Planetary constraints for solar evolution

Solar models with early mass loss

Suzannah R Wood
Katie Mussack
Joyce Ann Guzik
Los Alamos National Laboratory

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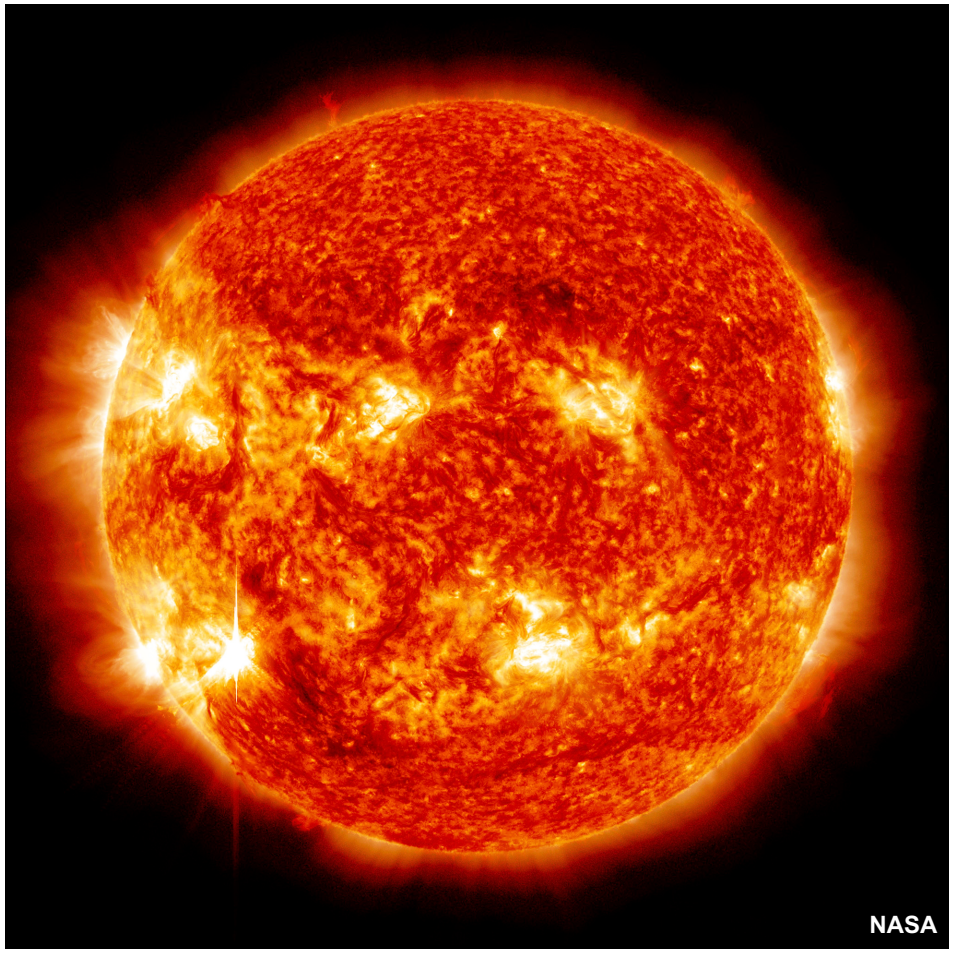
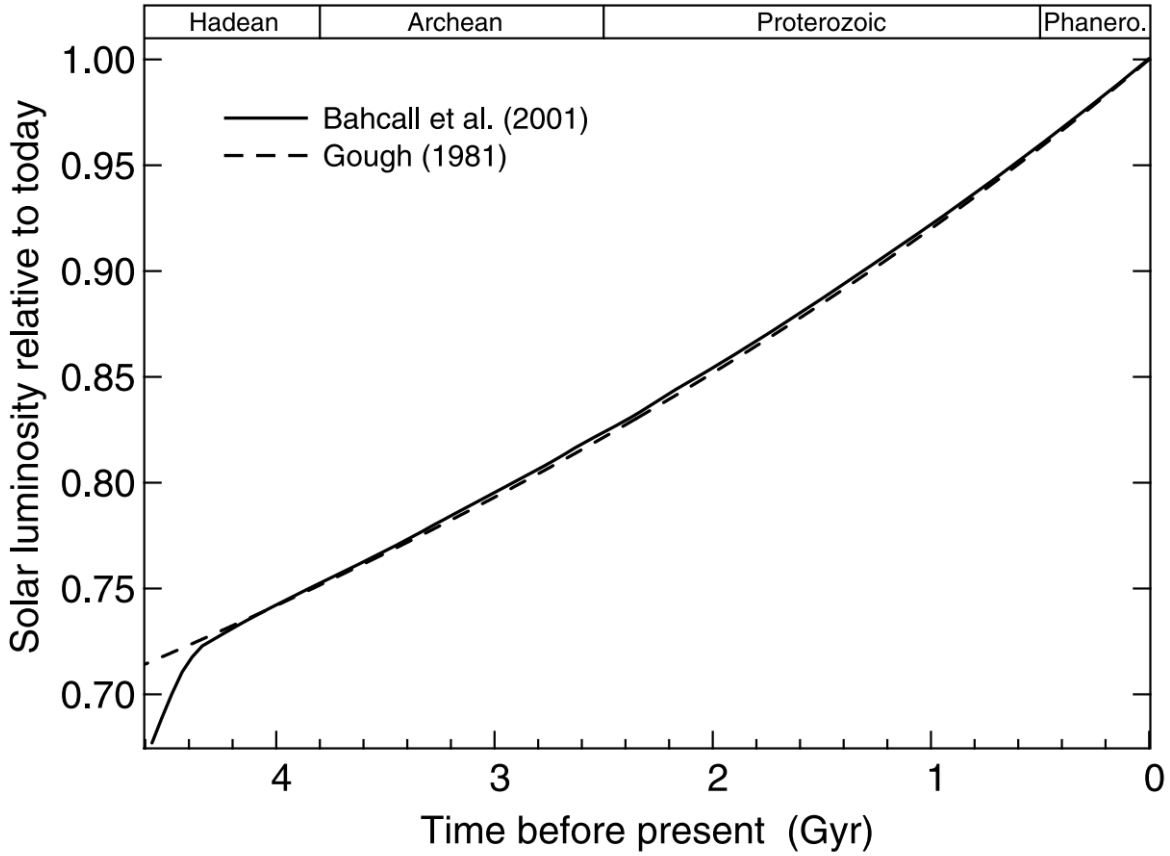
Why do we study the sun?



sun is a laboratory to test understanding of stellar structure and evolution

Faint Early Sun and Standard Solar Models

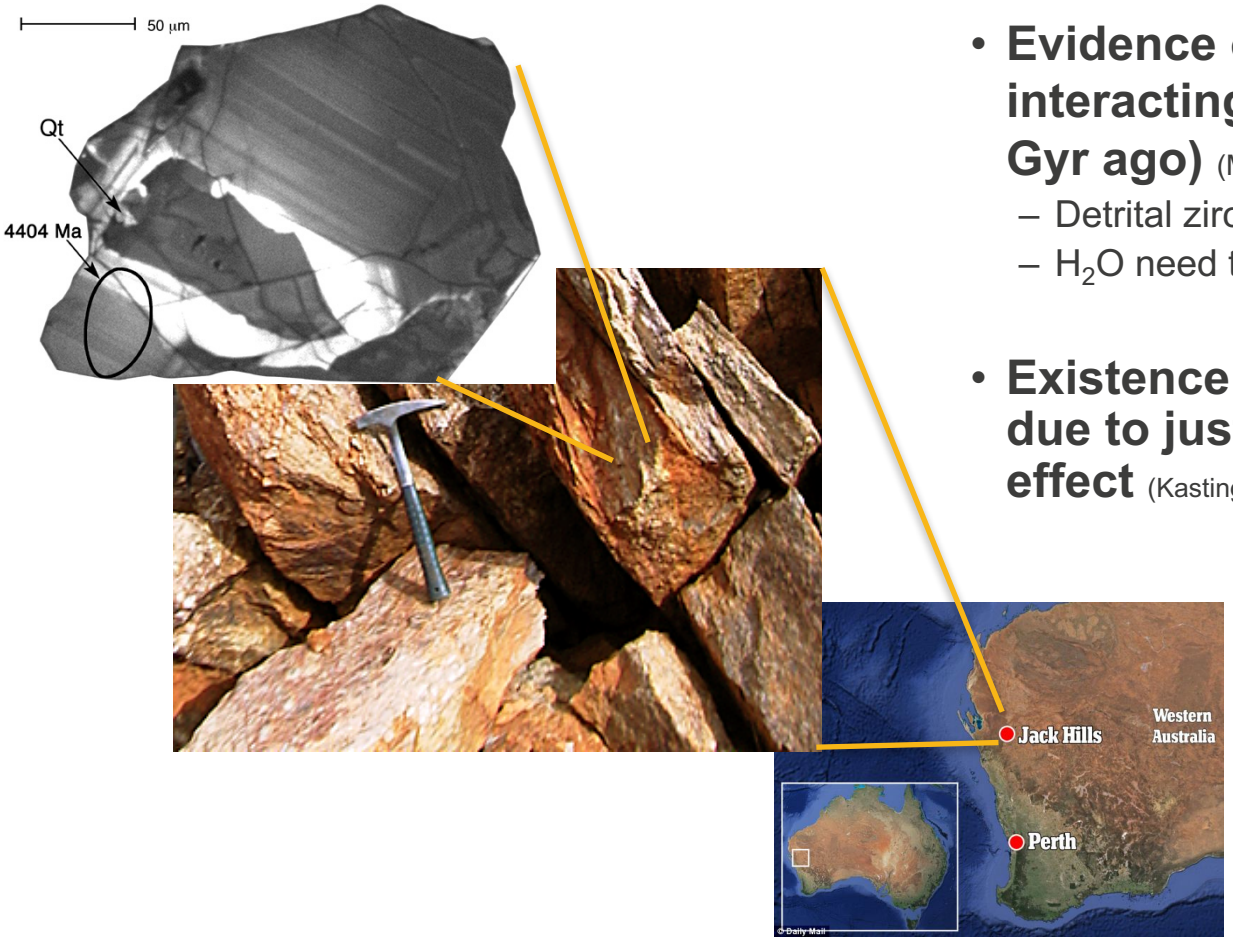


The standard model suggests early solar luminosity was 70% of L_{sun}

Feuler, G. Review of Geophysics 2012, 50, 2011RG000375.

Constraining the luminosity of the Sun – Early Earth

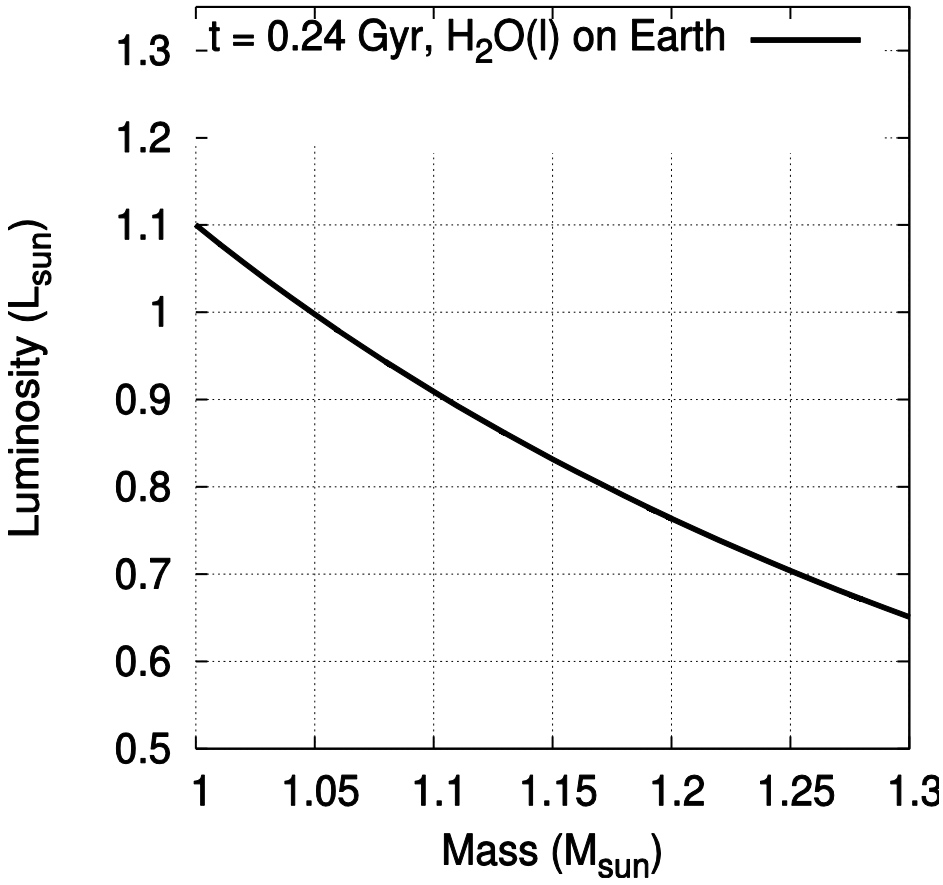
Introduction



- **Evidence of a hydrosphere interacting with crust (4.300 Gyr ago)** (Mojzsis *et al.* 2001)
  - Detrital zircons found in quartzitic rock
  - H_2O need to form zircons
- **Existence of liquid water is not due to just the greenhouse effect** (Kasting 2010) & (Wiess & Hener 2013)

Liquid water on earth can be explained by a more luminous early sun

Constraining the luminosity of the Sun – Early Earth



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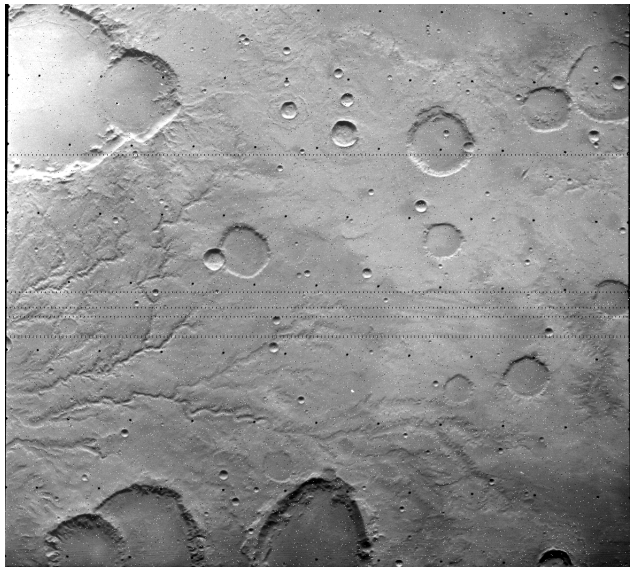
Constraining the luminosity of the Sun – Early Mars



- **Geomorphological evidence for water**
  (Carr 1996, Malin & Edgett 2000, 2003)
- **Minerals that require water to form**
  - Clay/phyllosilicates
    (Poulet *et al.* 2005, Bibring *et al.* 2006, Ehlmann *et al.* 2011)
  - Sulfates
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  - Opaline silica
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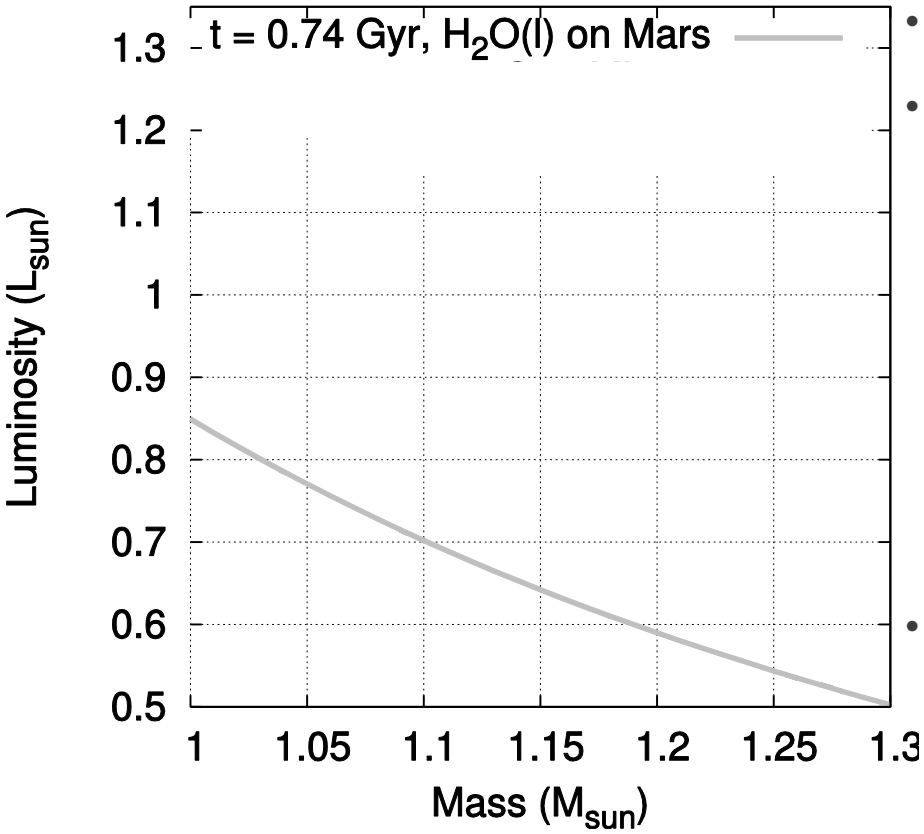
  - Chloride minerals
    (Osterloo *et al.* 2008)
- **Thick CO_2 atmosphere cannot account for liquid water**
  (Forget *et al.* 2013)

Liquid water on Mars can be explained by a more luminous early sun

Constraining the luminosity of the Sun – Early Mars



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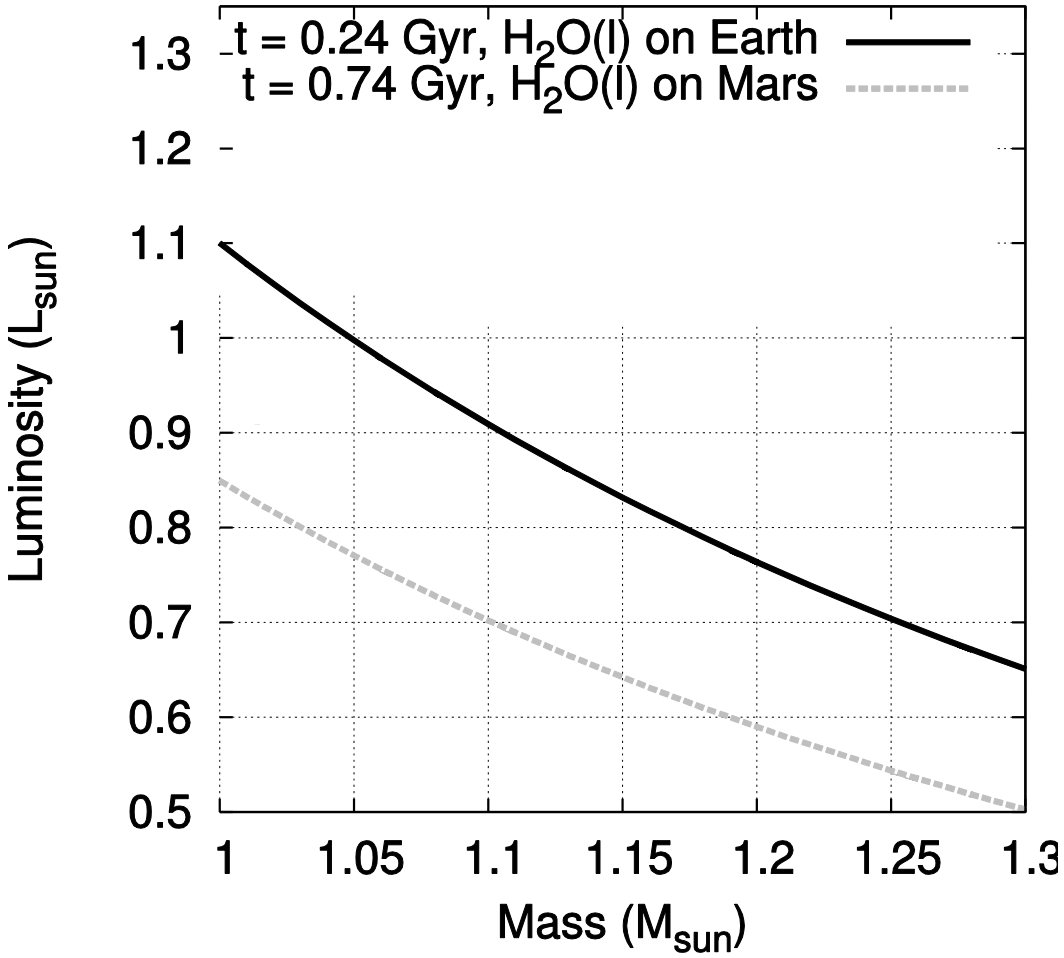
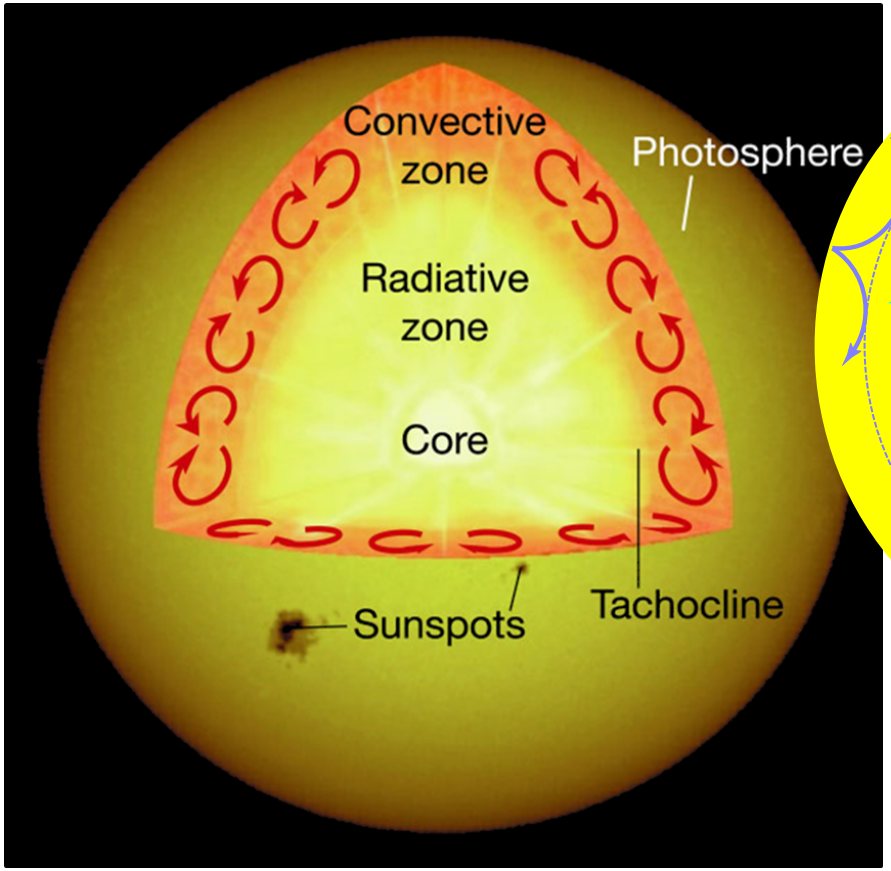
Liquid water on Mars can be explained by a more luminous early sun

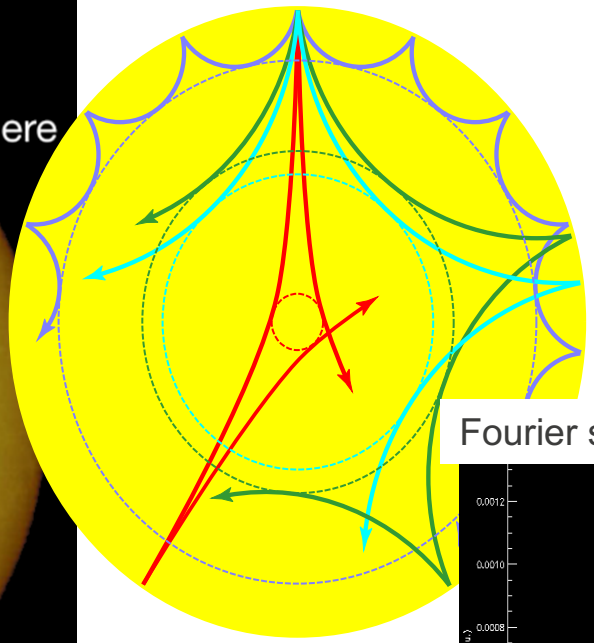
Constraining the mass of the Sun – Early Earth & Mars



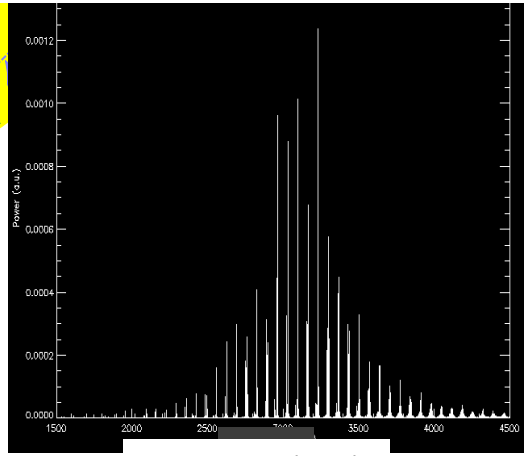
Earth provides an upper limit and Mars a lower limit on solar luminsity

Helioseismology and elemental abundances provide information about the solar interior





Fourier spectrum of frequencies

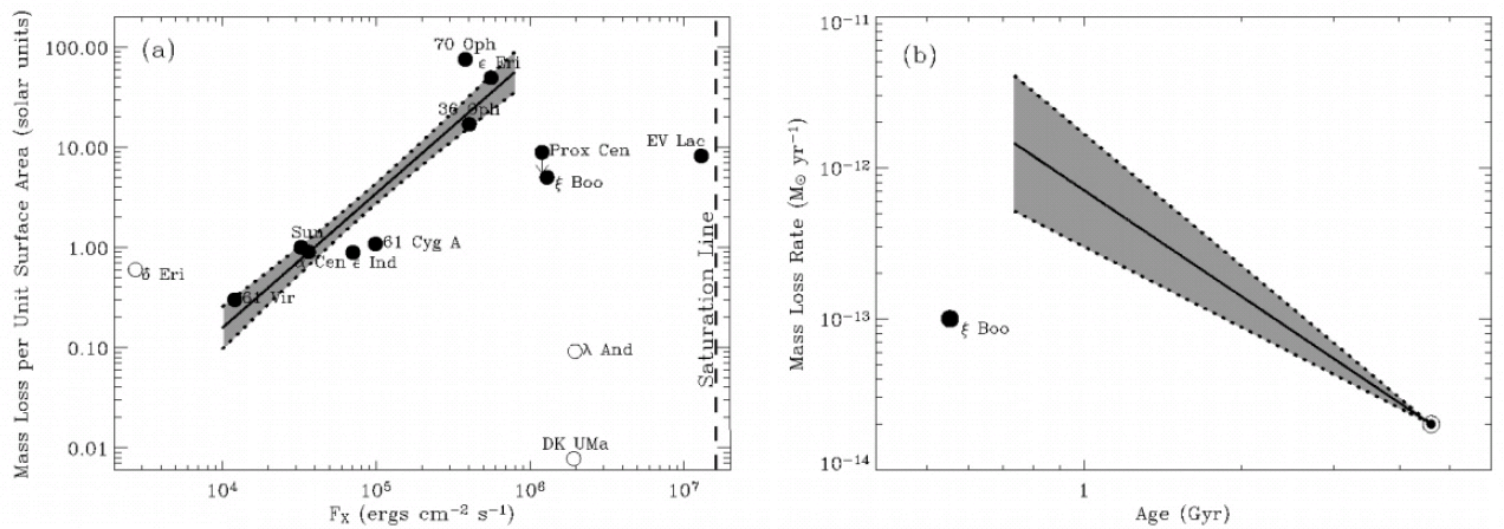


GOLF

We compare and calibrate solar evolution models to these measurements

Constraining the Initial Mass of the Sun – Wind from solar-like stars

- **Stellar observations of Mass Loss**
  - Direct observation of mass loss less than $10^{-9} M_{\odot}$ yr $^{-1}$ is difficult (Brown *et al.*1990)
  - Indirect observation possible (B. Wood *et al.* 2002, 2005)
    - HI Lyα line observations
    - Mass loss decreased with time

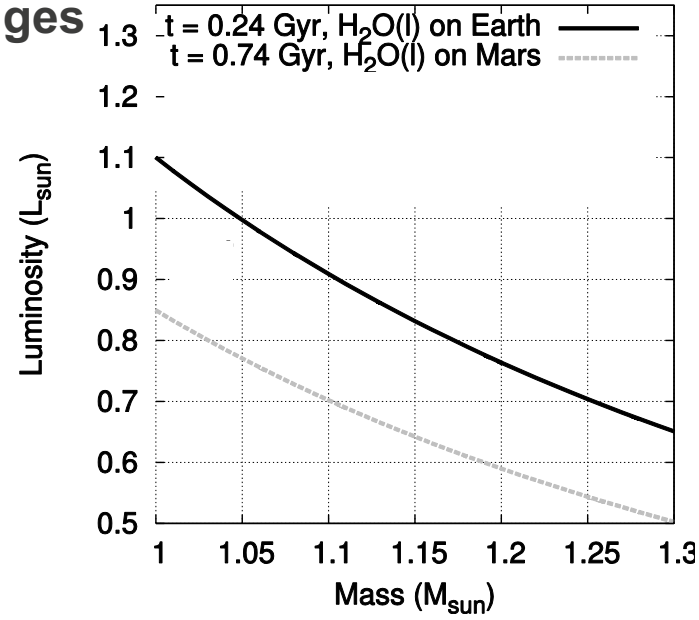


Our mass loss rates employed are 1-2 orders of magnitude larger

Input physics into our solar model

Mass Loss Constraints

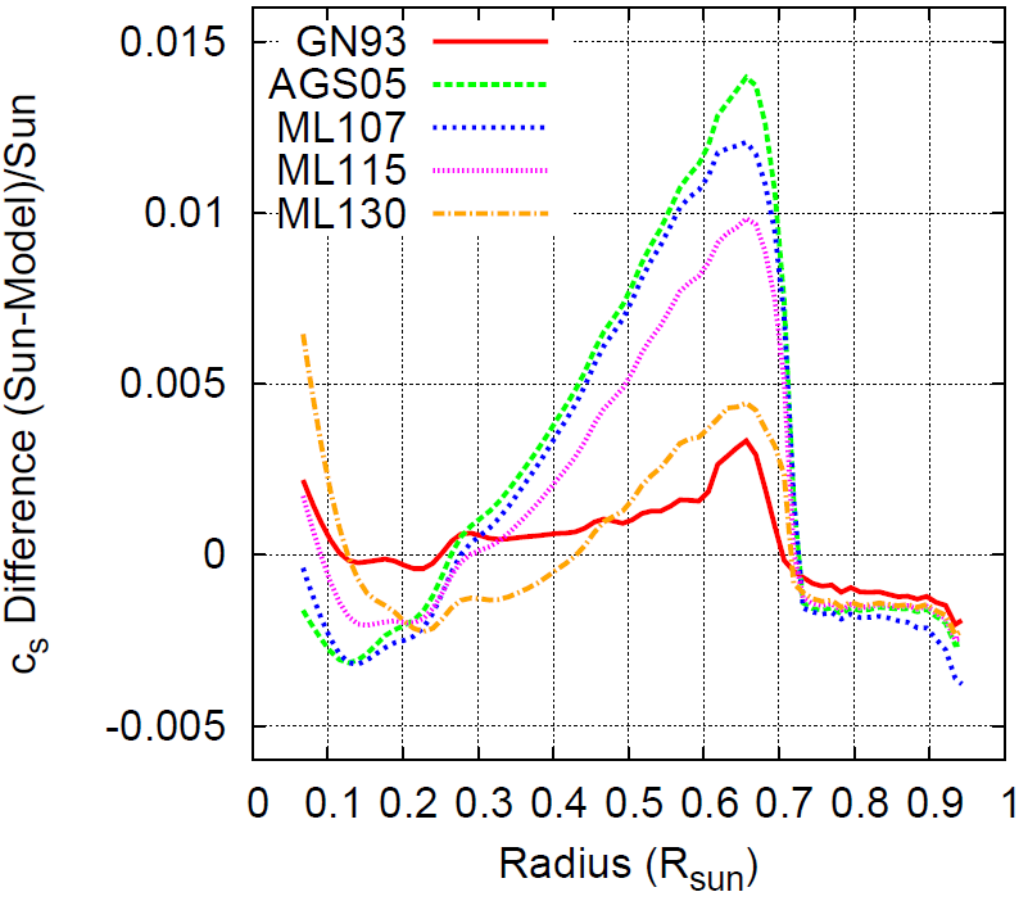
- One-dimensional model
- Initial homogeneous composition
- Neglect rotation and magnetic fields
- Simple surface boundary conditions
- No additional mixing or structural changes
- Mass loss (Exponentially-decreasing)



By changing the initial solar mass, the luminosity history is tuned

Can mass loss improve agreement with helioseismic data?

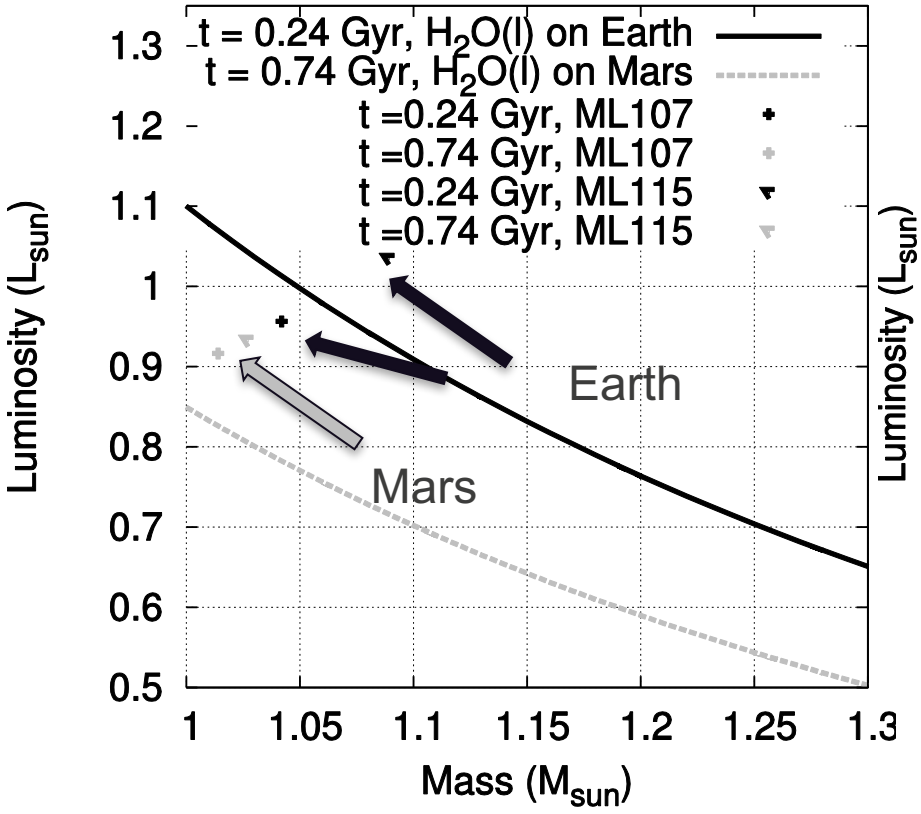
Mass Loss Constraints

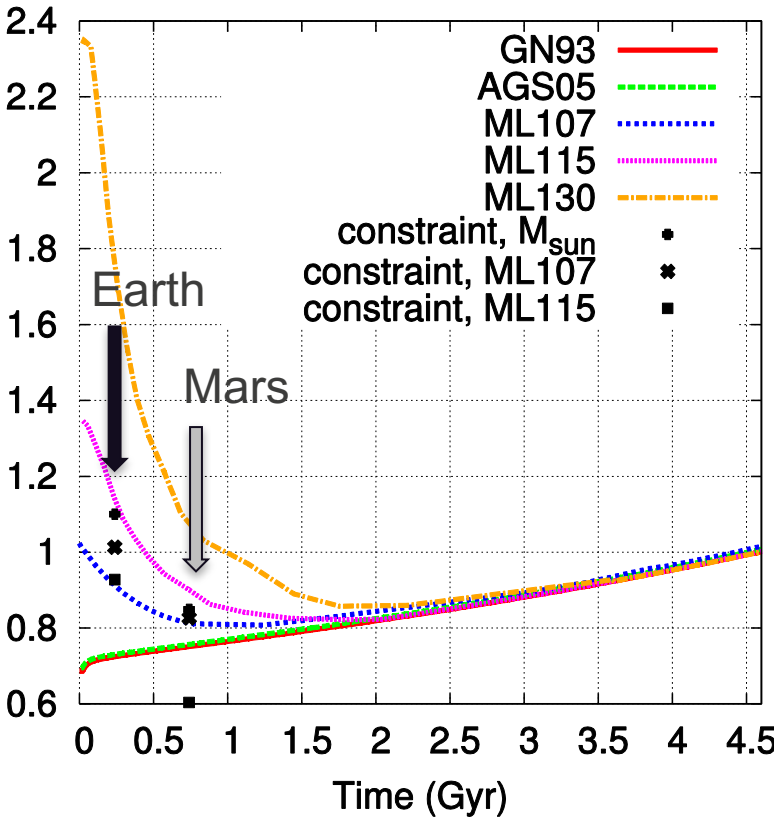


Better sound speed agreement for mass loss models with new abundances

Comparing the luminosity for early Earth and Mars

Mass Loss Constraints



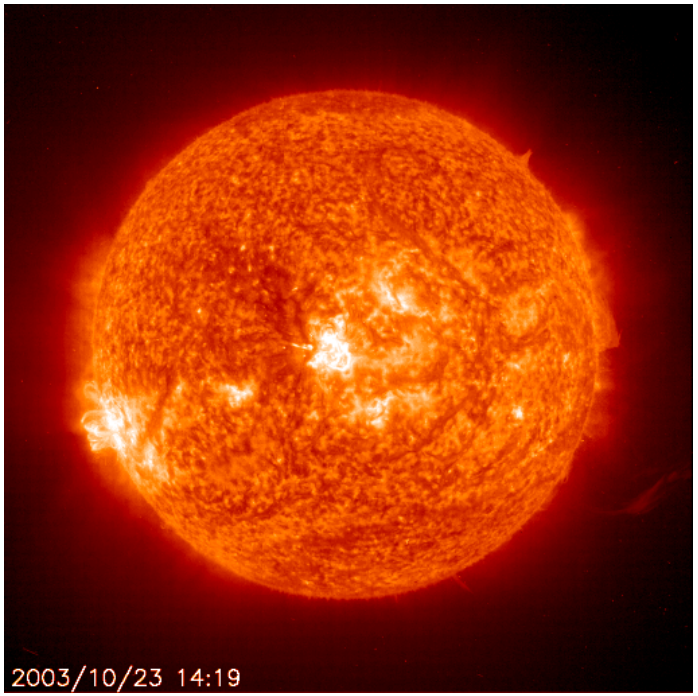


Initial solar mass should be between 1.07 and 1.15 M_{sun}

Planets and stellar observations place constraints on the solar evolution model

Summary

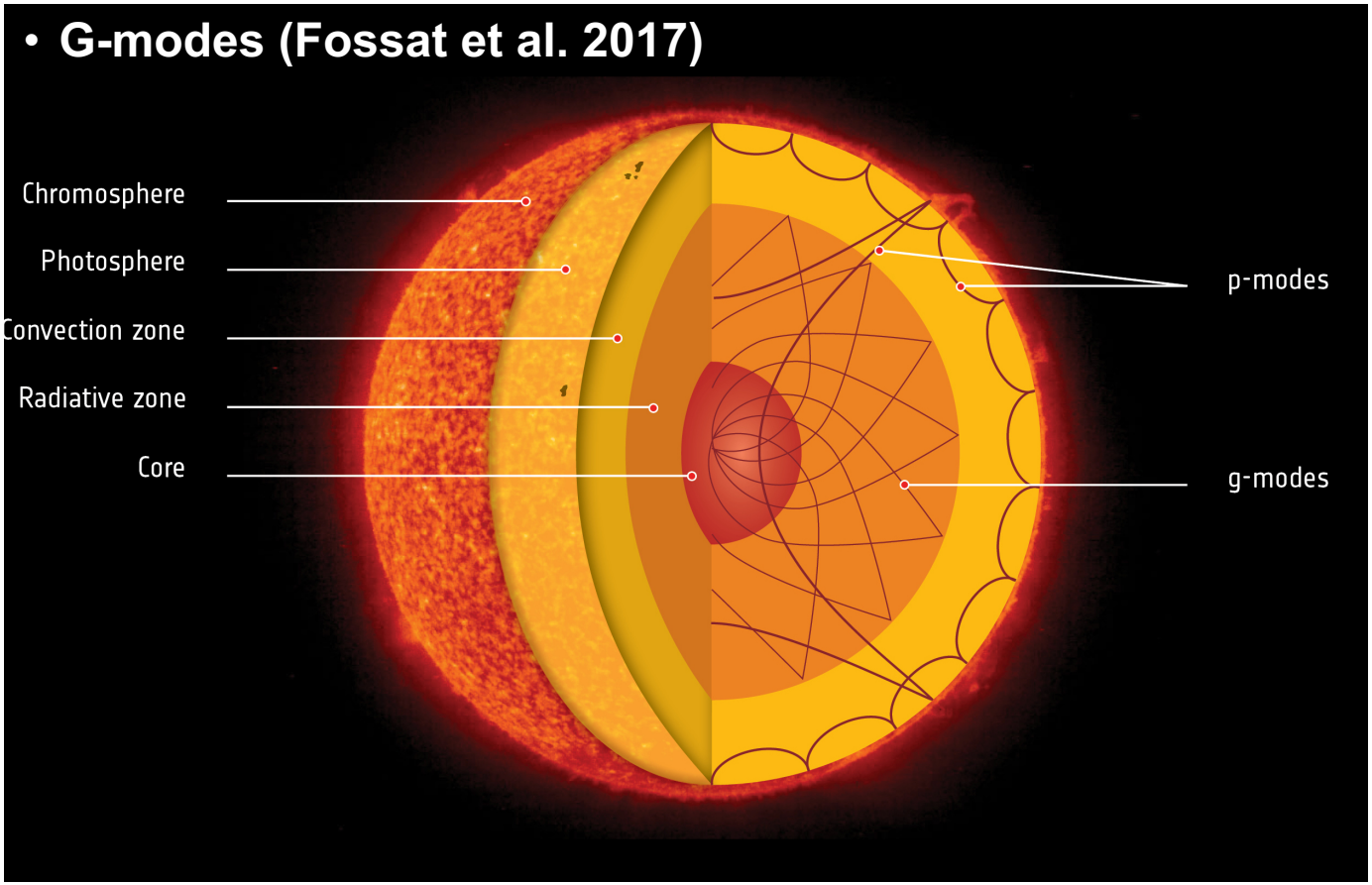
- **Constraints based on solar system cannot be ignored**
- **ML107 & ML115 bound future models**
  - Constraints set by Earth
  - Constraints set by Mars
  - Constraints set by stellar observations



Planetary evidence needs to be used in solar modeling

Future directions for solar modeling efforts at LANL

Summary



Acknowledgements and Questions?

Summary

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Manuscript submitted to Solar Physics