Solar History Effects on Venus and Earth Climate

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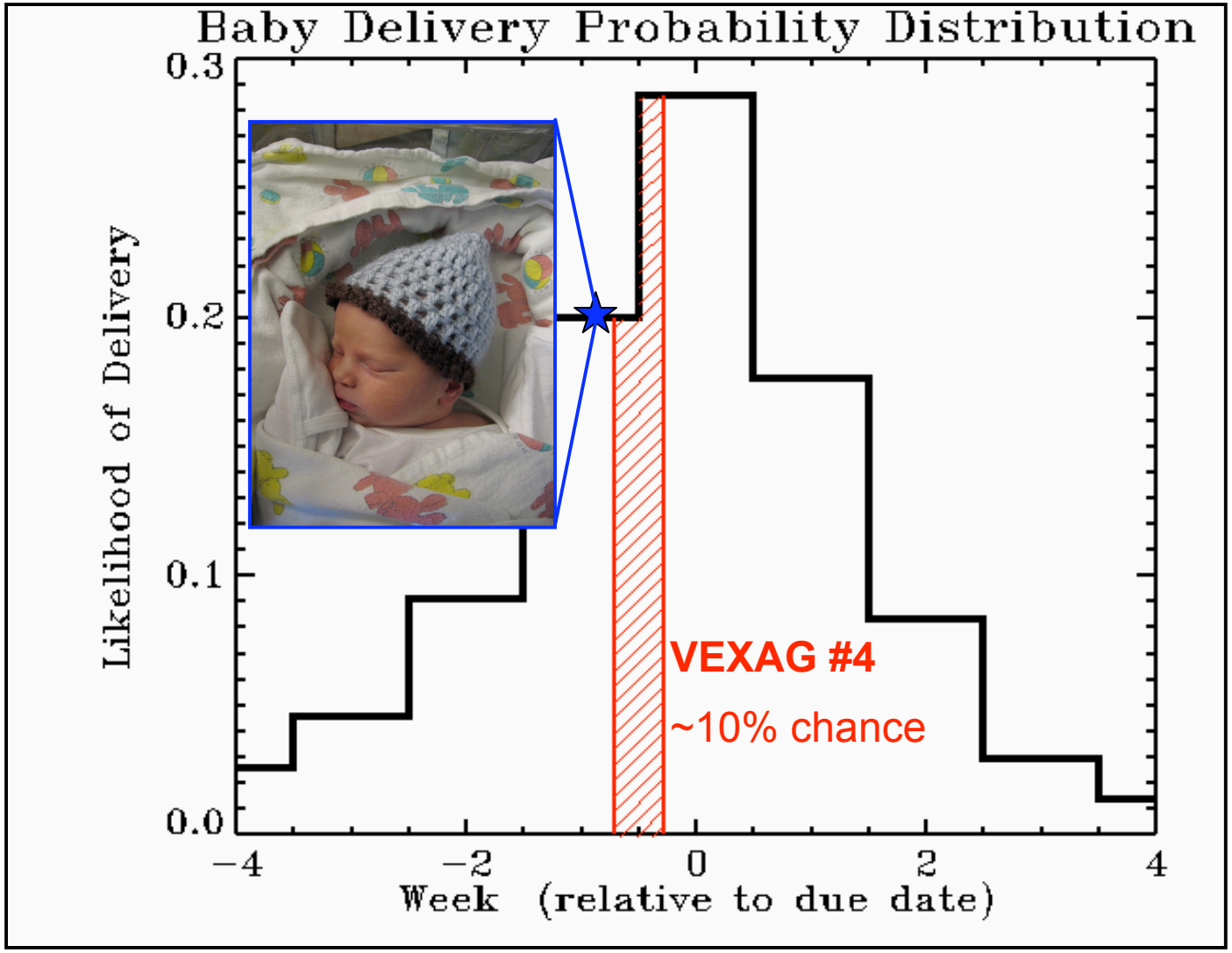
(for Dave Brain)

UC Berkeley Space Sciences Lab

VEXAG Meeting #4

05 November 2007

Where's Dave?


Baby Delivery Probability Distribution
Likelihood of Delivery
0.3
0.2
0.1
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−4
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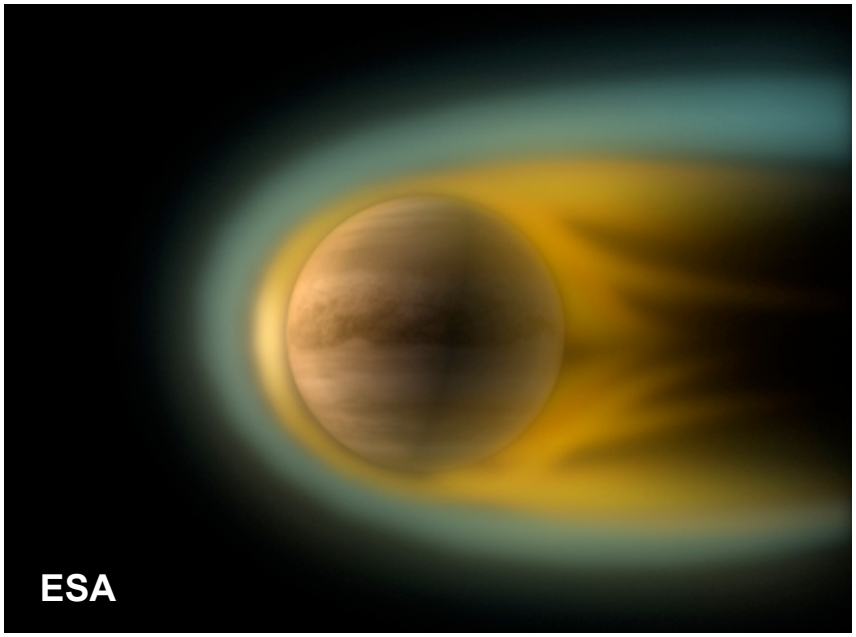
2
4
Week (relative to due date)
VEXAG #4
~10% chance

Motivation

- Climate is influenced by atmospheric inventories as well as solar irradiance
- Atmospheric inventories result from source and loss processes acting over the lifetime of a planet
- Venus D/H ratio indicates a major loss process has been atmospheric escape to space
- "Escape to space" is a collection of processes for neutrals and ions, all of which require energy input from the Sun. The Sun's energy input varies in time.
- How have both radiative and non-radiative solar processes affected Venus climate? To what extent have the same processes affected Earth climate?

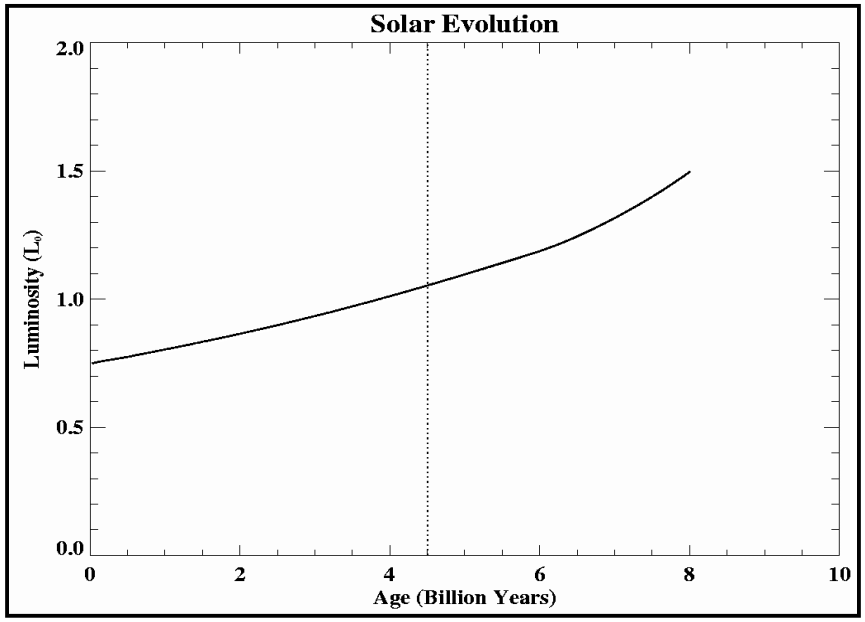


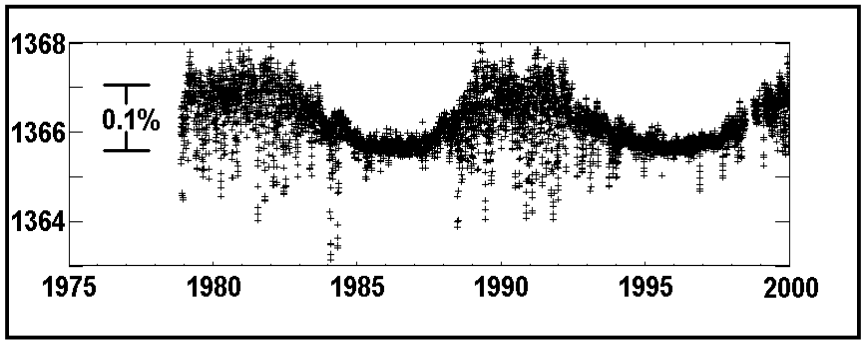
Can solar history help account for the Venus water content?

Solar Influence and History

Solar Photons

- Upper atmospheres are principally affected by X-rays and EUV (XUV)
- These photons provide heating and ionization sources for upper atmospheres
- This drives chemistry, dynamics, and escape
- Solar luminosity has increased over 4.5 Gy (~30%) according to stellar counterpart studies
- Total solar irradiance now varies by only ~0.1% over solar cycle
- But XUV varies by 10-500% over solar cycle
- How has XUV affected the atmosphere?

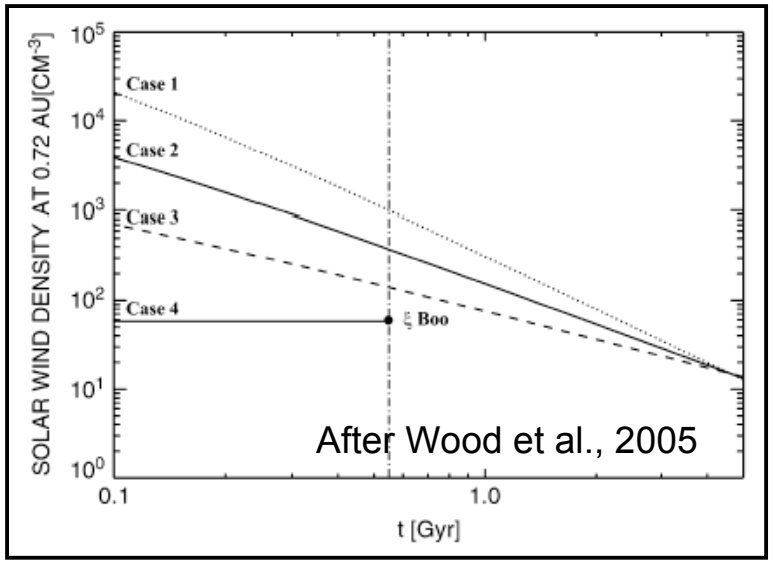


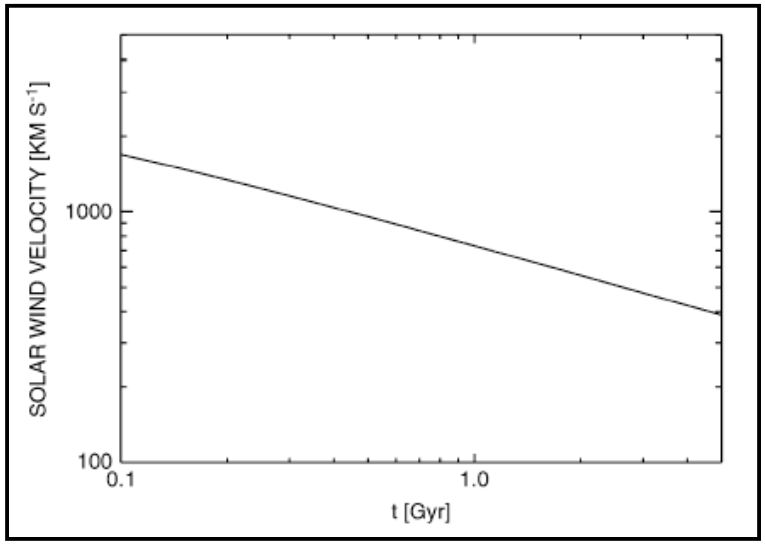


Solar Influence and History

Solar Wind

- Solar wind particles (mostly protons) can directly deposit energy in areas of atmospheres unprotected by magnetic fields
- They also Ionize planetary neutrals via charge exchange and electron impact
- In addition, the solar wind electric field accelerates planetary ions
- It has been suggested that the early Sun was more active and had a more significant wind
- Work by Wood et al. (2002, 2005), the most authoritative to date, instead suggests the earliest solar ouflows were weaker –
- Are there other considerations, based on our knowledge of solar activity, for Venus and Earth?

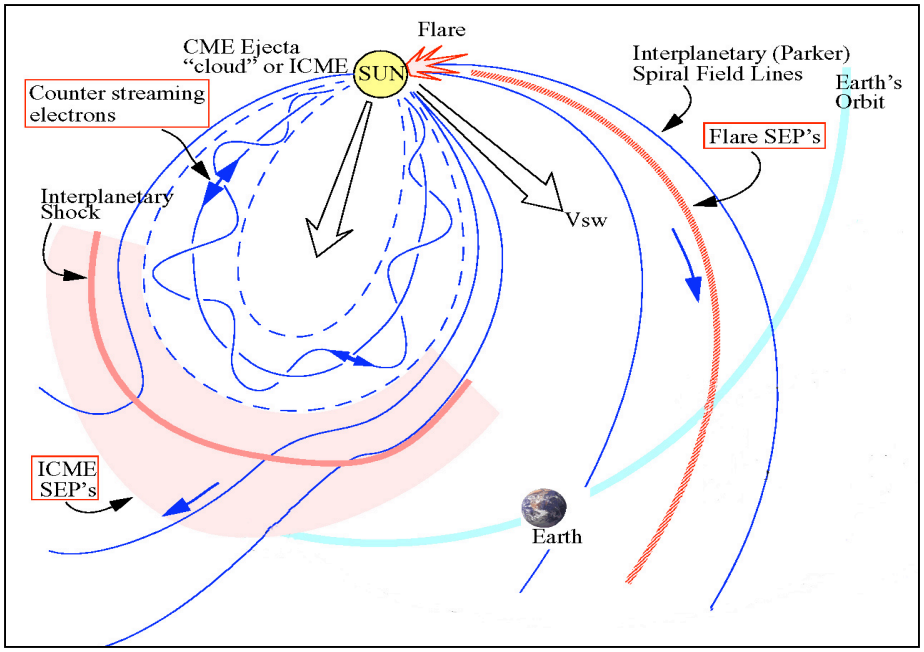


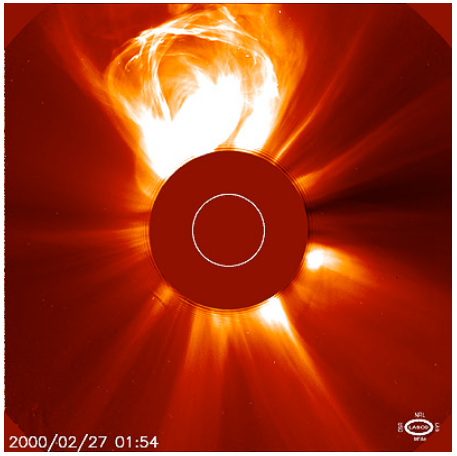


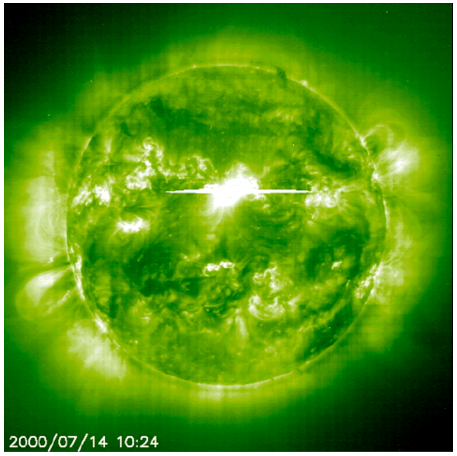
Solar Influence and History

Solar Storms

- Solar flares provide short periods (minutes?) of increased ionization and heating in upper atmospheres
- Coronal mass ejections (CMEs) produce interplanetary shocks and strong density, velocity and magnetic field increases that allow the solar wind to penetrate deeper in an atmosphere for hours-days.
- Solar energetic particles (SEPs) deposit additional energy deep in an atmosphere for hours-days, affecting chemistry, ionization, etc.
- Solar storms were likely more frequent and possibly more intense in the past.
- Are these events responsible for stripping away atmospheres of planets around more active stars?



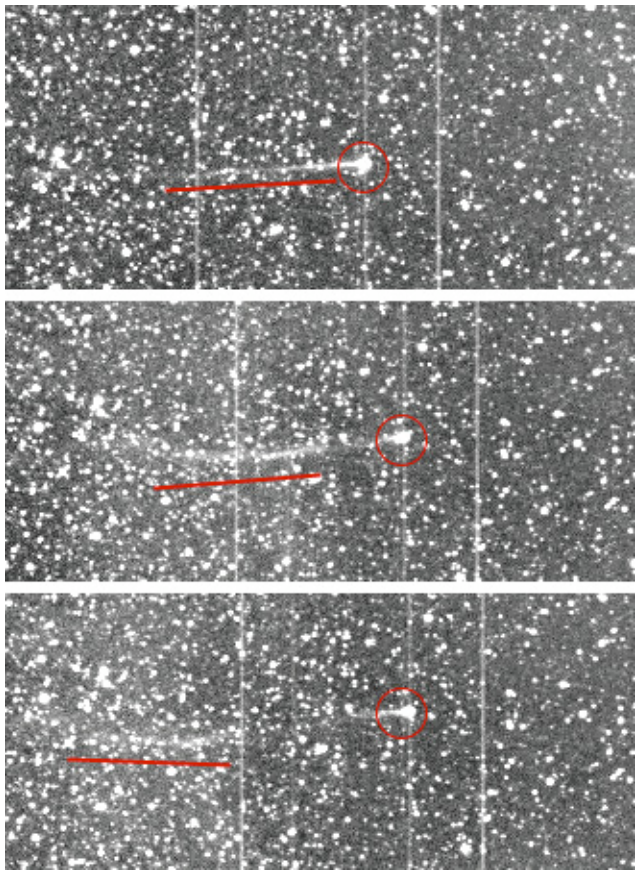




Solar Influence and history

Solar Storms (cont.)

- STEREO's Heliospheric Imager observed comet Encke during a passing CME
- The entire comet tail appears to disconnect when a CME passes
- Inspires the suggestion that magnetic reconnection rips away the entire tail in bulk escape event
- Demonstrates possible importance of intermittent events in atmospheric evolution at unmagnetized bodies



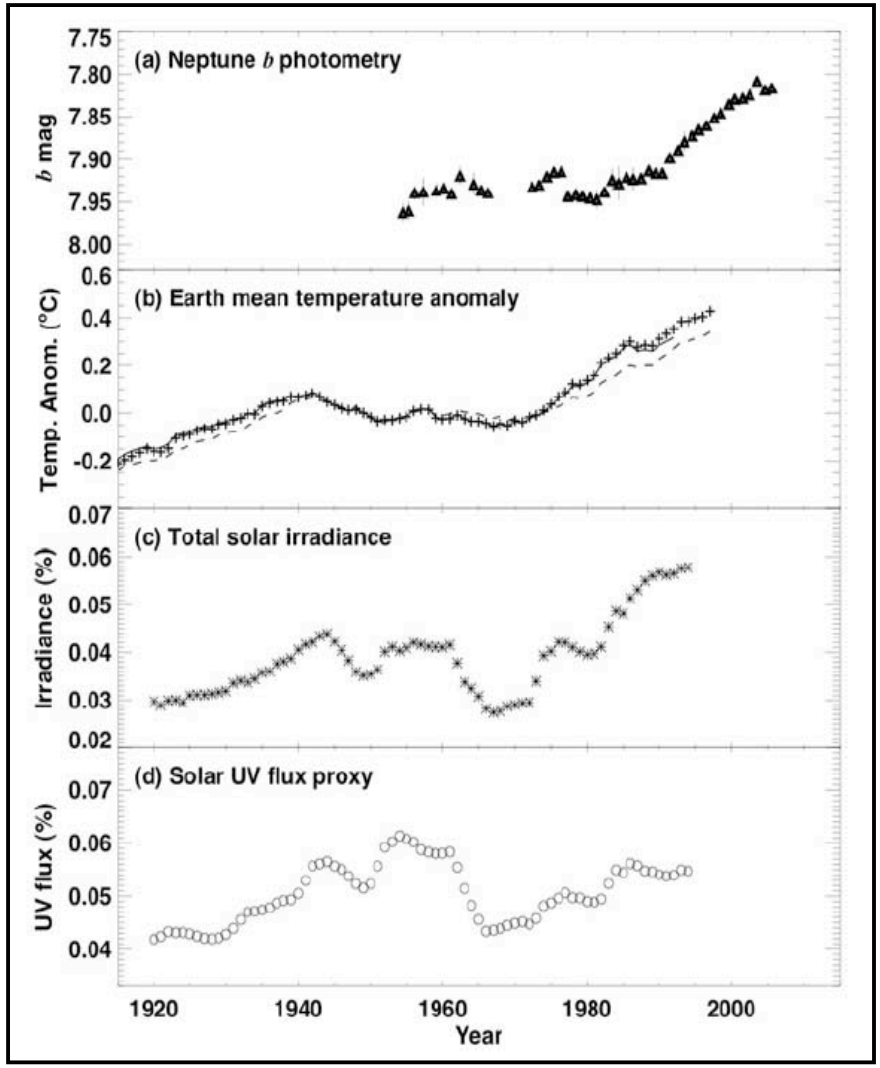
http://www.nasa.gov/mission_pages/stereo/news/encke.html

NASA / STEREO

Solar Influence and history

Planetary Albedo effects?

- Reflectivity of Neptune over last 60 years is correlated with Earth surface temperatures and solar variability
- Correlation requires a ~15 year time lag between Earth and Neptune
- This correlation of 20% may be due to chance, but is suggestive.
- Is there a mutual response of climates to planetary albedos at Venus and Earth?
- What common effects could alter planetary albedos? (e.g. some suggest certain high altitude cloud formation at Earth is affected by solar activity via the related cosmic ray flux modulation)



Hammel and Lockwood, 2007

Models of Solar History Effects

- Recent efforts by Kulikov, et al., 2006, 2007 and Lammer, et al. 2006 incorporate the results of past observational efforts relating so solar effects toward climate and upper atmospheric modeling efforts.

- Their work adds new calculations and simulations to evaluate the role of the upper atmosphere changes and escape to space in the evolution of the atmospheres of Venus, Earth, and Mars.

- More such observation-inspired modeling experiments need to be done to simulate evolutionary scenarios that we can’t directly observe

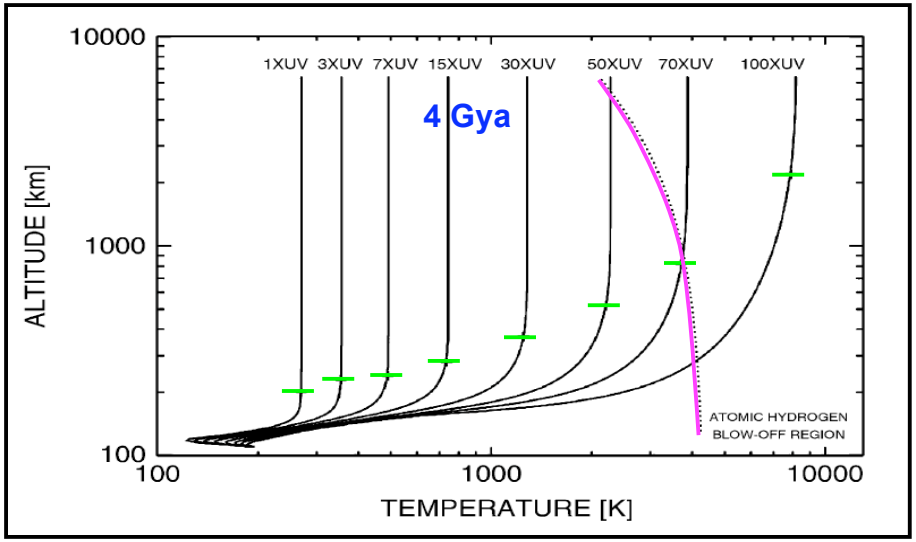
Models of Solar History Effects

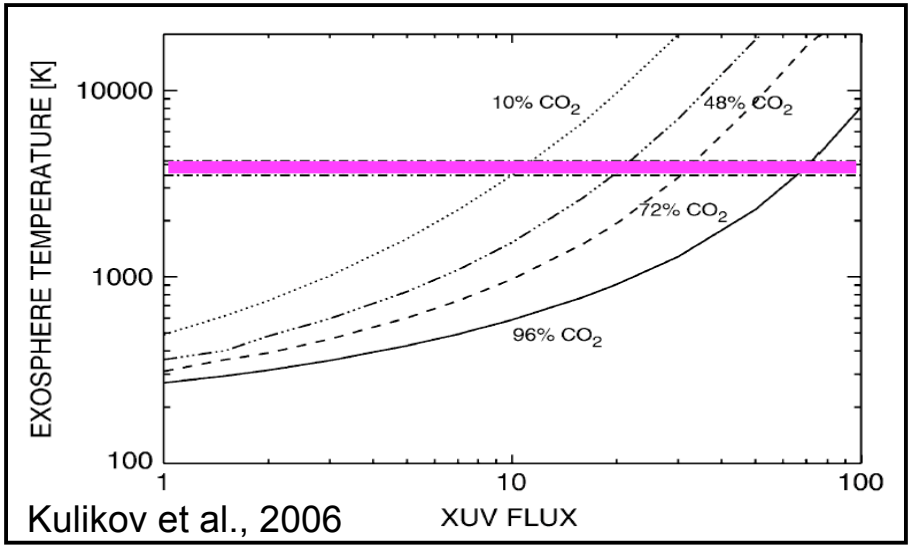
Thermospheric / Exospheric Models

- Their 1-D thermospheric model includes:
  - Heating via photoionization
  - Heating via photodissociation
  - Chemical heating
  - Conduction in neutral gas
  - IR cooling
  - Turbulent energy dissipation

Some Findings:

- Exobase altitudes and temperatures were (much) higher in the past
- Hydrogen blow-off occurred for at least the first few hundred Myr
- 2-3 bar of oxygen (~1% terr. ocean) could have been removed over first 100 Myr along with the hydrogen





Kulikov et al., 2006

Models of Solar History Effects

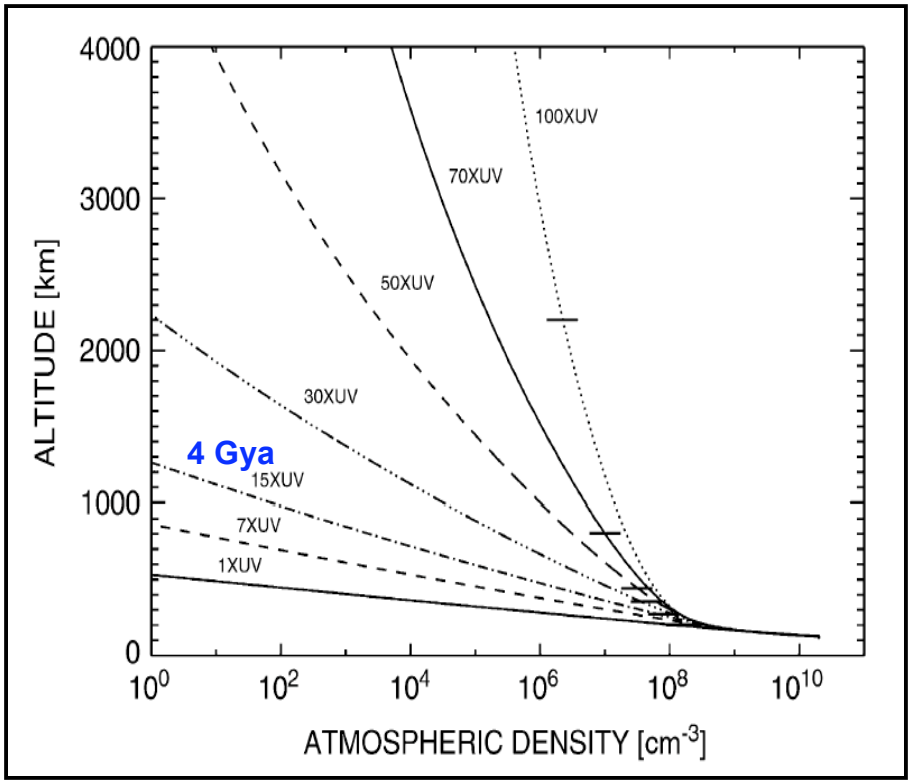
Thermospheric / Exospheric Models (cont.)

Kulikov et al., 2006

Conclusions:

Greater + hotter exosphere implies more thermal escape and ultimately hydrodynamic outflows

This modeled effect is from the increased solar XUV heating only

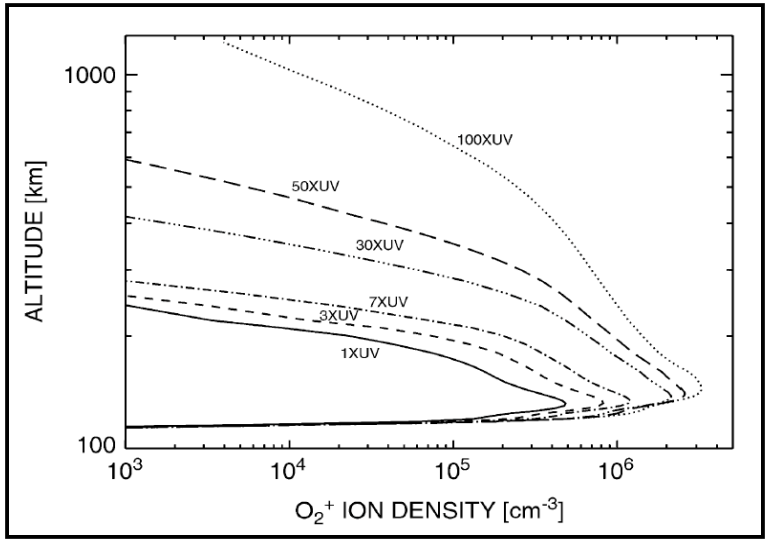


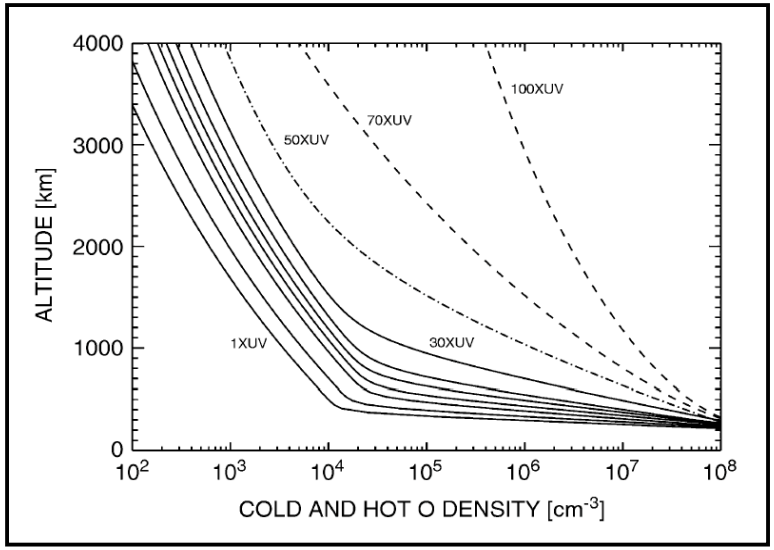
Models of Solar History Effects

Ionosphere and Hot Exosphere

Kulikov et al., 2006

- The model of Shinagawa et al., (1987) was applied to the neutral density profiles to obtain ionospheric densities for a Venus-like atmosphere
- A Monte Carlo model (Lammer et al., 2004) was then used to simulate the associated hot oxygen corona
- For Venus the exobase was found to lie above the altitude of pressure balance between the solar wind and the ionosphere for ~2.5 Gy, implying the solar wind collided directly with the collisional atmosphere during that time, resulting in increased heating, ionization, mass loss.
- Effects for magnetized planets???



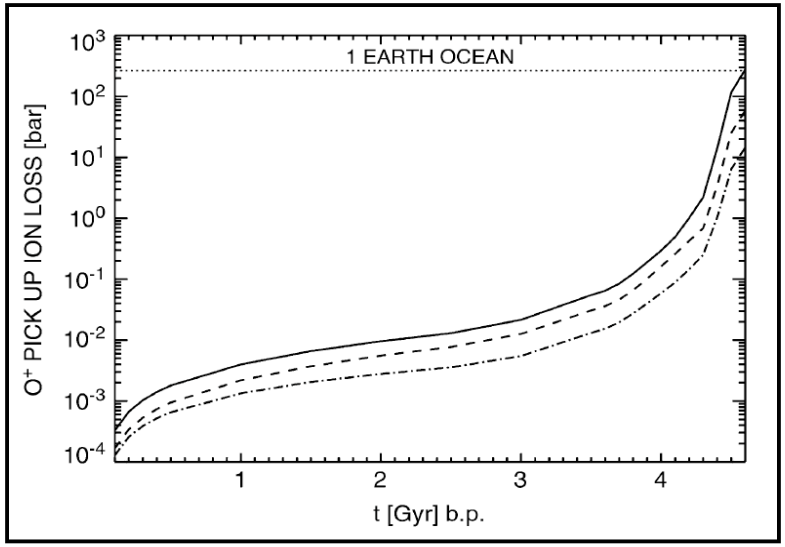


Models of Solar History Effects

Pickup Ion Loss

Kulikov et al., 2006

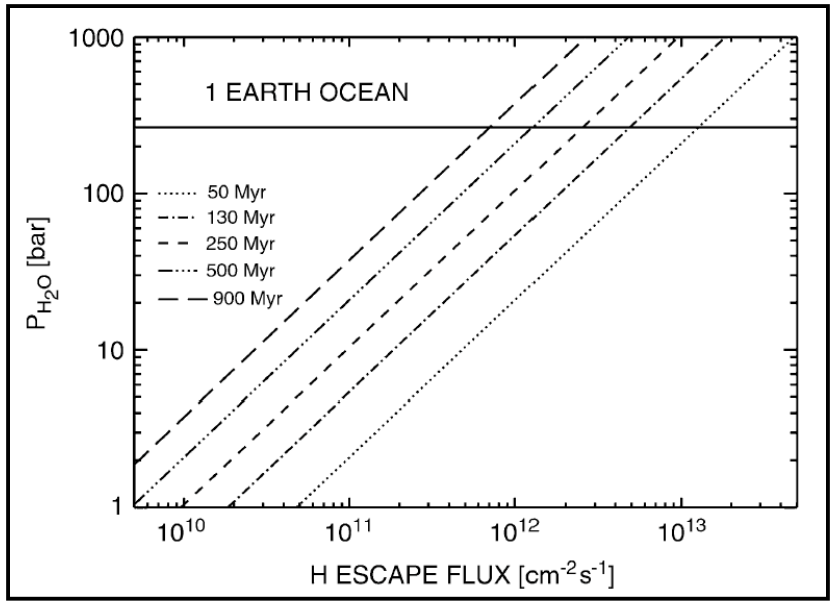
- The model used test particle tracing in gasdynamic solar wind interaction models, with specified ion production rates and density profiles
- It was assumed all ions produced in the upper atmospheres of unmagnetized planets are lost
- Integrated oxygen ion loss depends upon the neutral atmosphere model and ionization rate- therefore on time history of XUV.
- They conclude that if the early Sun was active for the first 700 Myr, then oxygen loss via pickup was 10-275 bars (up to a terrestrial ocean) for Venus
- If the early Sun was NOT active for the first 700 Myr, then oxygen loss via pickup was ~2 bar.
- Calculations neglect other non-thermal escape mechanisms and storm effects, but show importance of early high XUV.



Models of Solar History Effects

Water Loss

- Here they follow Kasting & Pollack, 1983
- The total hydrogen escape flux was calculated as function of an assumed partial pressure of H_2O and an assumed duration of hydrodynamic escape conditions
- A terrestrial ocean of hydrogen could have been removed in the first 100 Myr.
- The related terrestrial ocean of oxygen could have been removed by the processes described earlier



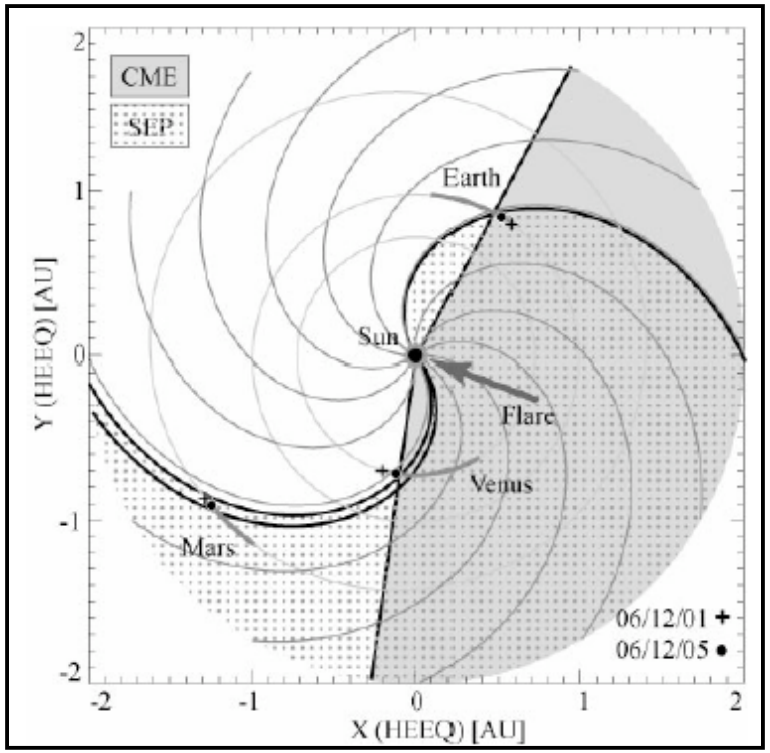
Kulikov et al., 2006

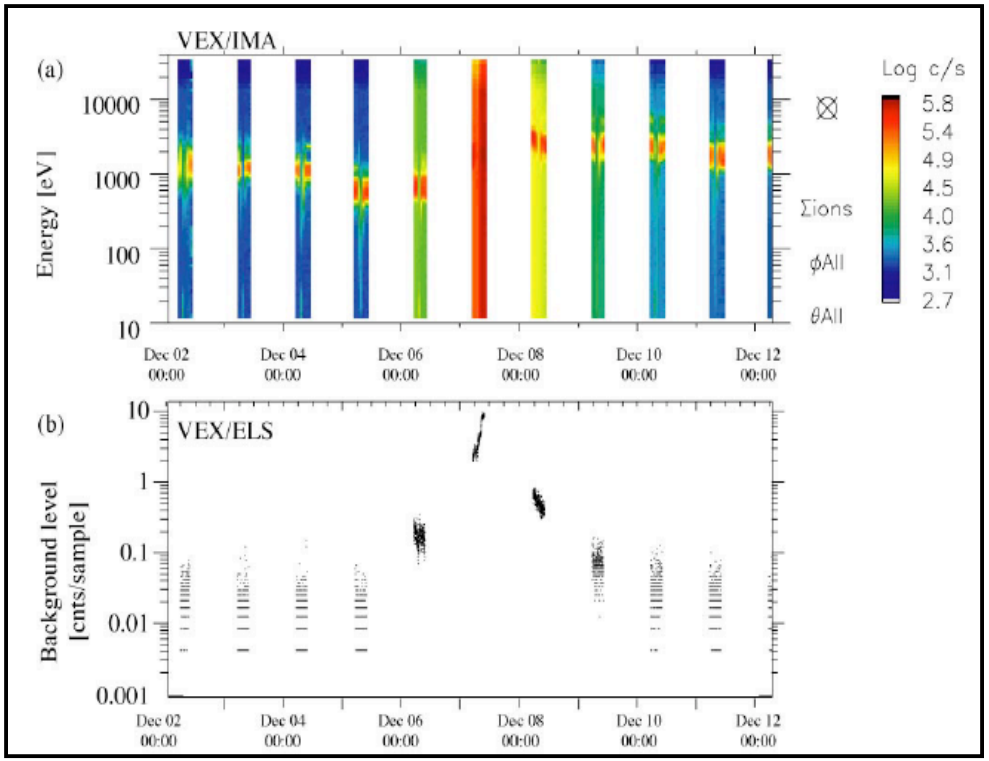
--> Early Venus need not have been dry

Recent VEX Measurements

- A Large solar storm in December 2006 was observed by STEREO, VEX, MEX
- Storm effects experienced at Earth and Venus, although they were far apart
- Particle instruments on VEX and MEX had high backgrounds
- MEX measurements suggest ion escape increased 10x during event
- VEX particle and photon detectors also indicated a response
- Do these measurements indicate an important part of the Sun/escape story?

Futaana et al., 2007





Summary

- Solar XUV, solar wind, and solar storms provided more significant atmospheric energy inputs early in solar system history, and can vary significantly over shorter timescales at present

- Recent modeling and observational efforts for Venus (and terrestrial planets) expand on previous work, showing that solar photon and particle output variability should influence upper atmospheric structure, atmospheric temperatures, and particle escape

- Solar variability may drive changes in the Venus climate over short timescales, and has most certainly influenced the Venus climate and atmospheric water content over the past 4.5 Gya. The parallel effects for Earth would need to be considered taking into account the effects of its planetary magnetic field.