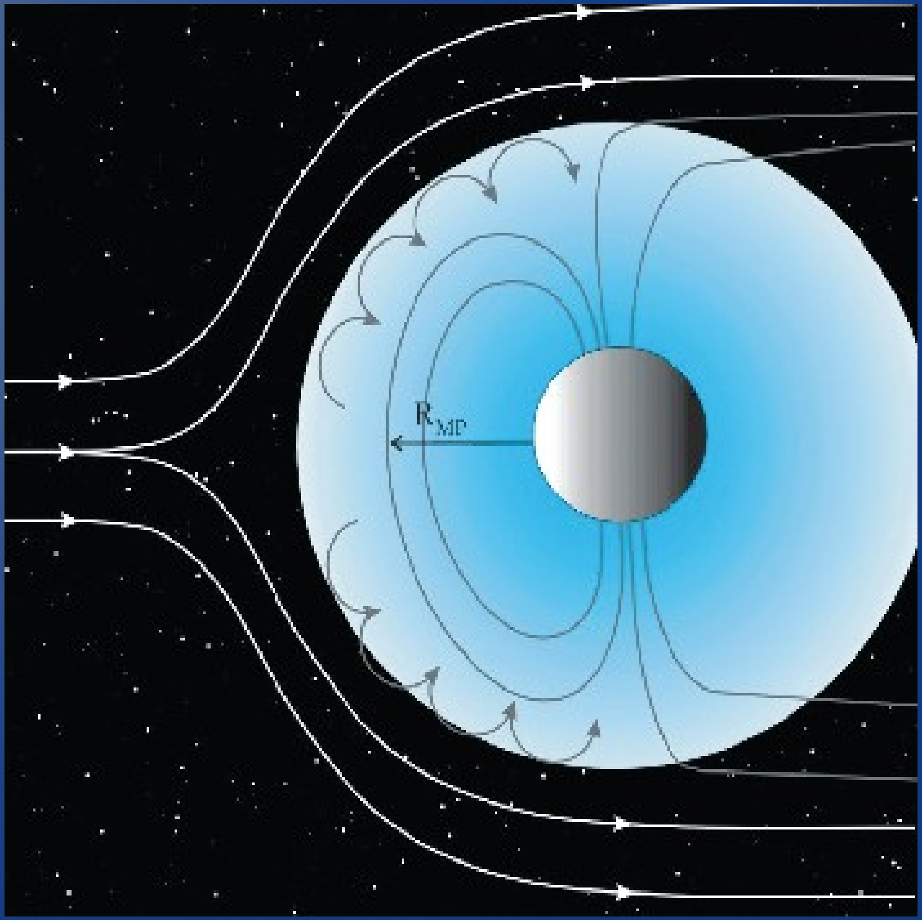
CME interaction with weakly magnetized exoplanet.

Ion Pick Up

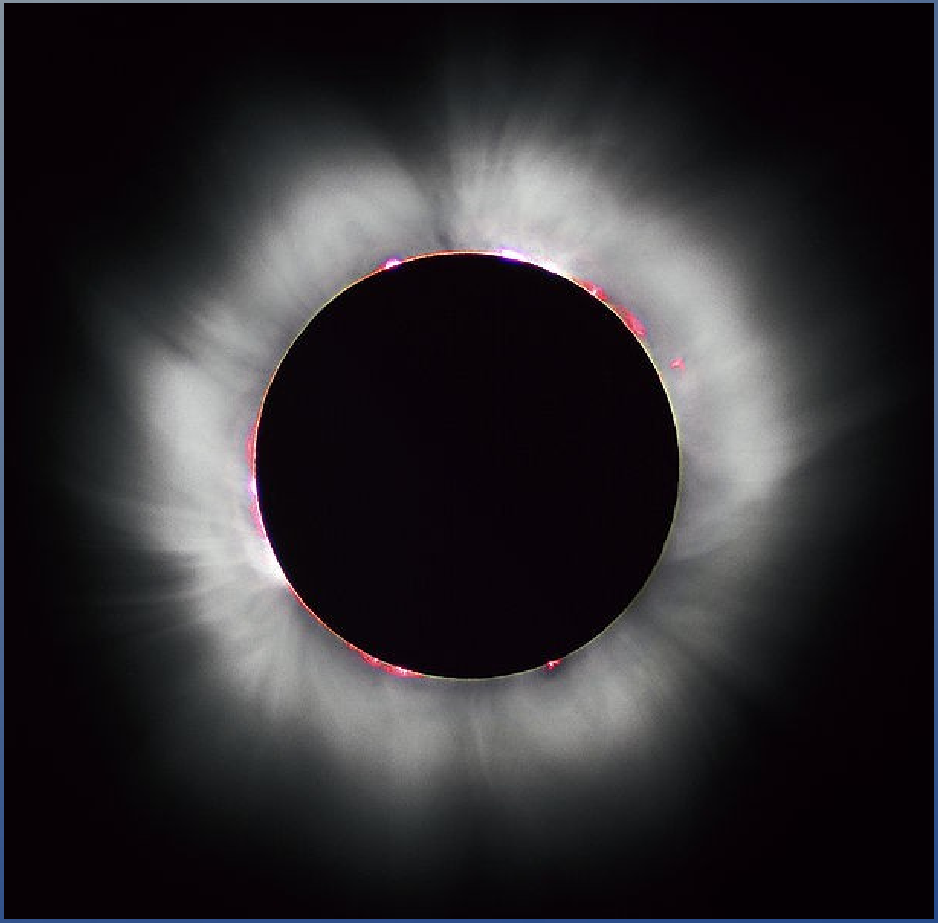
- Titan like
  - Moderate (but insufficient) magnetic field
  - Moderate Ionospheric pressure at exobase (also insufficient)
  - Intensive collisions in upper thermosphere
    - Below exobase
  - Similar to Venus

Compression entails substantial exposure to CMEs

CME interaction with compressed magnetized exoplanet and extended thermosphere



So What ARE CMEs?



- A coronal mass ejection is an ejection of material from the solar corona, usually observed with a white-light coronagraph.
- The ejected material is a plasma consisting primarily of electrons and protons, plus the entraining coronal magnetic field. (and trace heavier elements)

Griefsmeier & Khodachenko Model

- Earth like Planets in close Hzs
  - Slow rotation
    - Tidal locking
  - Model holds for Earth
  - Use scaling to predict magnetic moment “M”
    - Dwarf Star (0.5 Sol)
    - .05, .1, .2 AU

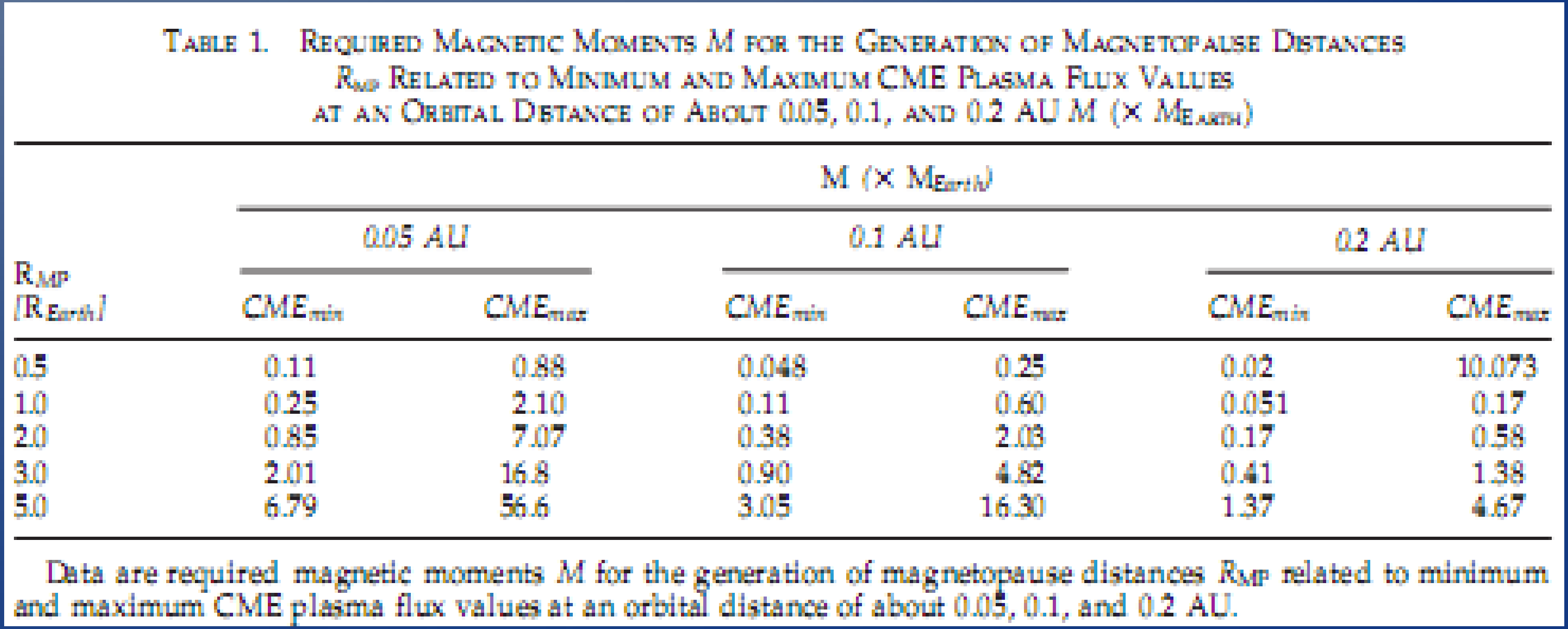


TABLE 1. REQUIRED MAGNETIC MOMENTS *M* FOR THE GENERATION OF MAGNETOPAUSE DISTANCES R_{MP} RELATED TO MINIMUM AND MAXIMUM CME PLASMA FLUX VALUES AT AN ORBITAL DISTANCE OF ABOUT 0.05, 0.1, AND 0.2 AU *M* (× M_{EARTH})

R_{MP} [R_{Earth}]	M (× M_{Earth})					
	0.05 AU		*0.1 AU*		*0.2 AU*	
	CME_{min}	CME_{max}	CME_{min}	CME_{max}	CME_{min}	CME_{max}
0.5	0.11	0.88	0.048	0.25	0.02	10.073
1.0	0.25	2.10	0.11	0.60	0.051	0.17
2.0	0.85	7.07	0.38	2.03	0.17	0.58
3.0	2.01	16.8	0.90	4.82	0.41	1.38
5.0	6.79	56.6	3.05	16.30	1.37	4.67

Data are required magnetic moments *M* for the generation of magnetopause distances R_{MP} related to minimum and maximum CME plasma flux values at an orbital distance of about 0.05, 0.1, and 0.2 AU.

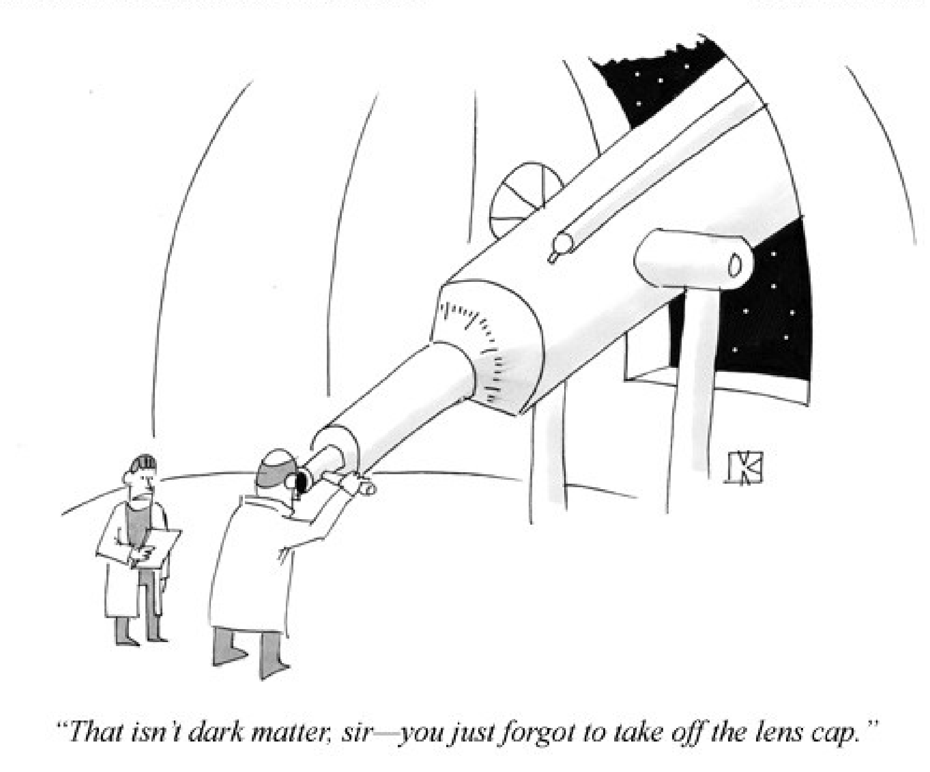
Maintaining a Magnetopause

- For weak CMEs at .5 AU, M=.25*Earth's is sufficient for only 1 Earth radius standoff.
- For strong CMEs, M = 2*Earth's, so cannot be generated by tidally locked Earth size and mass exoplanets
- At 0.1 AU, the largest M value, the Magnetopause remains below 1* Earth's radius.
- At 0.2 AU, the largest M can produce an acceptable magnetopause at 2* Earth's radius for weak CME, 1* for strong

Test Particle Model

- Spreiter and Stahara
  - Plasma flow around magneto- and iono- pause
  - Successfully explained several features noted by Pioneer Venus and Phobos 2.
- Erkaev et al and Pruesse et al
  - Stellar winds behave differently at <.1 AU
  - Unlike Sol some very near exoplanets could build obstacles.
- Khodachenko et al
  - Found the rate of interaction with CMEs was not significantly higher within close HZs

I think we forgot something

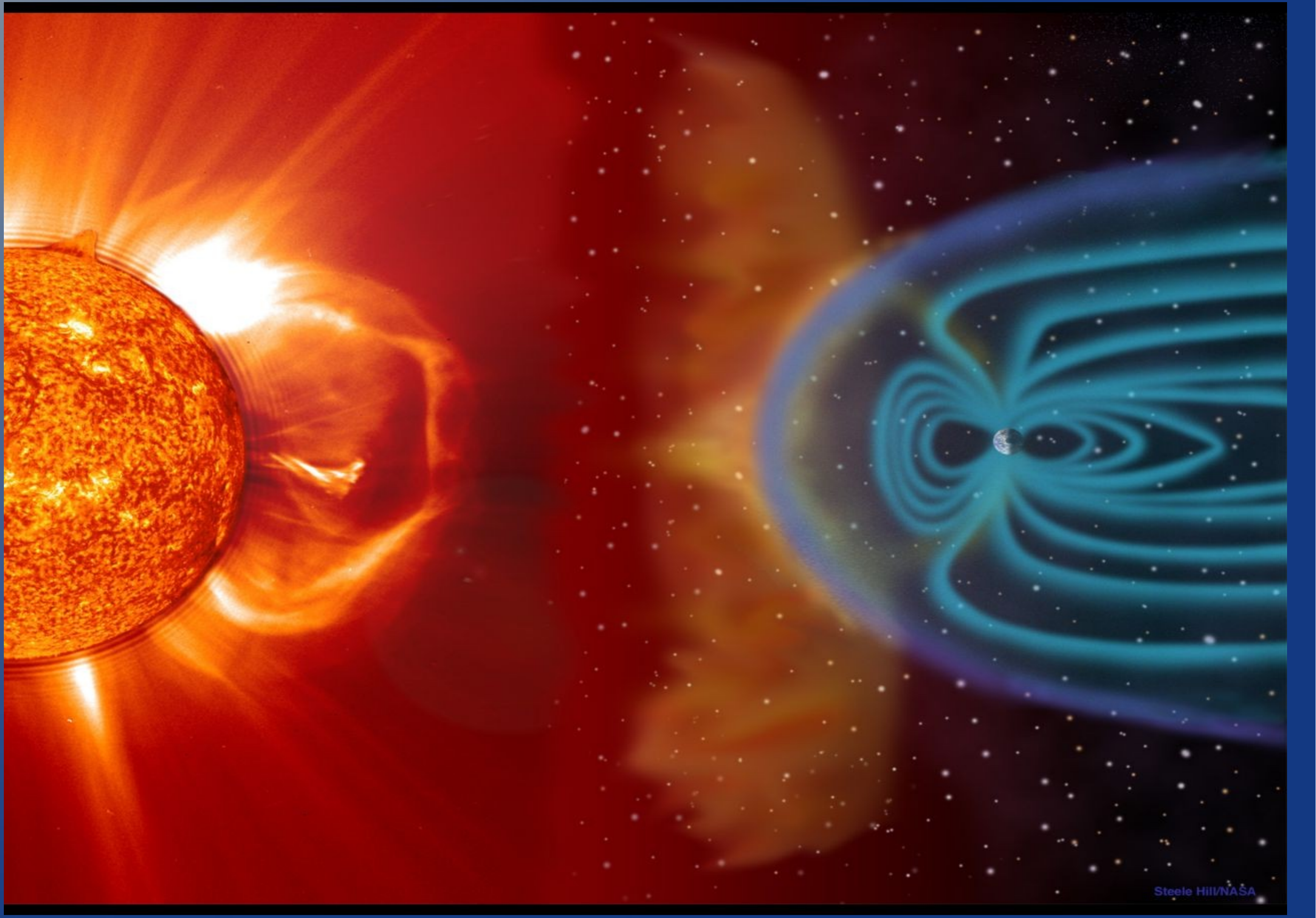


"That isn't dark matter, sir—you just forgot to take off the lens cap."

- They did not account for ordinary stellar wind
  - CMEs in our study turn out to act like solar wind in Sol
- How exactly do we calculate the flux interaction?
  - Very long equation
  - ???

The Point of All This Muck

- CME induced Atmospheric Erosion Due to Ion Pickup at C)2-Rich Earth-like Exoplanets Orbiting Close-in HZs



CME Erosion

- Strong dependence on the planetary magnetic moment and CME plasma density
  - Venus-like exoplanets fare worst, losing up to several hundred bars of pressure in the model
    - Variation (min-max CME) is greatest also
  - Earth-like exoplanets with relatively weak moments still lose tens of bars
  - Planets with strong moments suffer very little loss.

CME Erosion

- Apply our model to the three cases

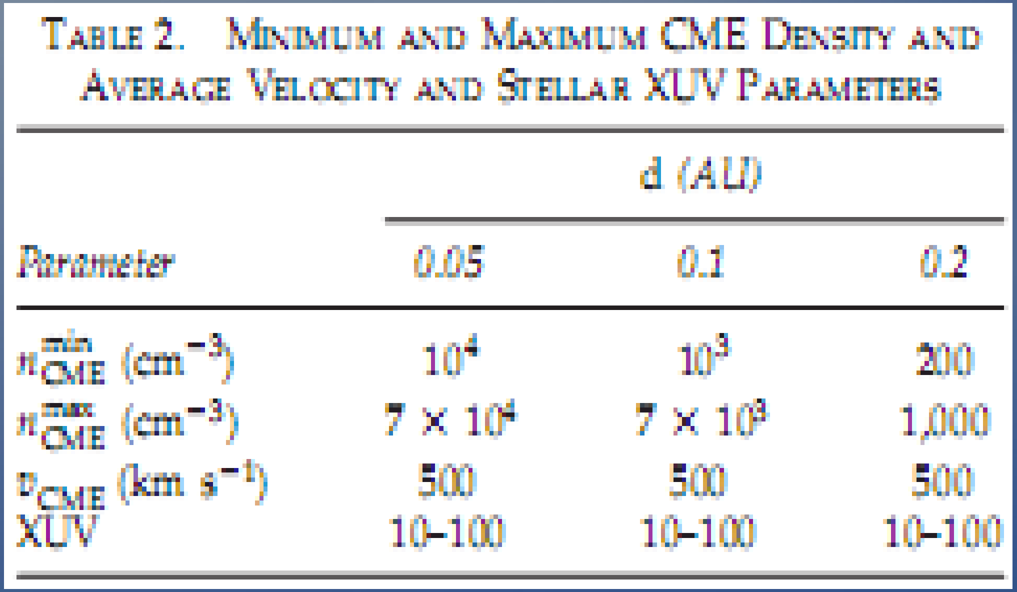
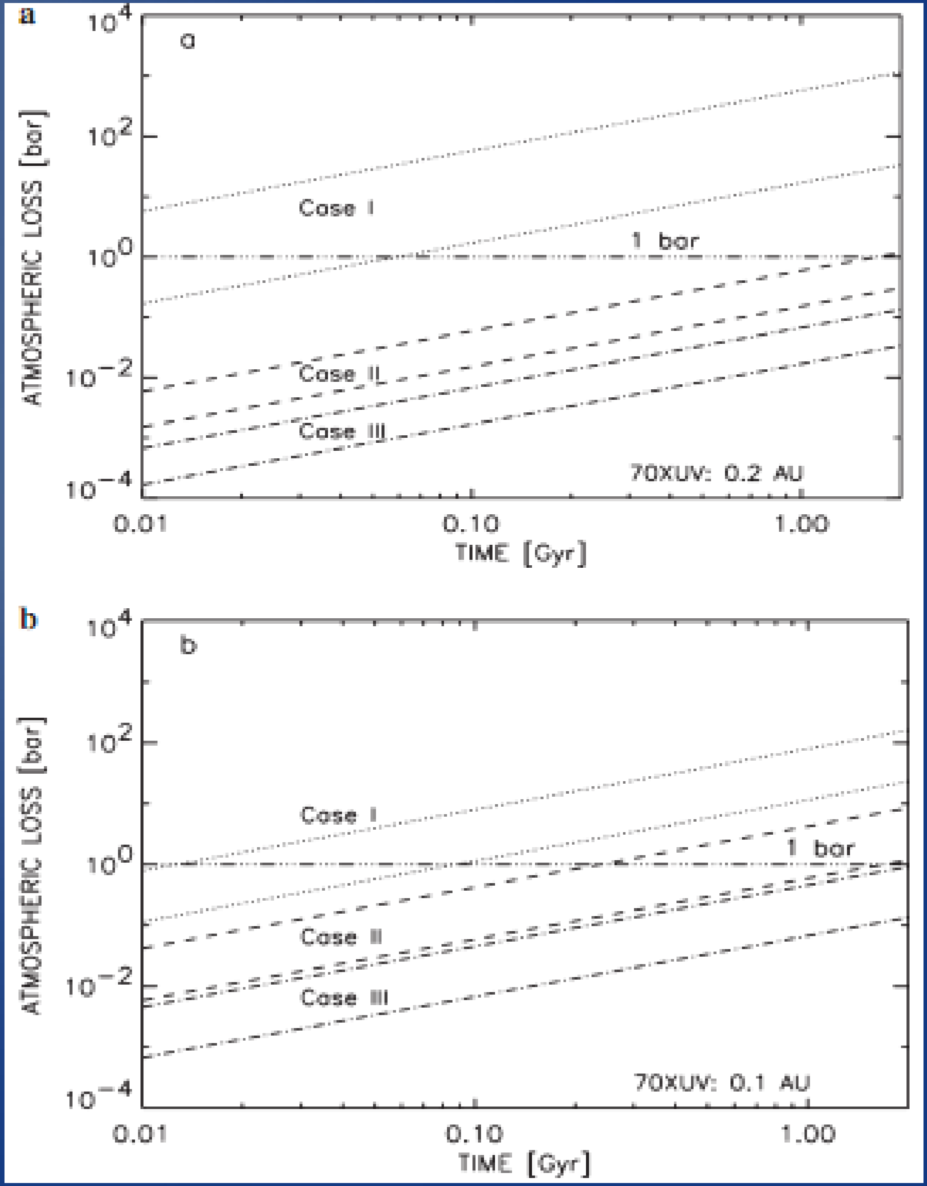


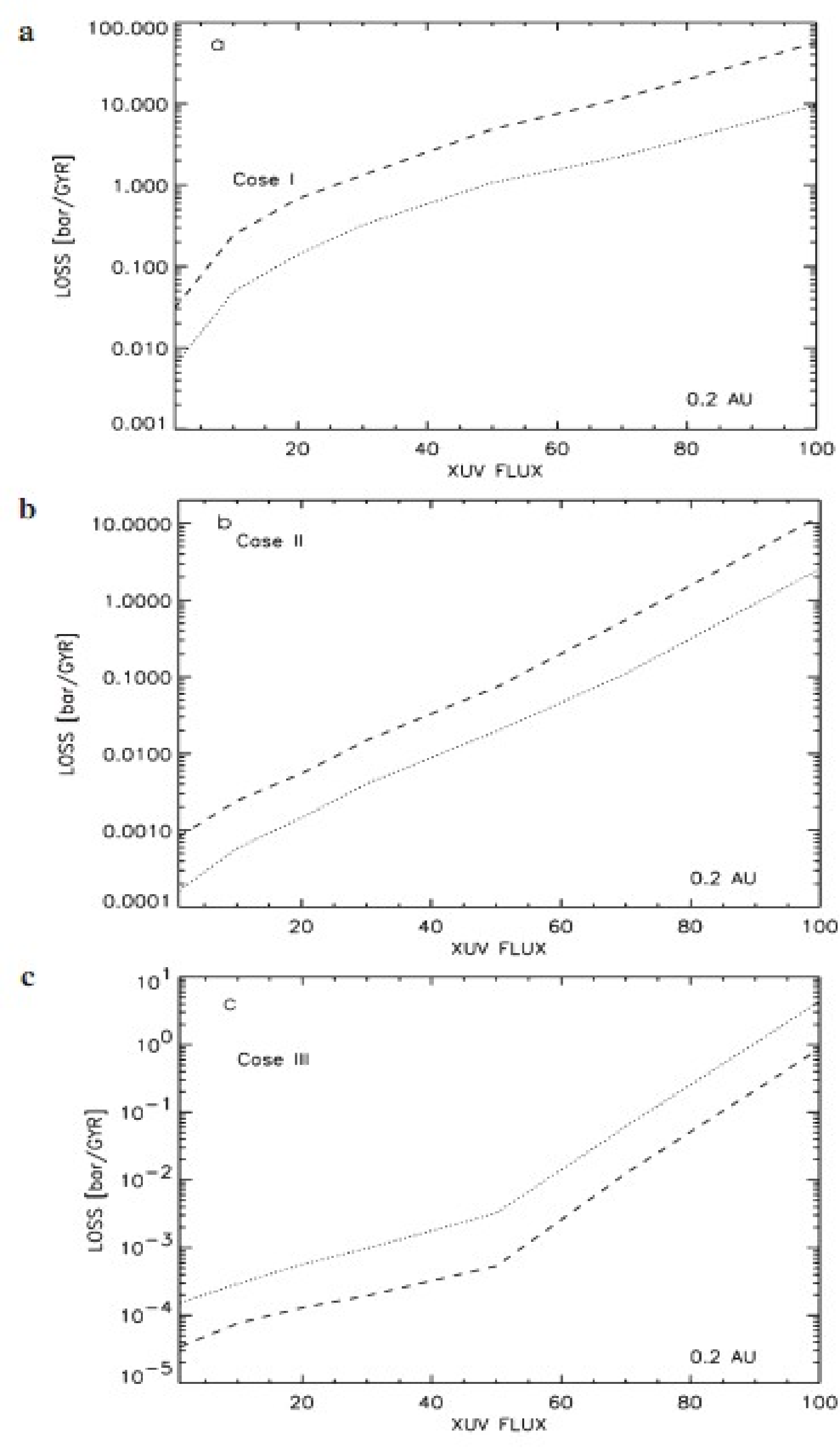
TABLE 2. MINIMUM AND MAXIMUM CME DENSITY AND AVERAGE VELOCITY AND STELLAR XUV PARAMETERS

	d (AU)		
Parameter	*0.05*	*0.1*	*0.2*
n_{CME}^{min} (cm^{-3})	10^4	10^3	200
n_{CME}^{max} (cm^{-3})	7×10^4	7×10^3	1,000
v_{CME} (km s^{-1})	500	500	500
XUV	10–100	10–100	10–100



Right: Time dependent atmospheric loss as function of minimum and maximum CME plamsa flux for XUV >70 times Earth's in M star HZs at 0.2 AU (a) and 0.1 AU (b)

CME Erosion cont'd



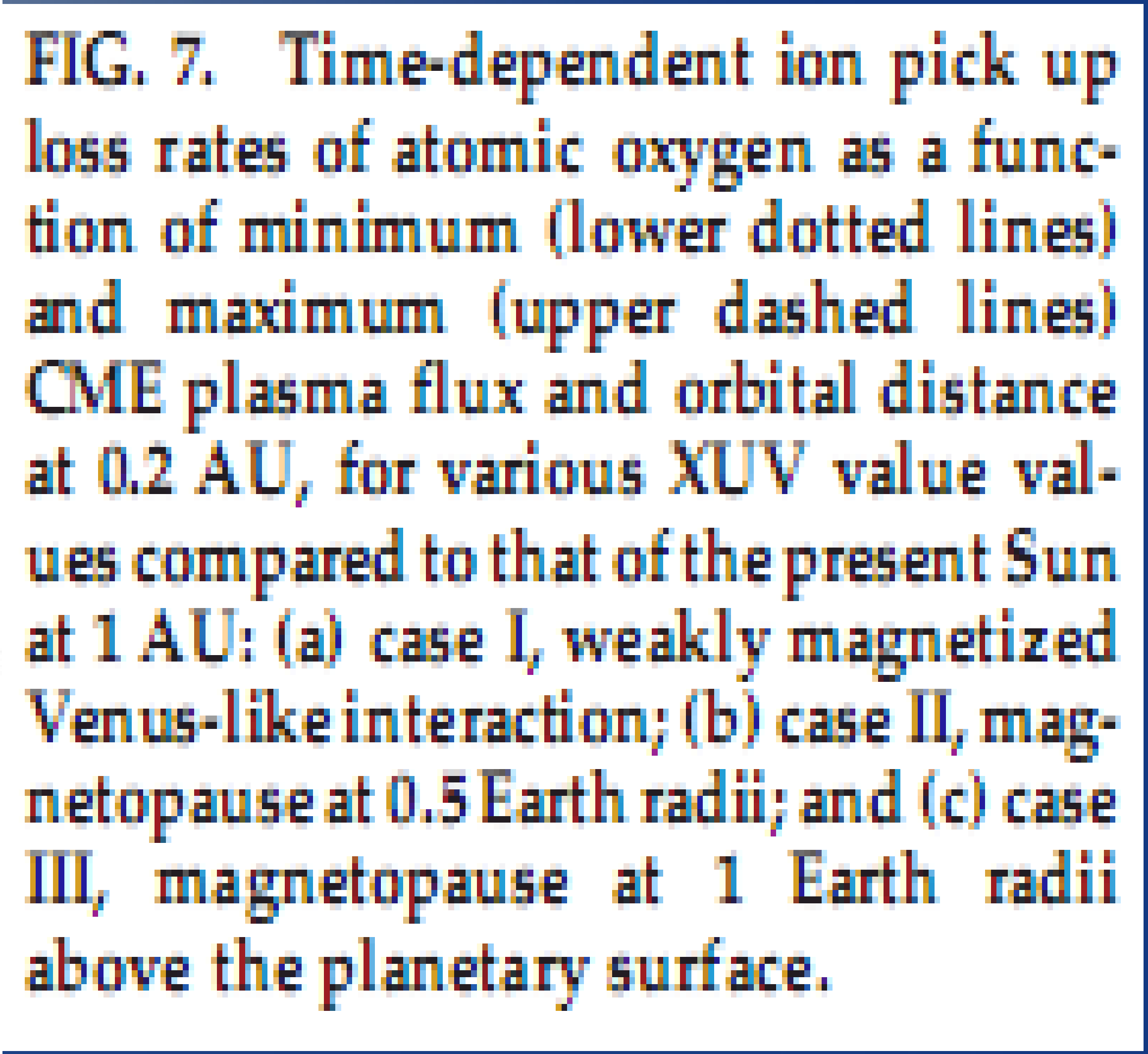


FIG. 7. Time-dependent ion pick up loss rates of atomic oxygen as a function of minimum (lower dotted lines) and maximum (upper dashed lines) CME plasma flux and orbital distance at 0.2 AU, for various XUV value values compared to that of the present Sun at 1 AU: (a) case I, weakly magnetized Venus-like interaction; (b) case II, magnetopause at 0.5 Earth radii; and (c) case III, magnetopause at 1 Earth radii above the planetary surface.

CME Erosion

- May yield Mercury-type exoplanets, despite being in their star's HZ
- Lammer, Michel, and Bauer estimated atmospheric loss from CME via a simple mass model, but they neglected XUV induced exospherical expansion

- Tidally locked, weakly magnetized earthlike planets typically lose their atmosphere entirely

What it means

- The Good
- The atmosphere of an Earth like exoplanet in the HZ (.05-.2 AU) has a high CO2 ratio (>96%) and must posess a strong magnetic dynamo to be preserved IF exposed to XUV fluxes NO greater than 50*Sol.

- The Bad
- Unfortunately, M stars typically have fluxes 70-100 times Sol.
- Weak magnetic moments of tidally locked exoplanets and intense radiation imply a loss of up to thousands of bars of atmosphere.

The ugly

- CME instills additional thermospheric heating, triggering further atmospheric loss due to ionospheric clouds
- Even more, the XUV and CME induced temperatures enables the escape of lighter gases
  - Hydrogen, Helium, etc.
- Essentially, the fixing of any one variable renders the others unacceptable.

So where to now?

- The future lies with larger "Super-Earths" or "Ocean Planets"
- Larger cores mean stonger magnetic moments
- Greater mass means shorter exospheric regions
- Profit!

New planet holds possibility for life

A planet 20.5 light years from our solar system is the first thought to have qualities – Earth-like temperatures and possibly water – that could sustain life.

GL-581 c

Gravity: 1.6 times that of Earth
Temperature: 34° F to 124° F
Orbit: 13 days

Rotation: unknown if any at all

Earth

Orbit: 365.25 days
Temperature: -126° F to 136° F
Rotation: 24 hours

NOTE: Image of Gl-581 c is an artist's rendering

SOURCES: European Organization for Astronomical Research in the Southern Hemisphere, NASA

AP

Final Thoughts

- High XUV (>50*Sol) = expansive atmospheres around Earth-like planets
- Weak magnetic moment = harsh XUV and CME impacts = stripped atmosphere
- High CO2 = denser atmosphere

- XUV > 70*Sol are too great for any real terran exoplanet in HZ
- Earth-like atmospheres are particularly at risk