universität wien

EXPOSE

„Non-thermal loss of earth-like planetary atmos-pheres“

Verfasser

Lin Tu, Msc.

Supervisor
Prof. Dr. Manuel Güdel

Outline

- Introduction

  - Stellar Radiation Evolution

  - History of terrestrial atmospheres

  - Loss Mechanisms and hydrodynamic escape

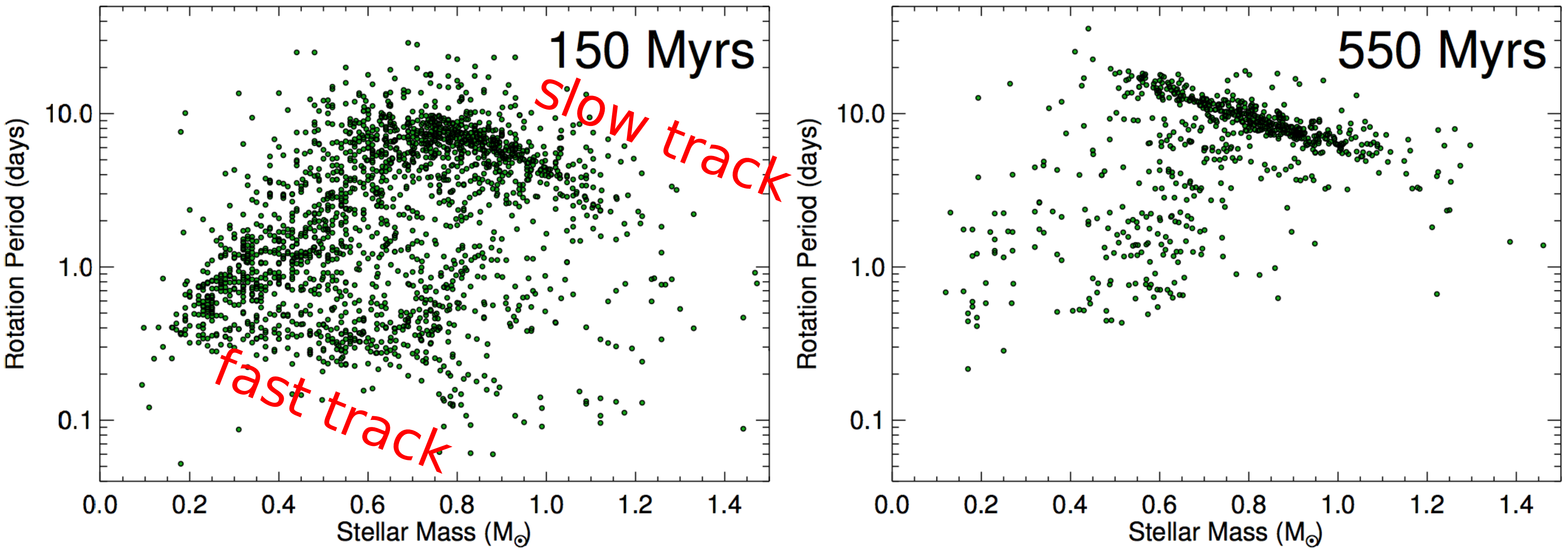
- PhD project and Current Status

  - X-ray paper

  - Charge-exchange code

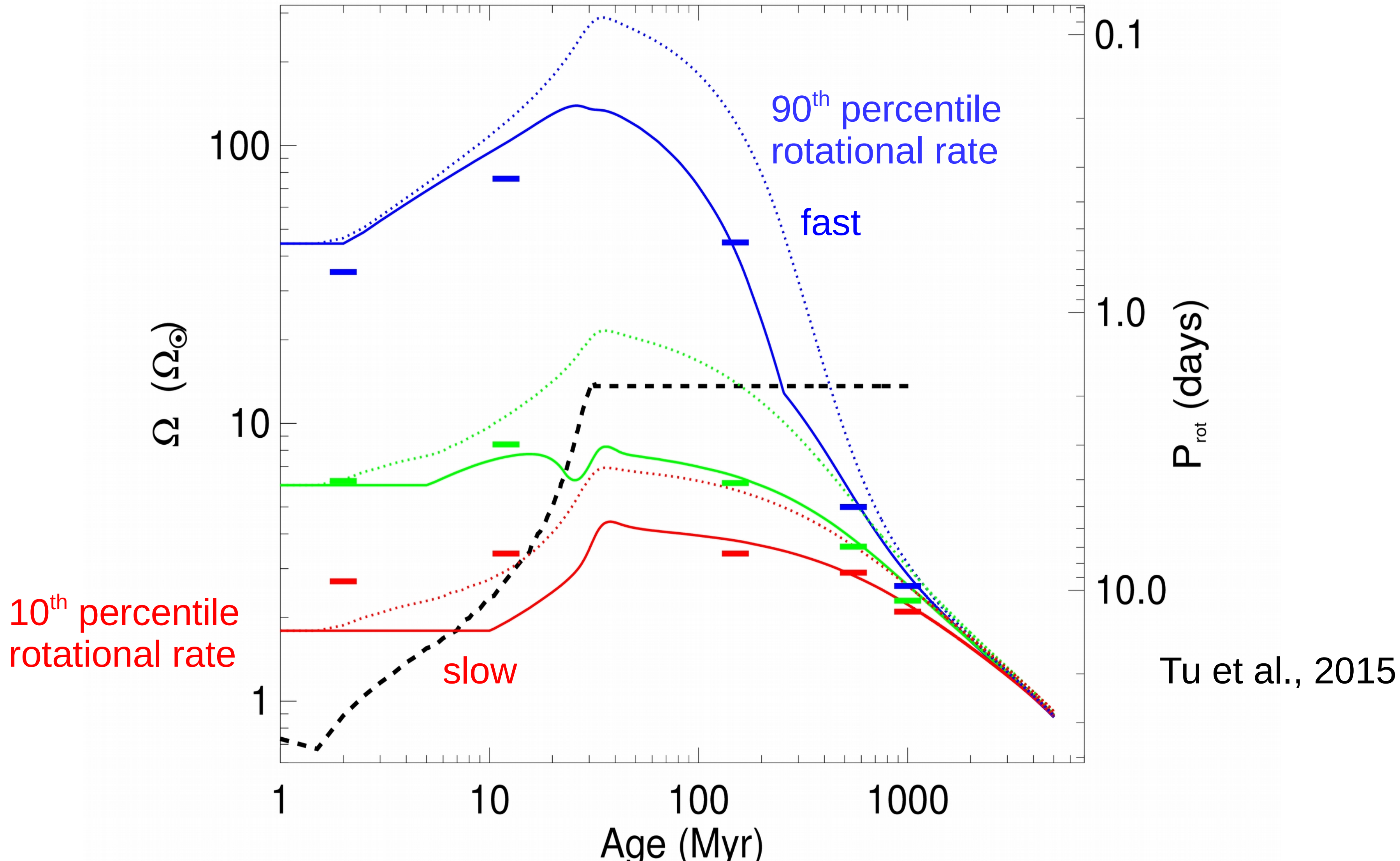
- Methods and Goals
- Time Plan
- Financial Aspects
- References

Mass Loss and Rotation: Introducing Rot. Distributions



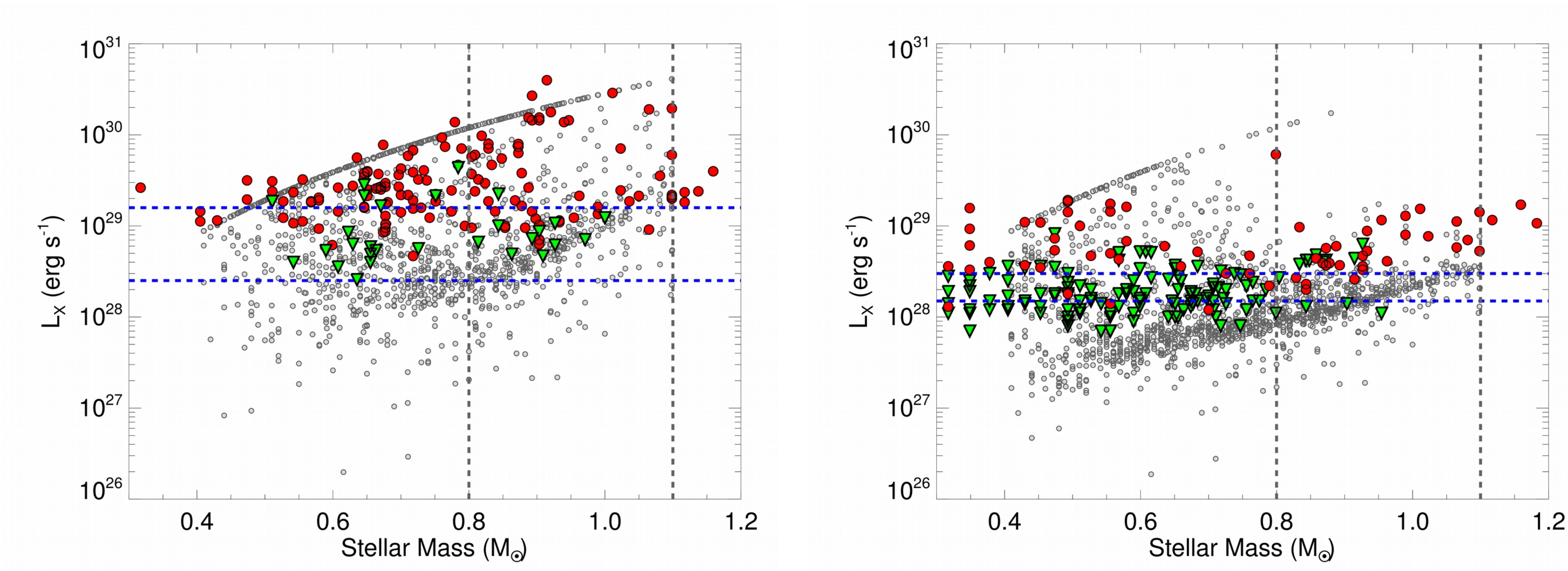
Johnstone et al., 2015

Stellar rotation rates evolution



The solid and dotted lines show the envelope and core rotational evolution, respectively, and the horizontal solid lines show the observational percentiles.

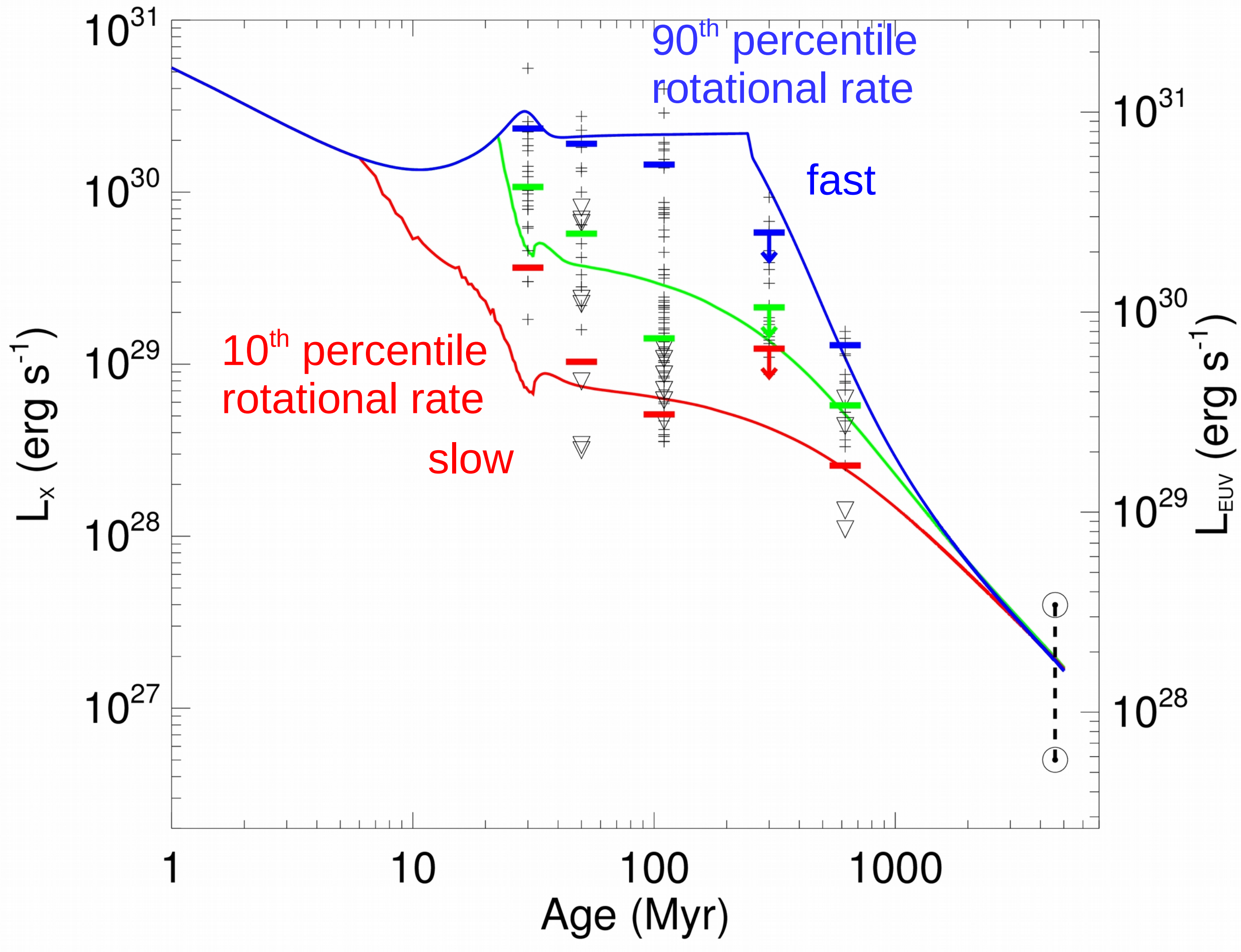
Model apply to Pleiades and Hyades



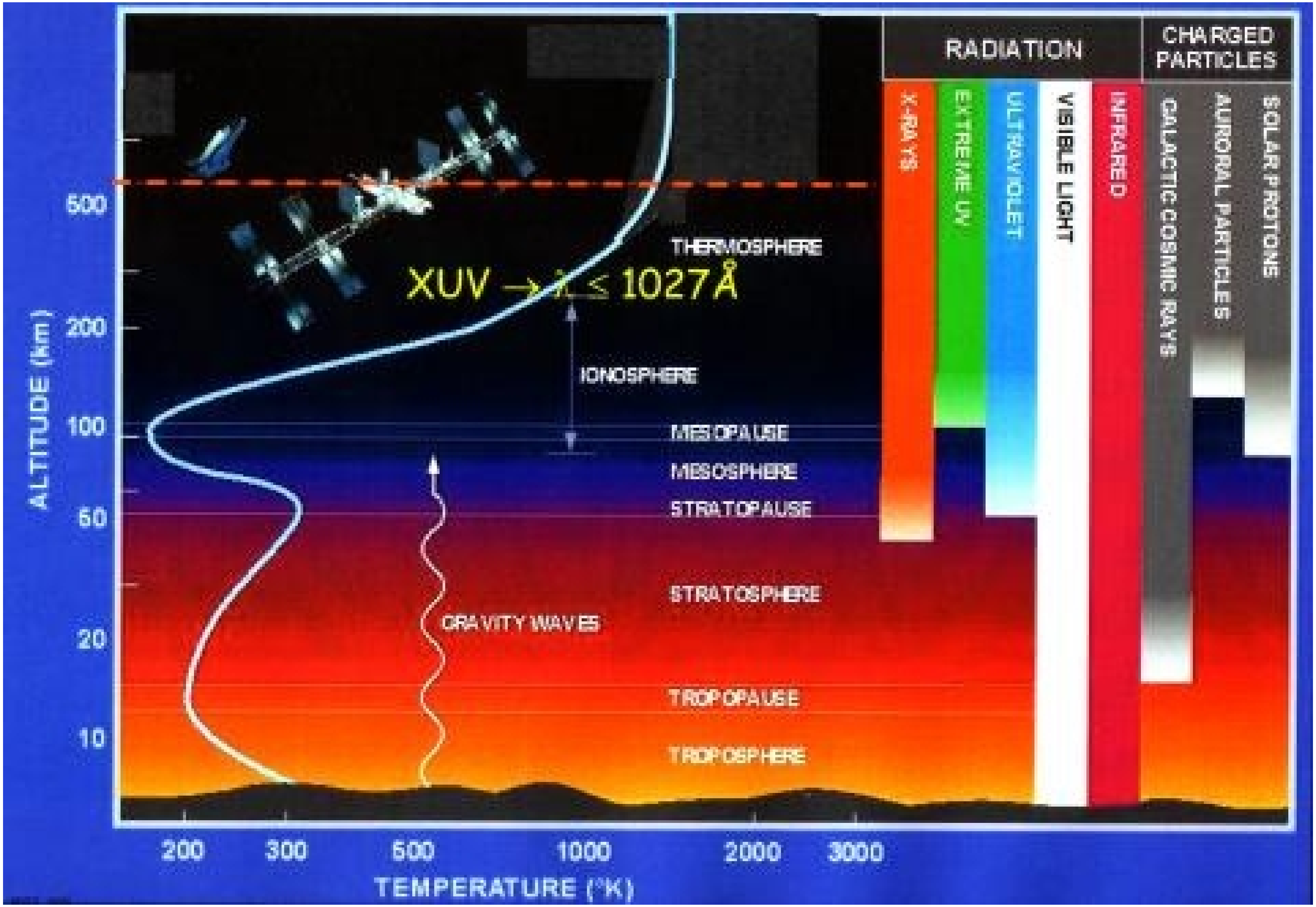
Tu et al., 2015

Comparisons between observed and predicted distributions of X-ray luminosity at ages of 150 Myr (left) and 620 Myr (right).

Stellar radiation evolution

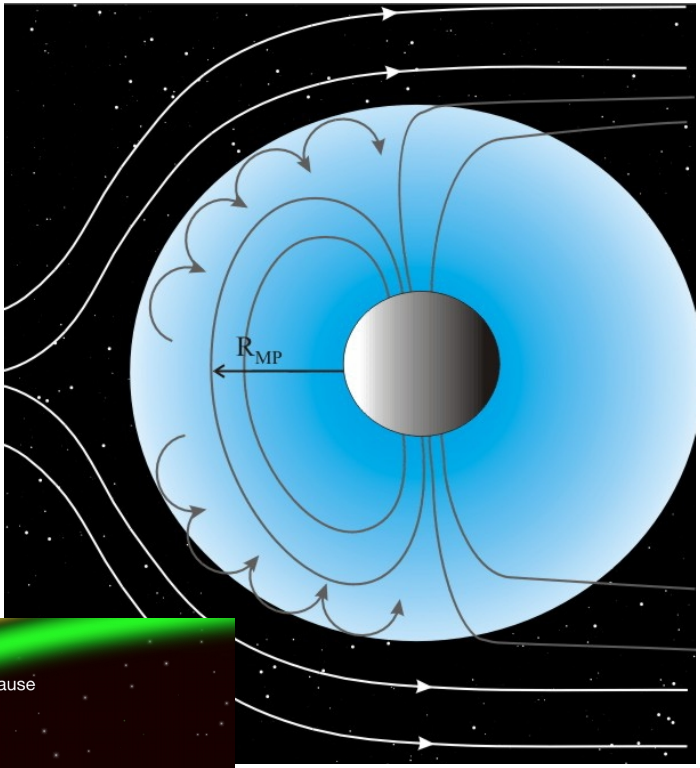


Atmospheric Profile

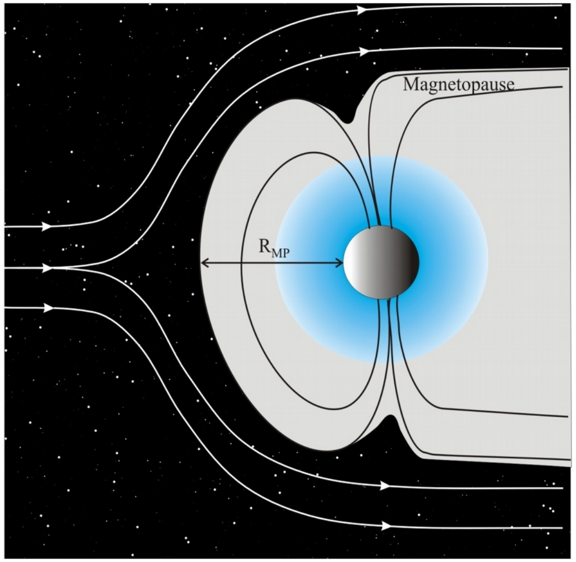


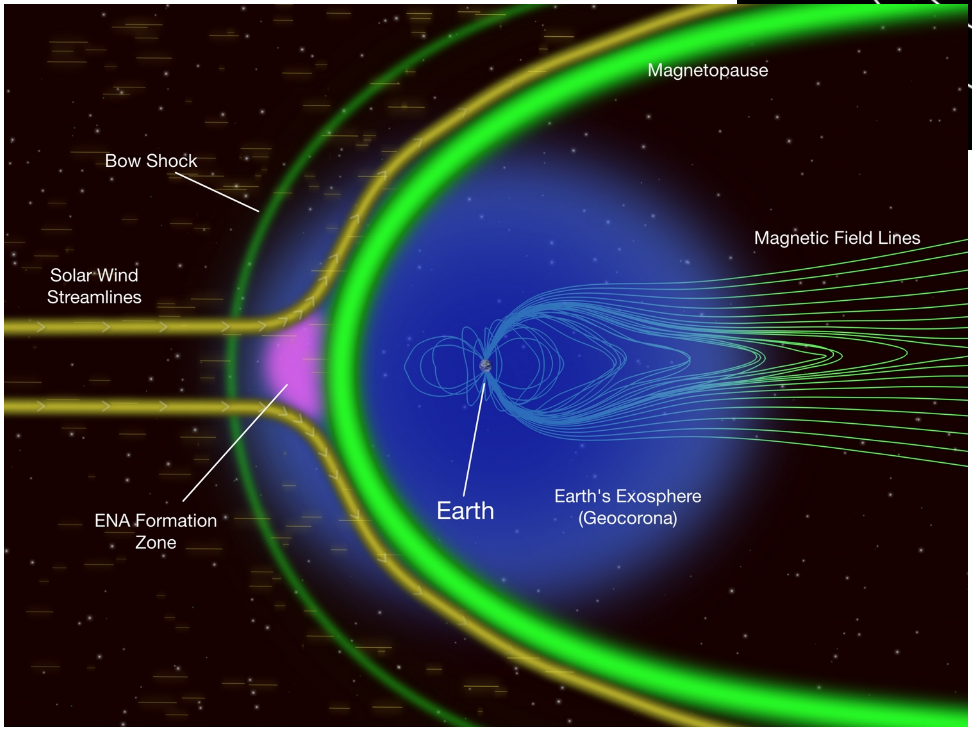
Comparison of Early Venus, Mars, and Earth

Early Earth

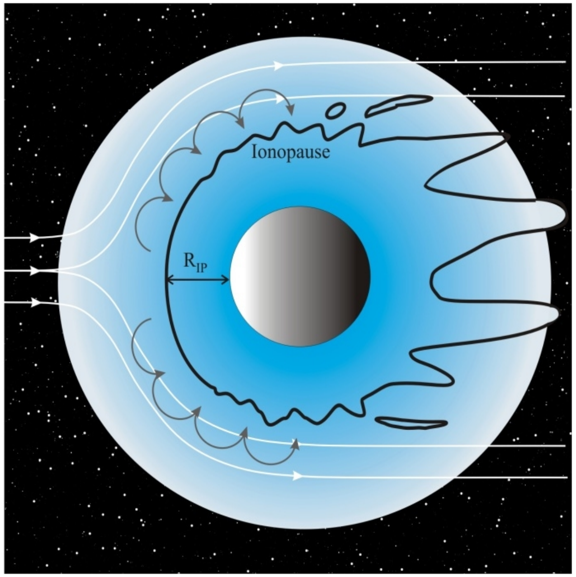


Present Earth





Present Venus, Mars



Lammer et al., 2011

History of Martian and Venus atmosphere

- First epoch (∼300-600 Myr)

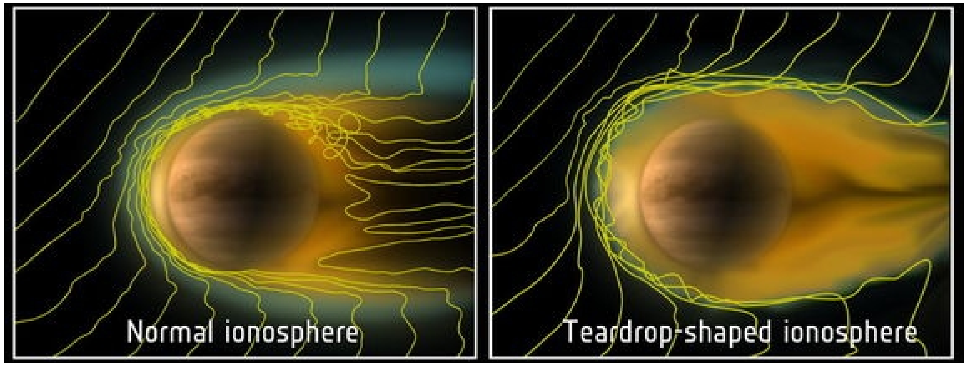
  -high EUV

  -low gravity

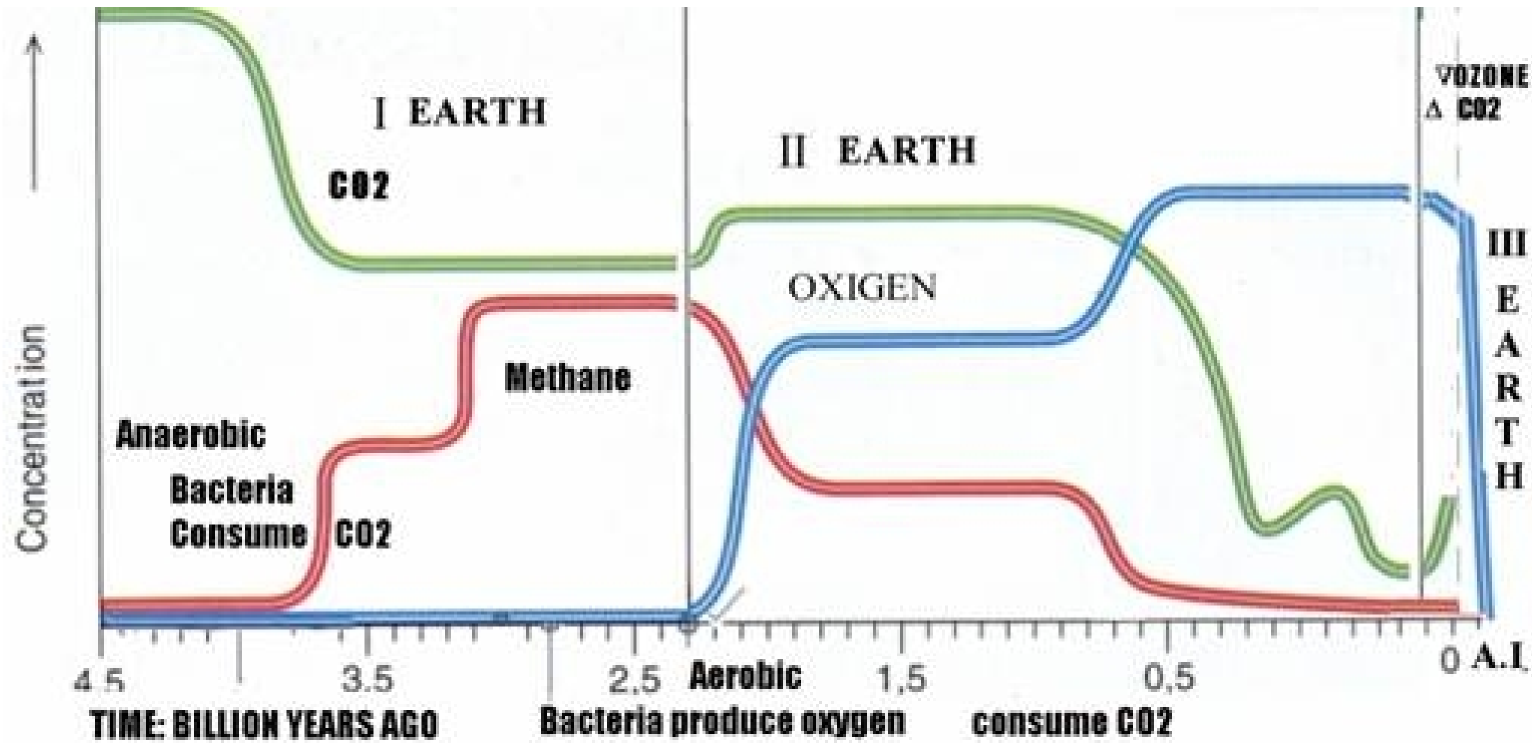
  -Hydrodynamic flow regime

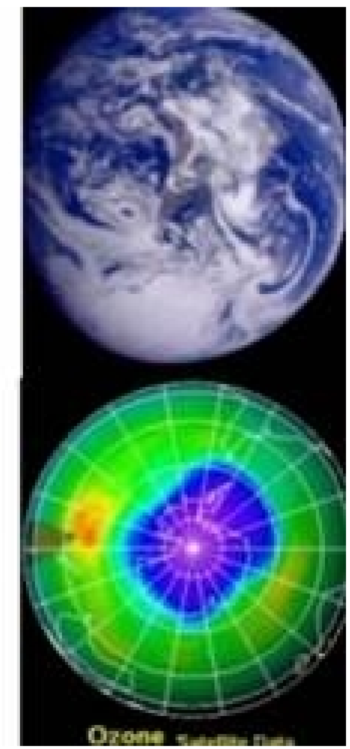
  -dragged heavier species such as O and C atoms
- Second epoch (∼4–4.3 Gyr ago)

  -secondary atmosphere (impact-related volatiles and mantle outgassing)



Earth atmospheric evolution





Escape mechanisms

- Thermal escape

  → Jeans escape

  → Jeans parameter

$$\lambda_c = \frac{GMm}{kT_{exo} r_{exo}}$$

→ Hydrodynamic flow regime

→ Blowoff criteria

λ_c < 1.5

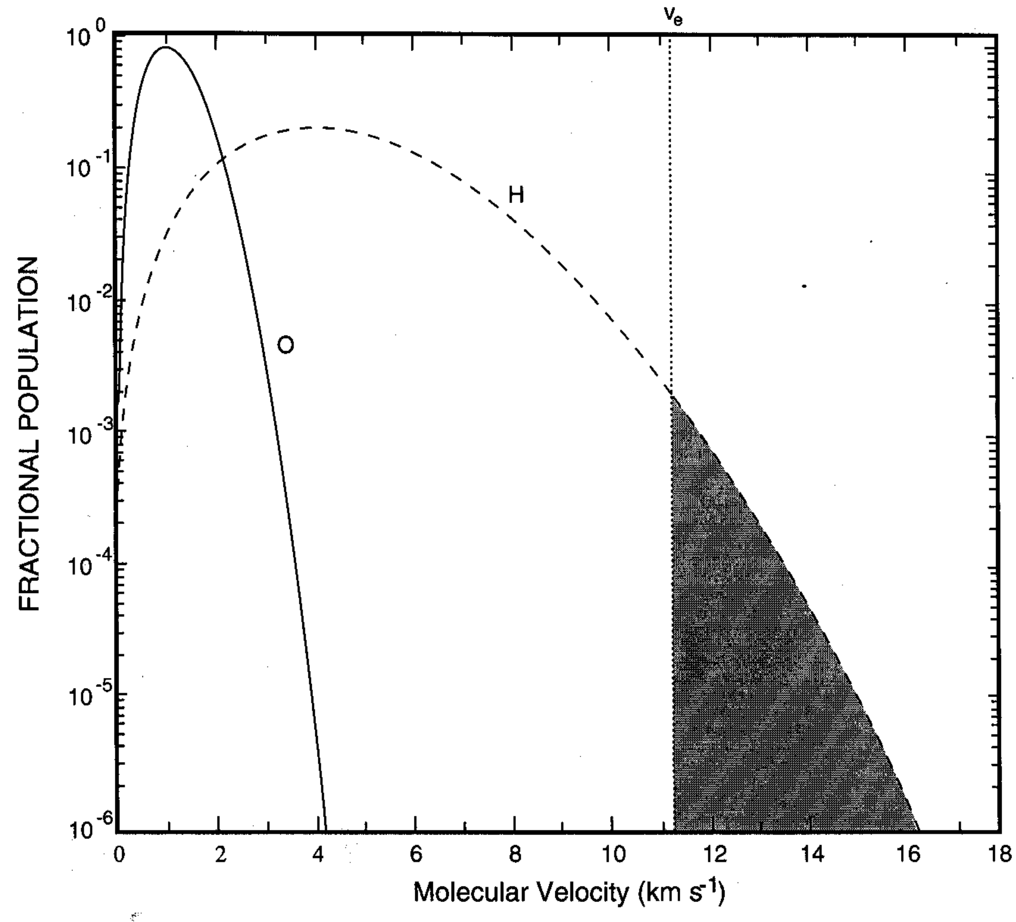
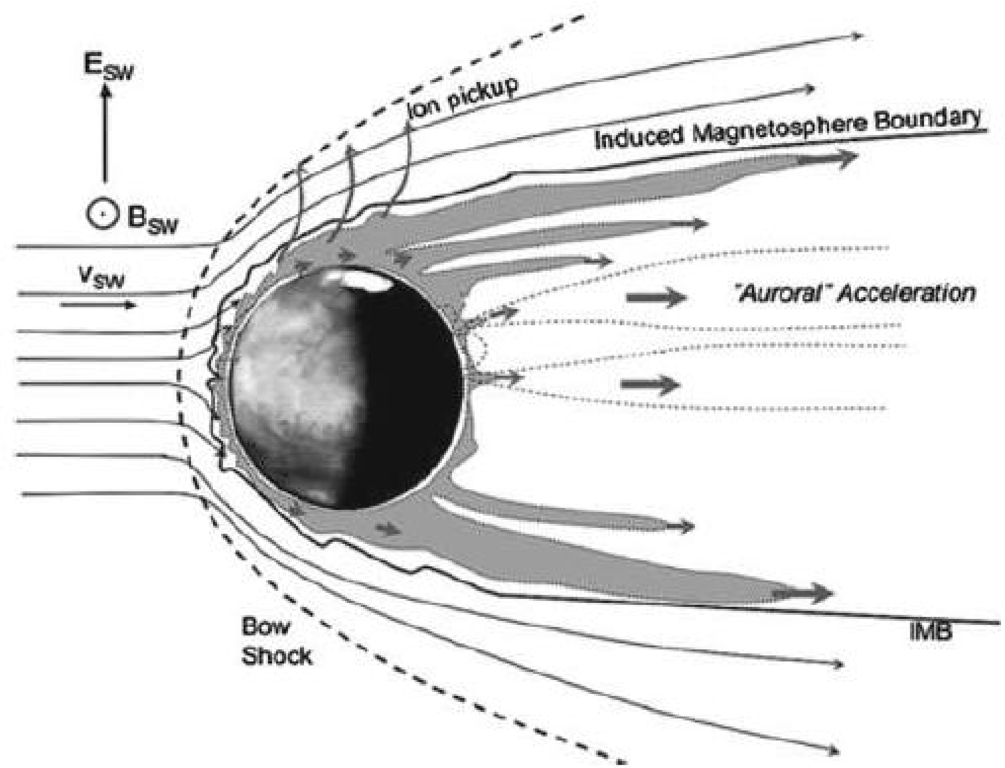


Figure 1.6 Boltzmann distribution of velocities for a molecular ensemble of oxygen atoms and hydrogen atoms. Escape velocity v_e for earth also indicated.

Non-thermal escape mechanisms

- Charge exchange
- Photochemical reaction
- Electron impact
- Pick-up ions
- Sputtering
- Electric field flow



Non-thermal escape mechanisms

- Sputtering

  → Impact of fast ions knocks atoms out of the atmosphere.

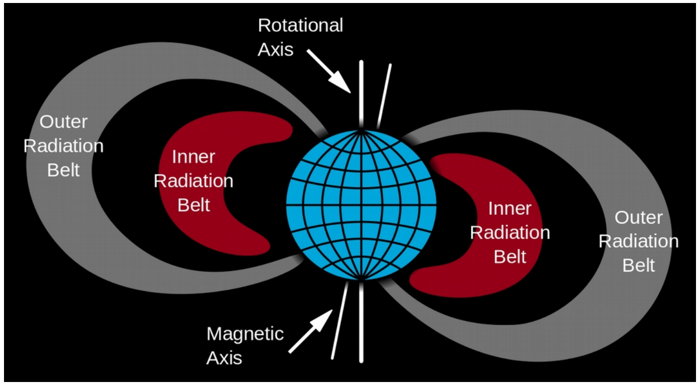
- Ion escape

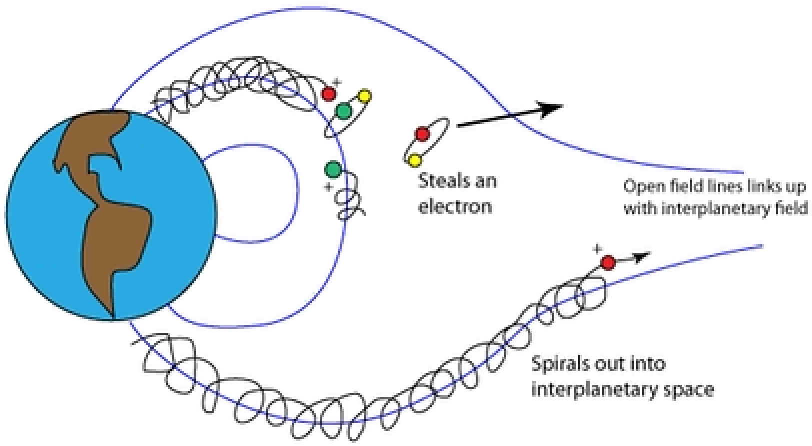
  → Ions flow upward along polar field lines and escape down magnetic field lines

  → They gain their energy from ambipolar diffusion, where the interaction of ions & electrons in a plasma causes them to diffuse at the same rate

  → The electrons have much higher thermal velocities and can easily escape. This sets up an electric field by charge separation and the ions are dragged after the electrons

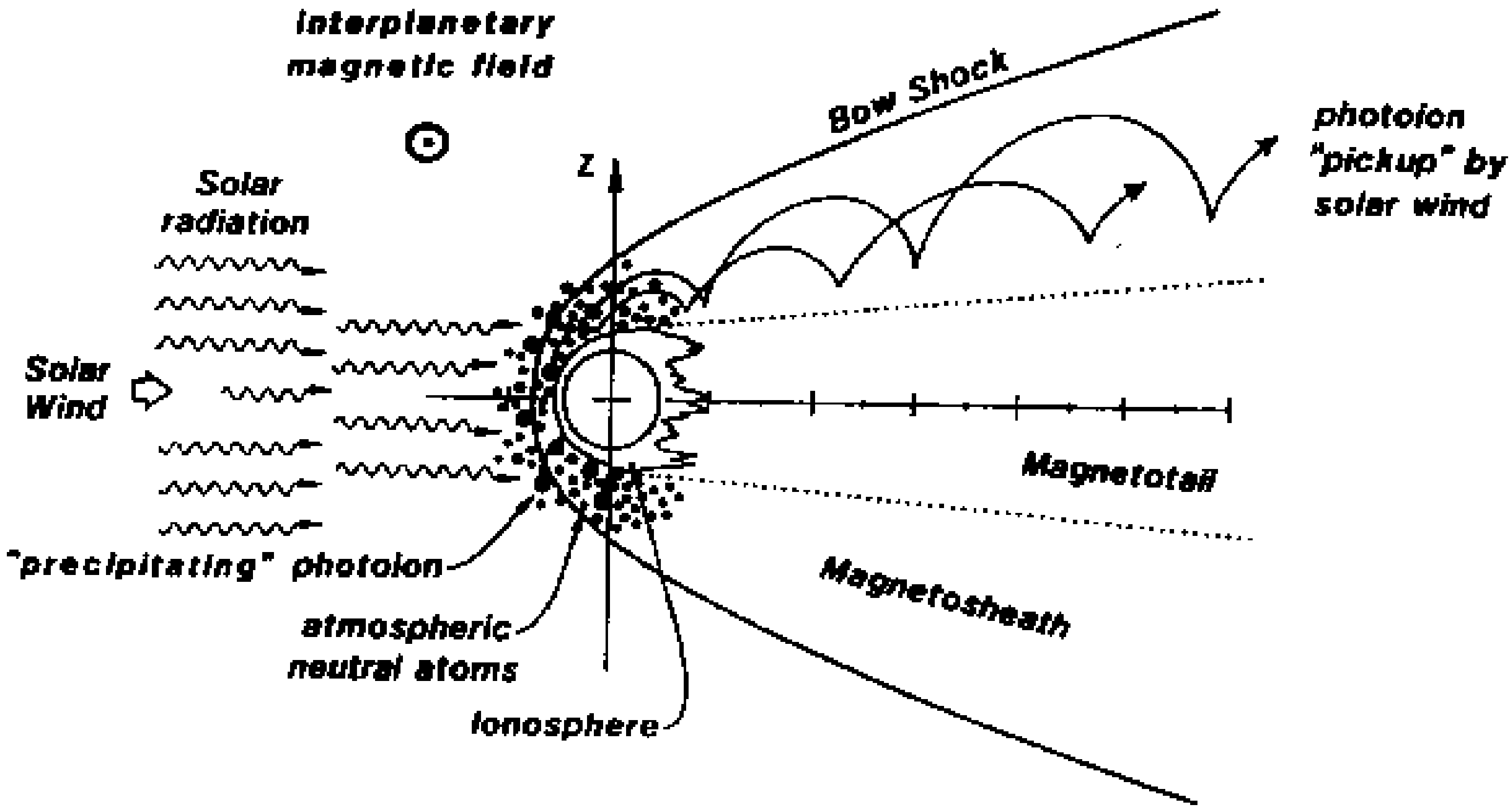
  → Occurs also at Mars





Non-thermal escape mechanisms

- Ion Pickup



Non-thermal escape mechanisms

- Charge exchange

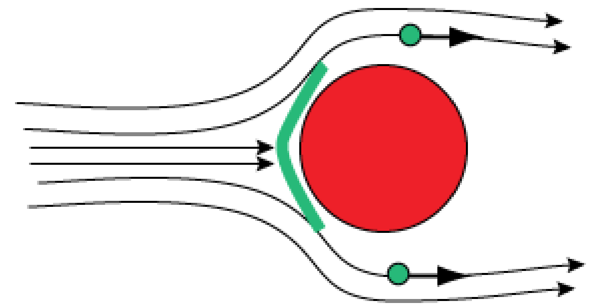
→ Slow neutral + fast ion => fast neutral + slow ion

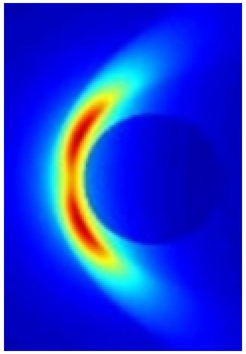
- Photochemical reactions

→ Convert the energy of absorbed X-ray photons to kinetic energy

→ Typical yield is a few eV

→ This may be enough to cause escape





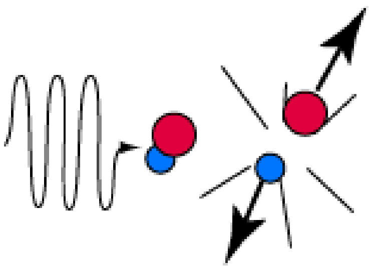
Solar wind hits high-altitude particles of a planet with no magnetic field

$$O^+ + O \rightarrow O + O^+$$

$$O^+ + H \rightarrow O + H^+$$

$$O^+ + H_2 \rightarrow O + H_2^+$$

Charge exchange on Venus

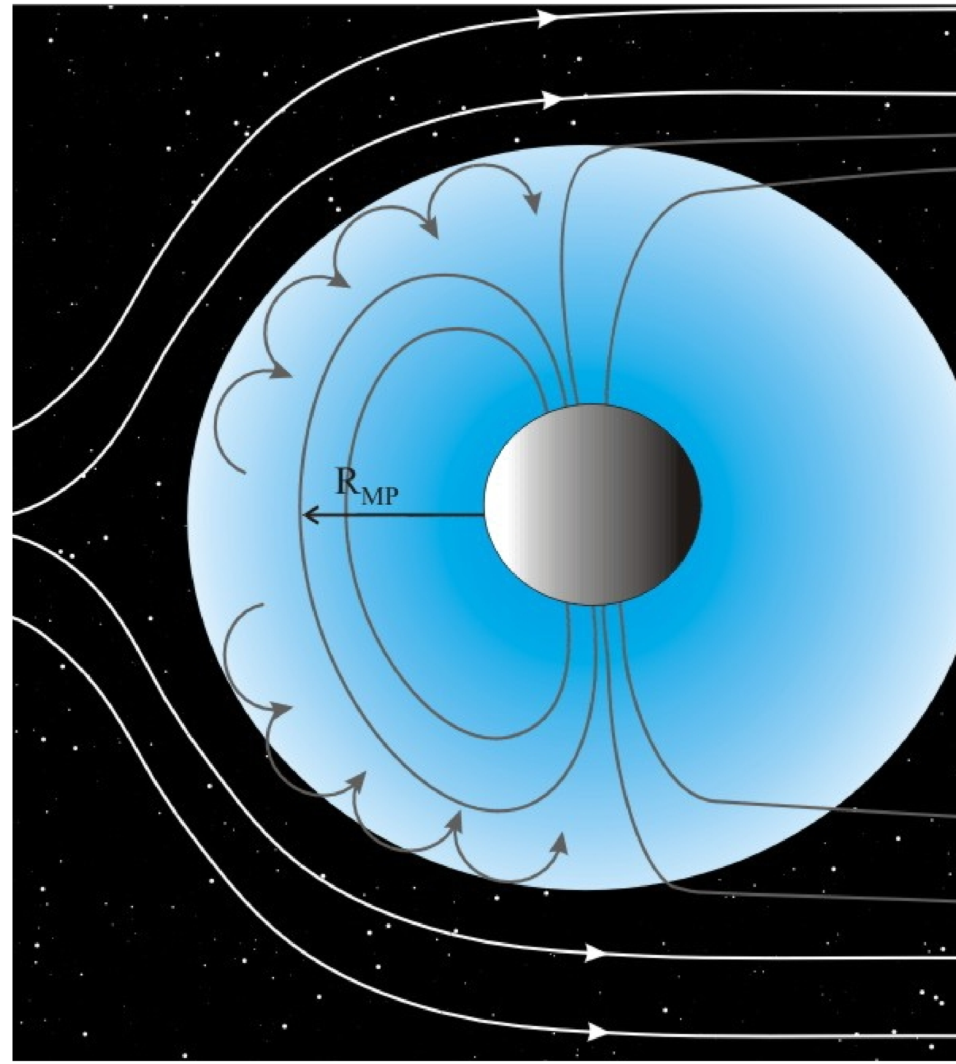


High-energy sunlight breaks apart molecules into higher-speed atoms

Heating & Cooling processes

- EUV heating ($\lambda \leq 1027$ Å) : photoionization
- UV heating ($1250 \leq \lambda \leq 3500$ Å) : photodissociation
- IR-cooling

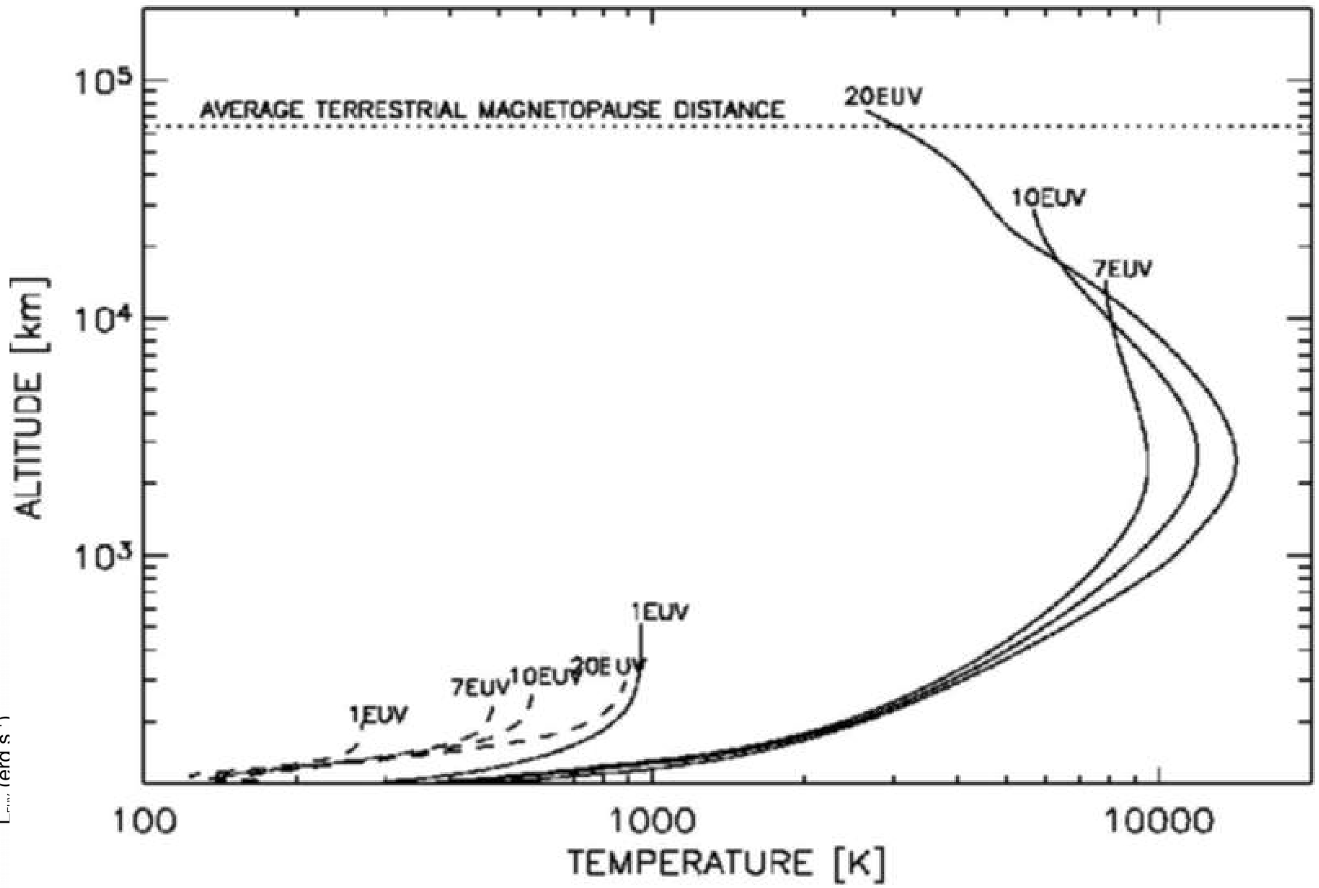
  → vibrational-rotational bands of atmospheric ions
- Adiabatic cooling



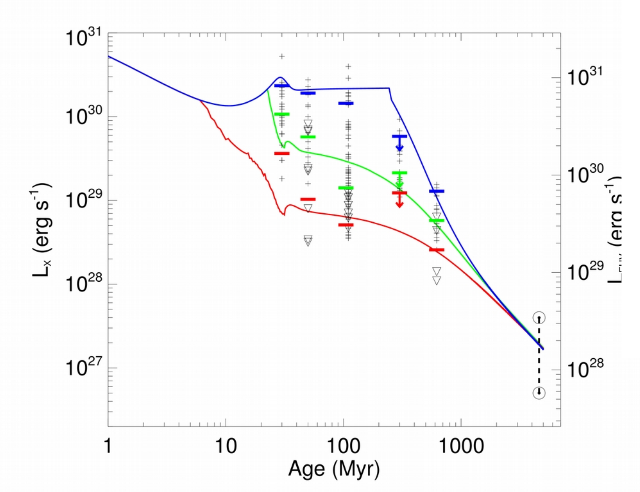
Lammer et al., 2002

EUV heating

- Cooling effect after 5 EUV
- Proto-atmosphere was lost
- Adiabatic cooling



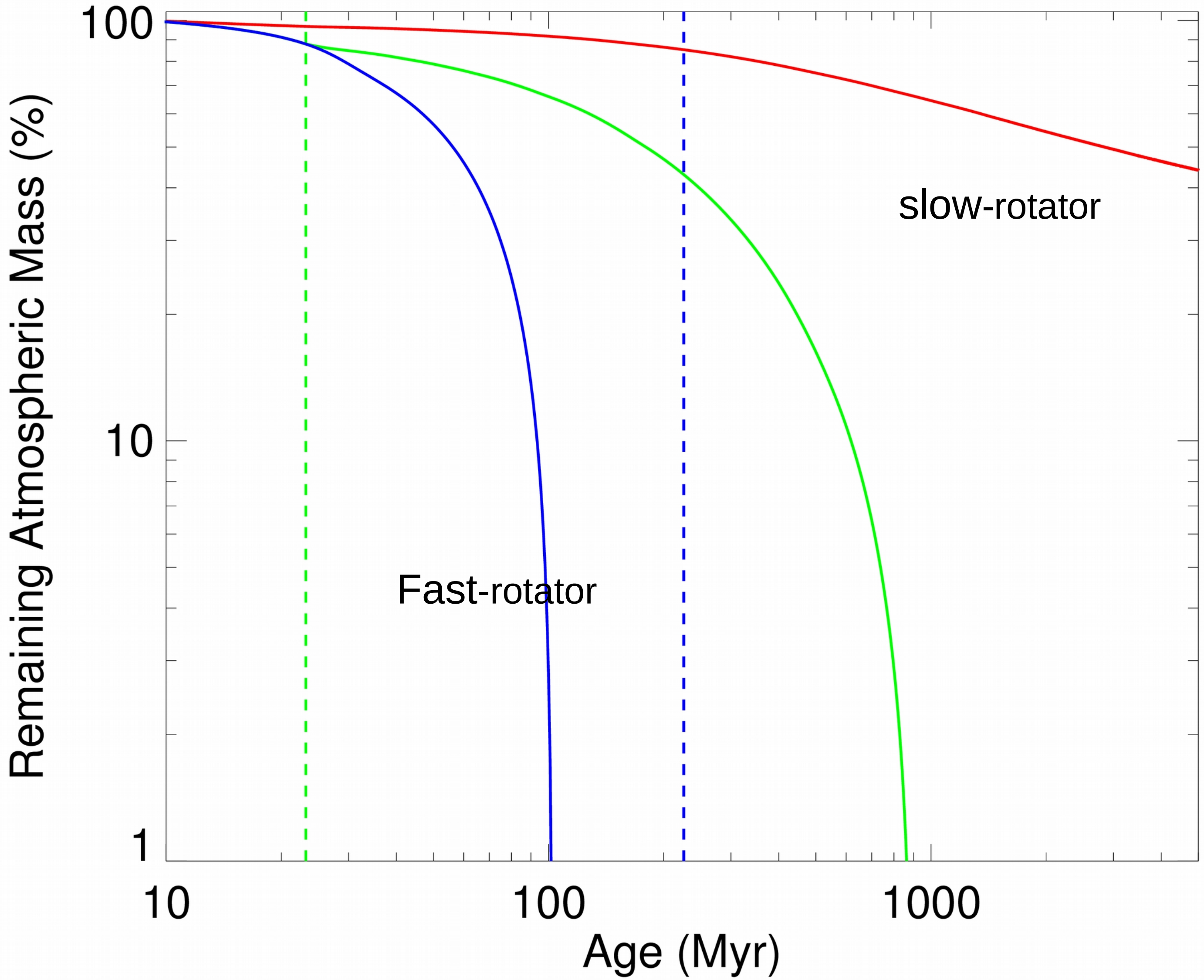
Tian et al., 2008



Tu et al., 2015

Evolutionary Atmospheric Loss

- The vertical lines show the stellar saturation times.



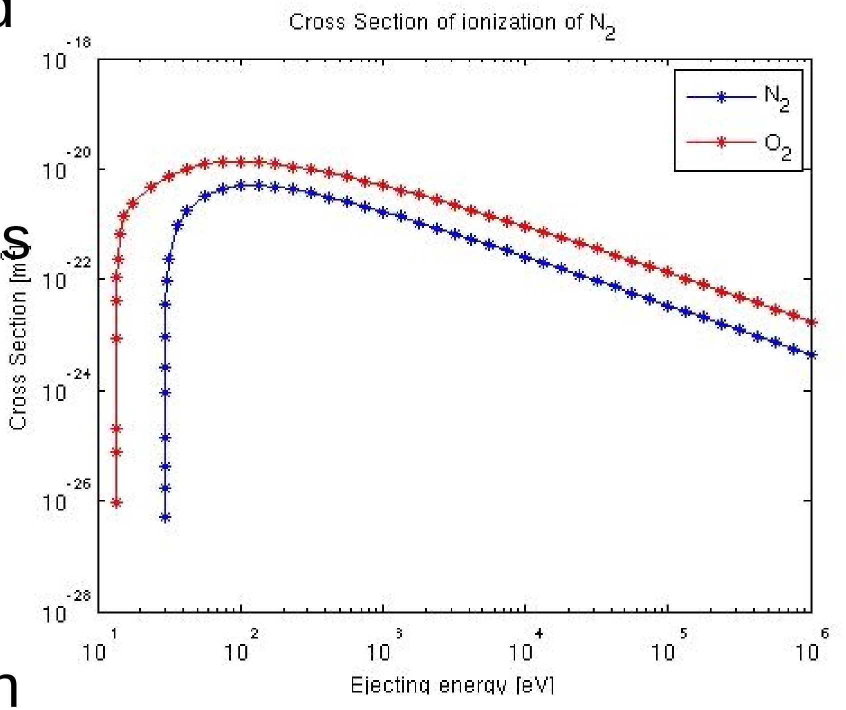
Current Status of PhD program

- The extreme ultraviolet and X-ray Sun in Time: High-energy evolutionary tracks of a solar-like star
- Charge exchange and Photoionization production rate calculation causing by different stellar wind condition
- Gui system

Goals and Future Work

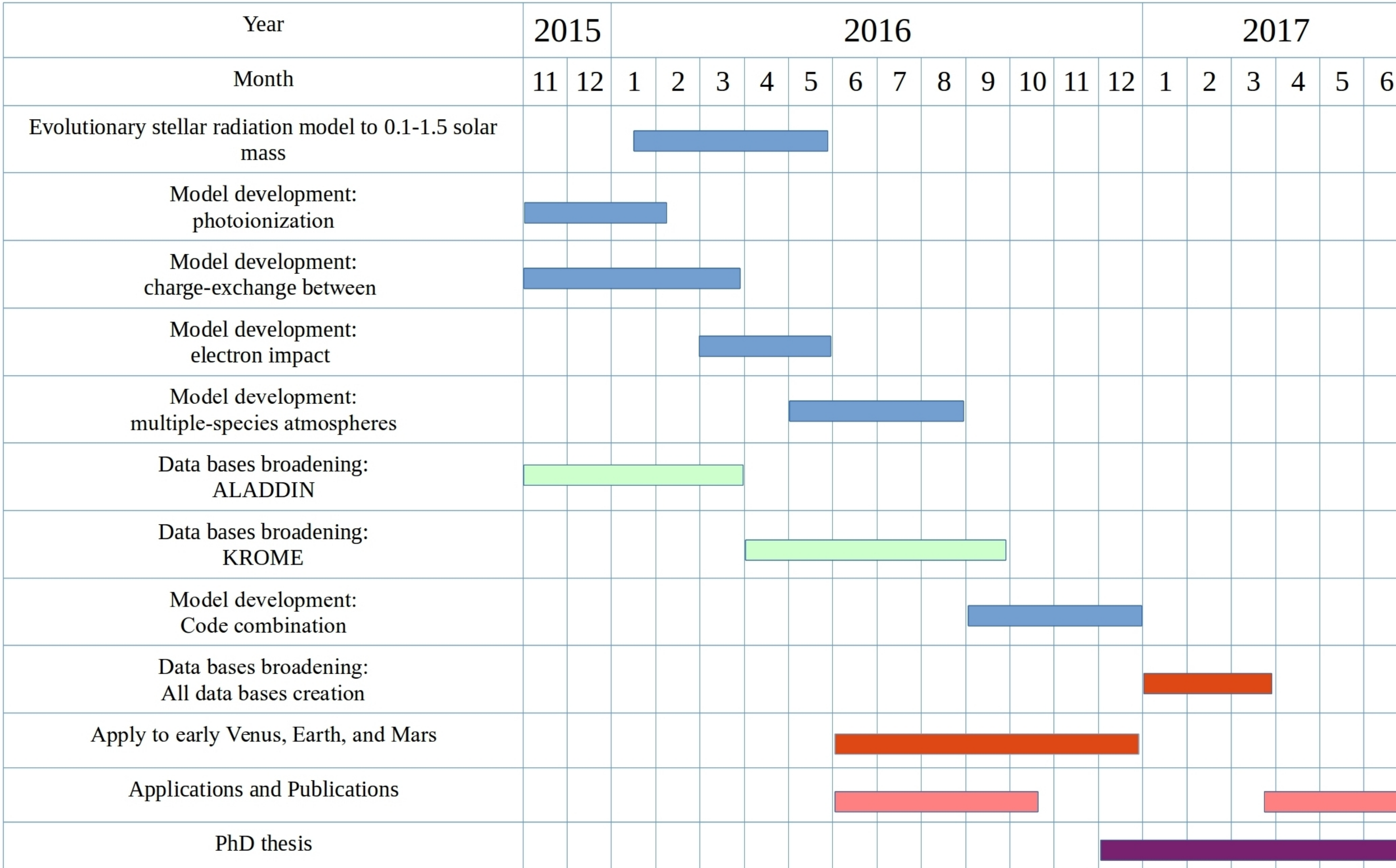
- High-energy evolutionary tracks of stars with masses between 0.1 and 1.5 solar masses
- Interaction between stellar winds and atmospheres under protection of magnetosphere
- Include multiple-species atmospheres
- Broaden ionization data bases:

  ALADDIN and KROME
- Apply this methodology to early Venus, Earth, and Mars
- Apply different EUV heating condition which causes expanding atmospheres



Cross section variation with different electron energy; from ALADDIN

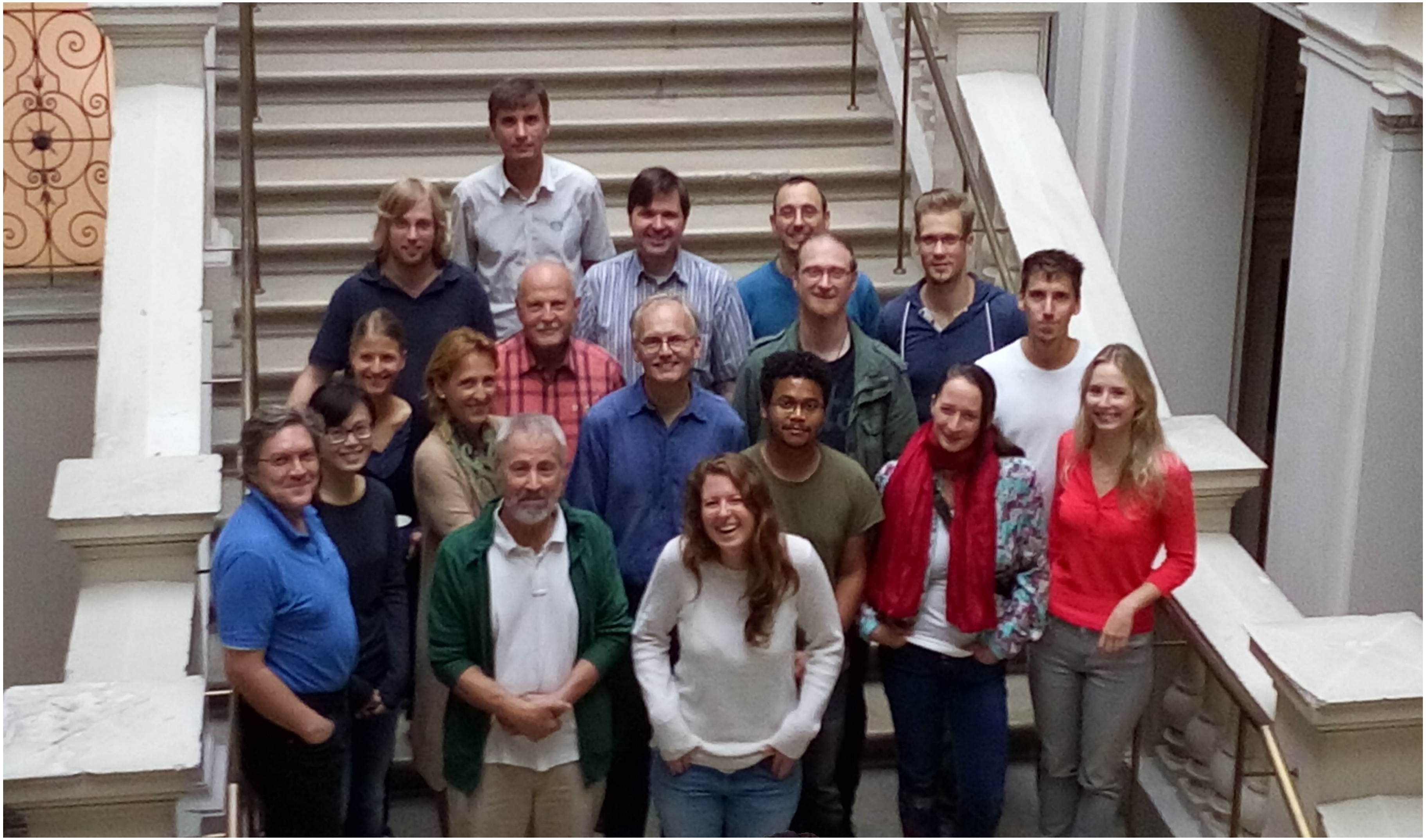
Time Plan


Year
2015
2016
2017
Month
11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6
Evolutionary stellar radiation model to 0.1-1.5 solar mass
Model development: photoionization
Model development: charge-exchange between
Model development: electron impact
Model development: multiple-species atmospheres
Data bases broadening: ALADDIN
Data bases broadening: KROME
Model development: Code combination
Data bases broadening: All data bases creation
Apply to early Venus, Earth, and Mars
Applications and Publications
PhD thesis

Financial Aspects

- The described PhD-project is funded by the Emerging Fields grant from FGGA faculty with
- support from the FWF NFN project 'Pathways to Habitability'. The grant includes personal
- costs for the PhD position (three years) and also a generous amount of travel money, which
- allows visits to the already mentioned collaborators and especially to Dr. Lammer.
- The official project start was 1.7.2014 and the funding period ends at 30.6.2017 which is
- also the expected end date for this PhD-project.

Thank you!



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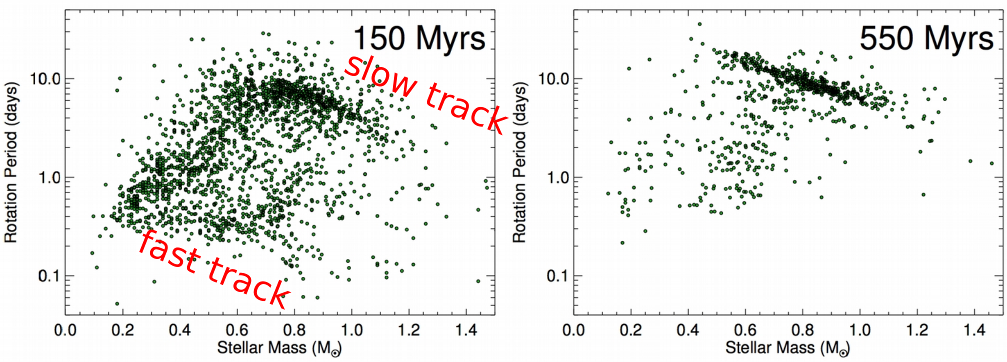
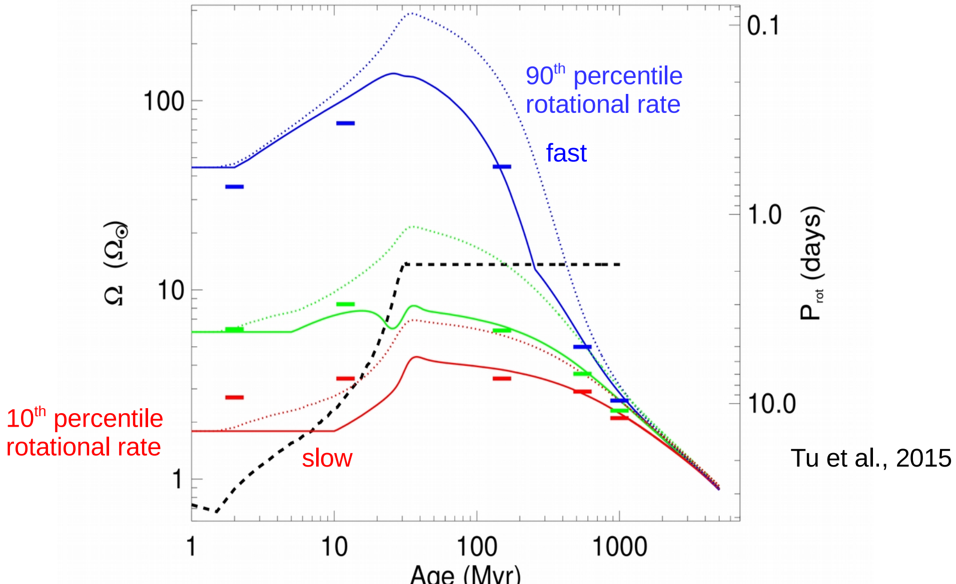
Mass Loss and Rotation: Introducing Rot. Distributions



Johnstone et al., 2015

Stellar rotation rates evolution



The solid and dotted lines show the envelope and core rotational evolution, respectively, and the horizontal solid lines show the observational percentiles.

Predicted rotational evolution tracks for stars at the 10th (red), 50th (green), and 90th (blue) percentiles of the rotation rate distribution.

The solid and dotted lines show the envelope and core rotational evolution, respectively, and the horizontal solid lines show the observational

B dip , and L X calculated assuming a

constraints on the percentiles. The dashed black line shows the time dependent saturation threshold for M,

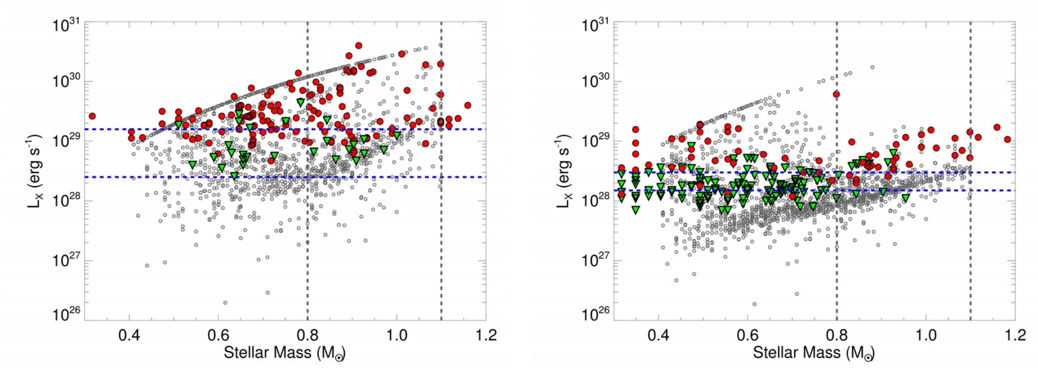
constant saturation Ro and the τ values of Spada et al. (2013). Right (b): Predicted L X along each of our rotation tracks and comparisons to

observed L X values of single stars in several clusters with upper limits shown by symbols. The solid horizontal lines show the 10th, 50th, and

90th percentiles of the observed distributions of L X at each age calculated by counting upper limits as detections. The two solar symbols at 4.5 Gyr

show the range of L X for the Sun over the course of

Model apply to Pleiades and Hyades



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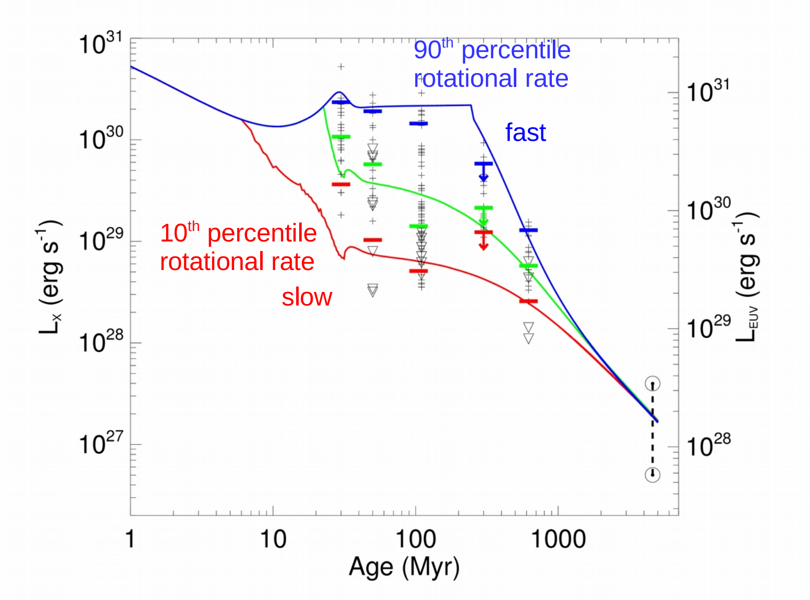
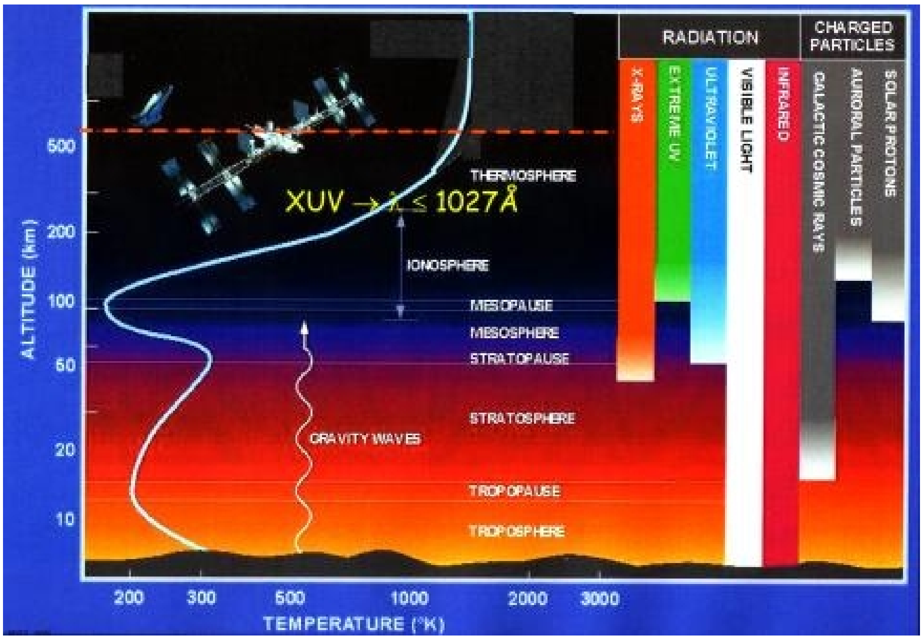
Comparisons between observed and predicted distributions of X-ray luminosity at ages of 150 Myr (left) and 620 Myr (right).

Stellar radiation evolution



Atmospheric Profile



Planetary examples[edit]

Approximate scale heights for selected Solar System bodies follow.

Venus: 15.9 km[5]

Earth: 8.5 km[6]

Mars: 11.1 km[7]

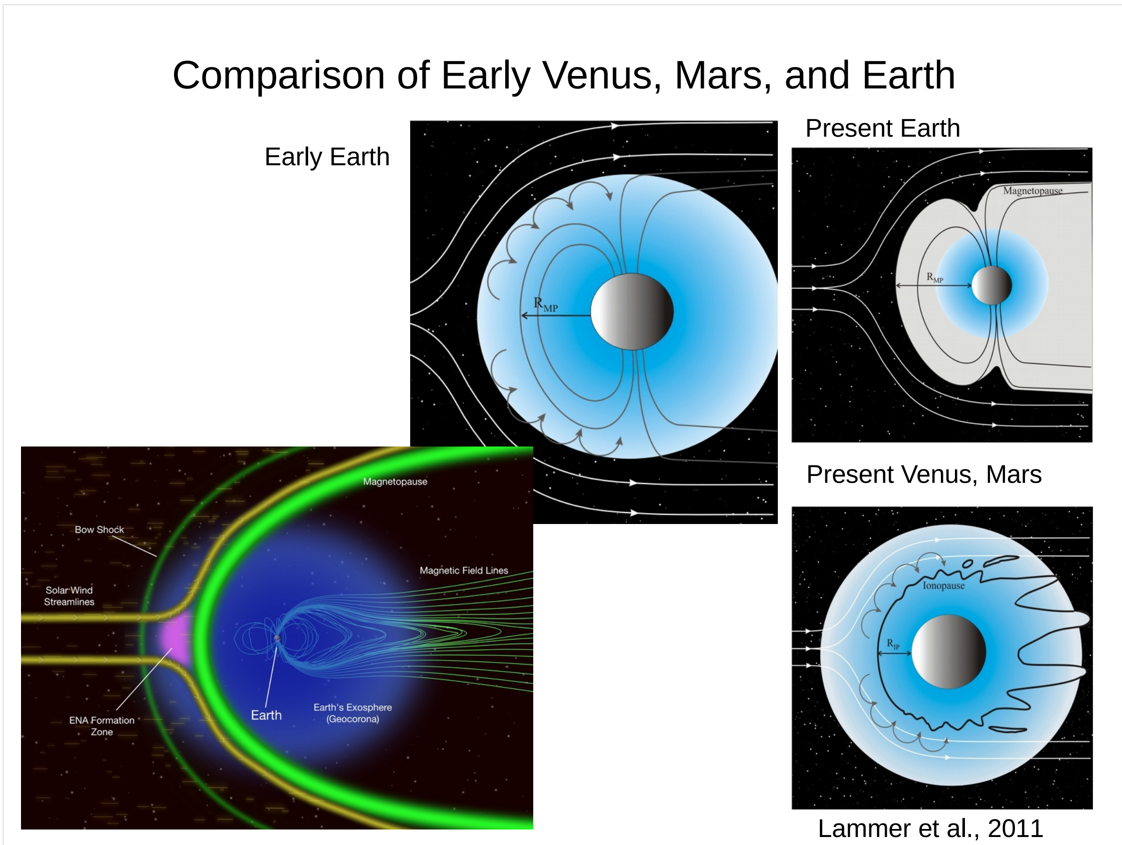
Jupiter: 27 km[8]

Saturn: 59.5 km[9]

Titan: 40 km[10]

Uranus: 27.7 km[11]

Neptune: 19.1–20.3 km[12]

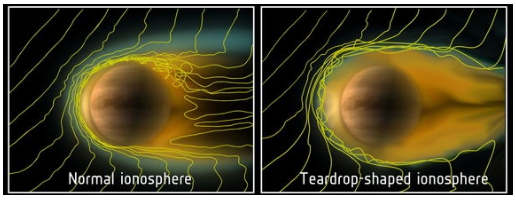


Raius
Atmospheric components
Distance to sun (stellar wind density)
EUV, X-ray comparison

Illustration showing the expected stellar wind – atmosphere interaction
in a case where the upper atmosphere expands above a compressed magnetosphere.
Neutral species above the magnetopause can be ionized and picked up by the stellar
wind plasma flow.

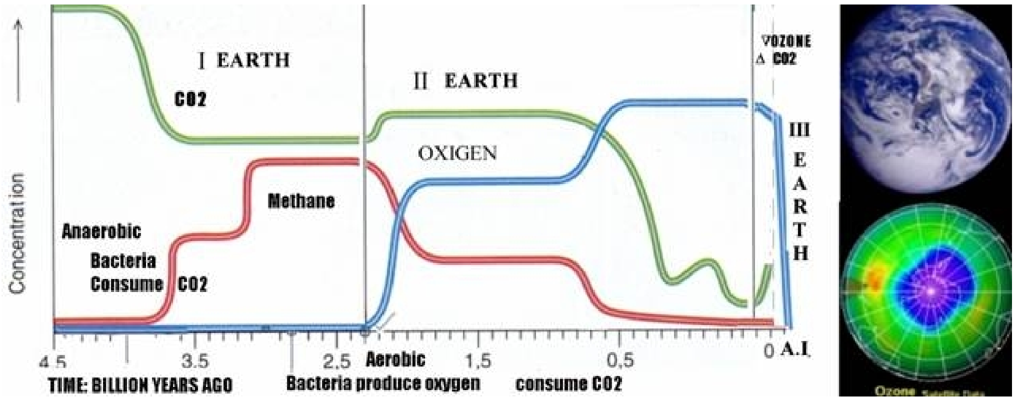
History of Martian and Venus atmosphere

- First epoch (~300-600 Myr)
  - -high EUV
  - -low gravity
  - -Hydrodynamic flow regime
  - -dragged heavier species such as O and C atoms
- Second epoch (~4–4.3 Gyr ago)
  - -secondary atmosphere (impact-related volatiles and mantle outgassing)



The evolution and escape of the martian atmosphere and the planet’s water inventory can be separated into an early and late evolutionary epoch. The first epoch started from the planet’s origin and lasted 500 Myr. Because of the high EUV flux of the young
Sun and Mars’ low gravity it was accompanied by hydrodynamic blow-off of hydrogen and
strong thermal escape rates of dragged heavier species such as O and C atoms. After the
main part of the protoatmosphere was lost, impact-related volatiles and mantle outgassing
may have resulted in accumulation of a secondary CO_2 atmosphere of a few tens to a few
hundred mbar around 4–4.3 Gyr ago. The evolution of the atmospheric surface pressure
and water inventory of such a secondary atmosphere during the second epoch which lasted

Earth atmospheric evolution



Escape mechanisms

- Thermal escape
  - → Jeans escape
  - → Jeans parameter

$$\lambda_c = \frac{GMm}{kT_{exo} r_{exo}}$$

  - → Hydrodynamic flow regime
  - → Blowoff criteria

$$\lambda_c < 1.5$$

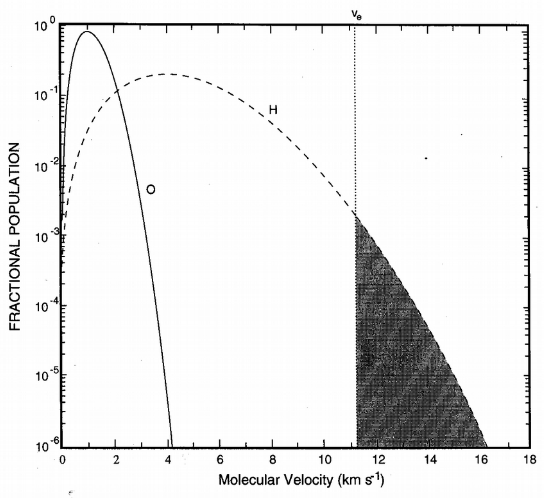


Figure 1.6 Boltzmann distribution of velocities for a molecular ensemble of oxygen atoms and hydrogen atoms. Escape velocity v_e for earth also indicated.

What's the main difference?

In thermal escape, particles are assumed to be in the Maxwelliam velocity distribution in the exobase. Because there is fully enough collisions between particles.

Jeans parameter:

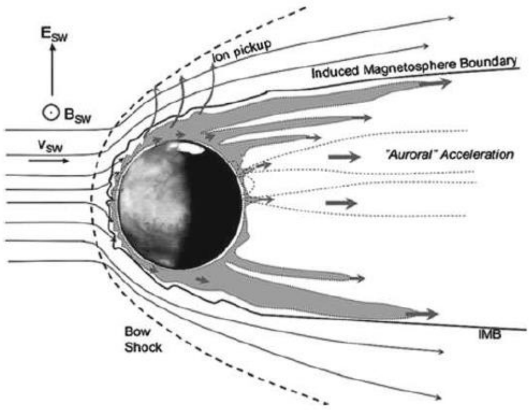
represents the ratio of the gravitational energy to the mean thermal energy of the particle, along with the number

Blow off: An extreme case of thermal escape is atmospheric “blowoff,” which occurs when the mean thermal energy of the major gases at the exobase level (where the mean free path of the gas particles is comparable to the scale height of the atmosphere) exceeds their gravitational potential energy (equivalent to l c < 1.5)

Non-thermal escape processes, such as H/H + charge exchange, the escaping atoms acquire energy from nonthermal sources, in this case hot H + ions

Non-thermal escape mechanisms

- Charge exchange
- Photochemical reaction
- Electron impact
- Pick-up ions
- Sputtering
- Electric field flow



The interaction between the solar winds and the magnetic field of the earth also plays a key role in the transport of atmospheric particles to outer space.

Non thermal mechanisms need to give the escaping particles energies of

– 0.6 eV/amu on Venus and Earth

– 0.125 eV/amu on Mars.

– This is relatively small in comparison with atomic energies and the energies

which might be gained from an electric field.

(b) Charge exchange

– Slow neutral + fast ion → fast neutral + slow ion

– By exchanging charge, the

fast ion fast ion (which was trapped by the planet's magnetic field) becomes a neutral and is able to escape.

– The resulting slow ion is trapped by the mag. field.

(c) Photochemical reactions

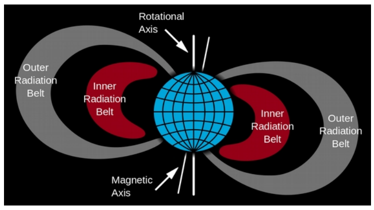
– These convert the energy of absorbed X-ray photons to

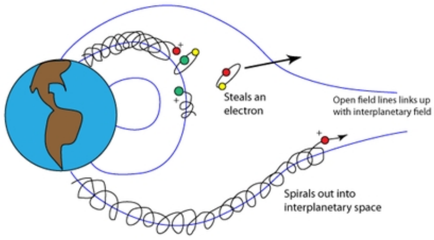
kinetic energy

- Typical yield is a few eV
- This may be enough to cause escape

Non-thermal escape mechanisms

- Sputtering
  → Impact of fast ions knocks atoms out of the atmosphere.
- Ion escape
  → Ions flow upward along polar field lines and escape down magnetic field lines
  → They gain their energy from ambipolar diffusion, where the interaction of ions & electrons in a plasma causes them to diffuse at the same rate
  → The electrons have much higher thermal velocities and can easily escape. This sets up an electric field by charge separation and the ions are dragged after the electrons
  → Occurs also at Mars



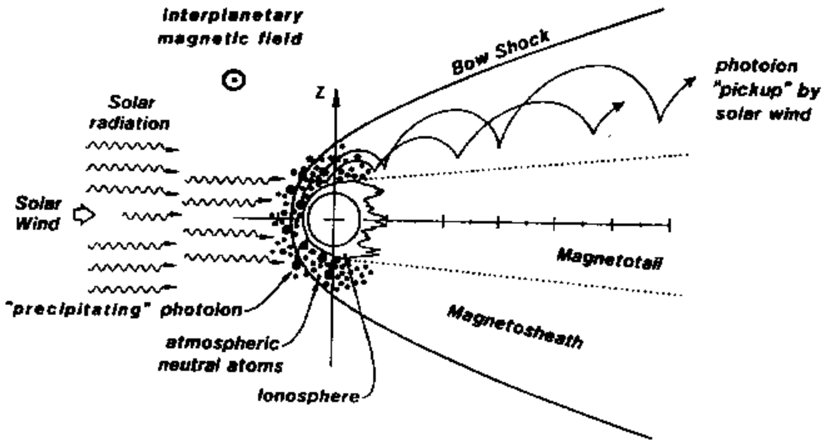


- Sputtering
- – Impact of fast ions knocks atoms out of the atmosphere. The fast particles could be solar wind or trapped radiation belt particles
- Sputtering refers to a mechanism by which incident energetic particles (mostly ions) interact with the upper atmosphere, resulting in ejection of atmospheric species. Sputtering has been recognized as an important source of atmospheric loss in the case of Mars and of less importance for larger planets like Venus (Luhmann and Kozyra 1991)

=>Important on Mars and less on Venus
- Van Allen Radiation Belt
  Most of the particles that form the belts are thought to come from solar wind and other particles by cosmic rays.
-

Non-thermal escape mechanisms

- Ion Pickup



Electric field
Neutral particles are ionised in the upper ionosphere
– The resultant ions are pulled out of the ionosphere by electric fields associated
with auroral activity into the co-rotating plasmasphere above
– The solar wind sets up a cross-tail electric field (downwards in this diagram)
– Blobs of cold plasma spin off under the influence of this field as shown and are
lost into the tail and eventually into the solar wind downstream
Ion pickup (solar wind scavenging)
– At Mars and Venus the exobase is above the boundary between the solar wind
flow and the planet.
– Once the particles become photoionised they can be picked up directly by the
solar wind flow and carried away.
– The energy is provided by the electric field in the solar wind.

Non-thermal escape mechanisms

- Charge exchange

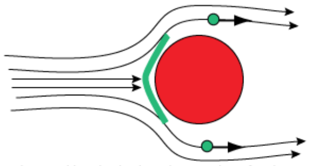
→ Slow neutral + fast ion => fast neutral + slow ion

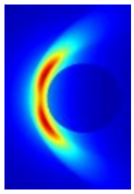
- Photochemical reactions

→ Convert the energy of absorbed X-ray photons to kinetic energy

→ Typical yield is a few eV

→ This may be enough to cause escape

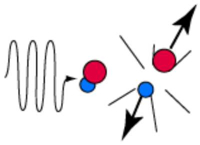




Solar wind hits high-altitude particles of a planet with no magnetic field

$$O^+ + O \rightarrow O + O^+$$
$$O^+ + H \rightarrow O + H^+$$
$$O^+ + H_2 \rightarrow O + H_2^+$$

Charge exchange on Venus



High-energy sunlight breaks apart molecules into higher-speed atoms

Charge-exchange

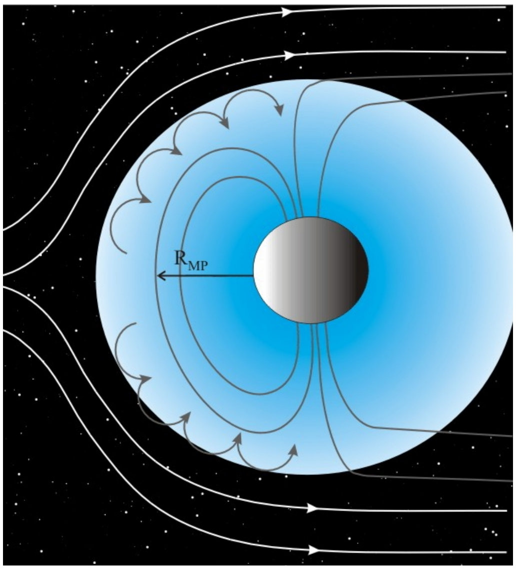
– By exchanging charge, the fast ion (which was trapped by the planet's magnetic field) becomes a neutral and is able to escape.The resulting slow ion is trapped by the mag. Field.

The production of ENAs after the interaction of stellar wind protons via charge exchange with various upper atmospheric species

Heating & Cooling processes

- EUV heating ($\lambda \leq 1027$ Å) : photoionization
- UV heating ($1250 \leq \lambda \leq 3500$ Å) : photodissociation
- IR-cooling

  → vibrational-rotational bands of atmospheric ions
- Adiabatic cooling



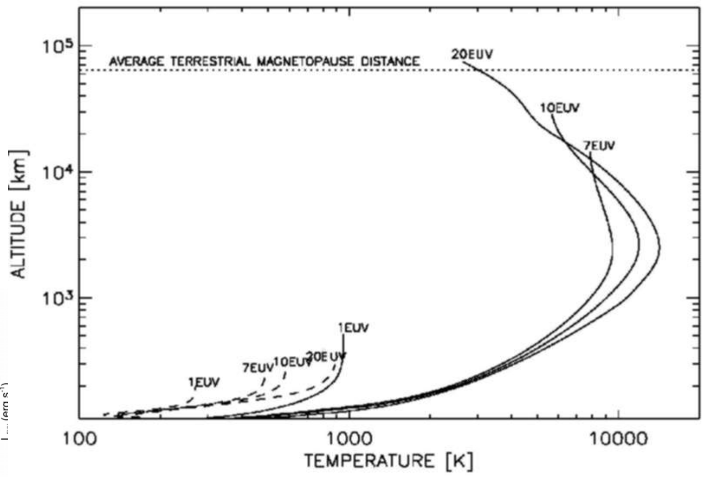
Lammer et al., 2002

ENA heating

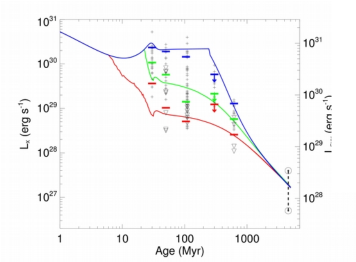
Due to the interaction between the stellar wind plasma flow and the XUV-heated non-hydrostatic upper neutral atmosphere of the planet, ENAs are produced. ENAs originate due to charge exchange when an electron is transferred from a planetary neutral atom to a stellar wind proton, which then becomes an ENA. This interaction process between the stellar wind plasma and the upper atmosphere and formation of hot atomic coronae around the planet play a significant role in the ion erosion of upper planetary atmospheres

EUV heating

- Cooling effect after 5 EUV
- Proto-atmosphere was lost
- Adiabatic cooling



Tian et al., 2008



Tu et al., 2015

exobase temperature of early terrestrial planetary atmosphere could have reached over 10,000 K

Although such high exobase temperatures

should have caused the major gases at the exobase to experience fast Jeans escape, and

the entire thermosphere should have experienced hydrodynamic flow.

The Joule heating term in the model is included by

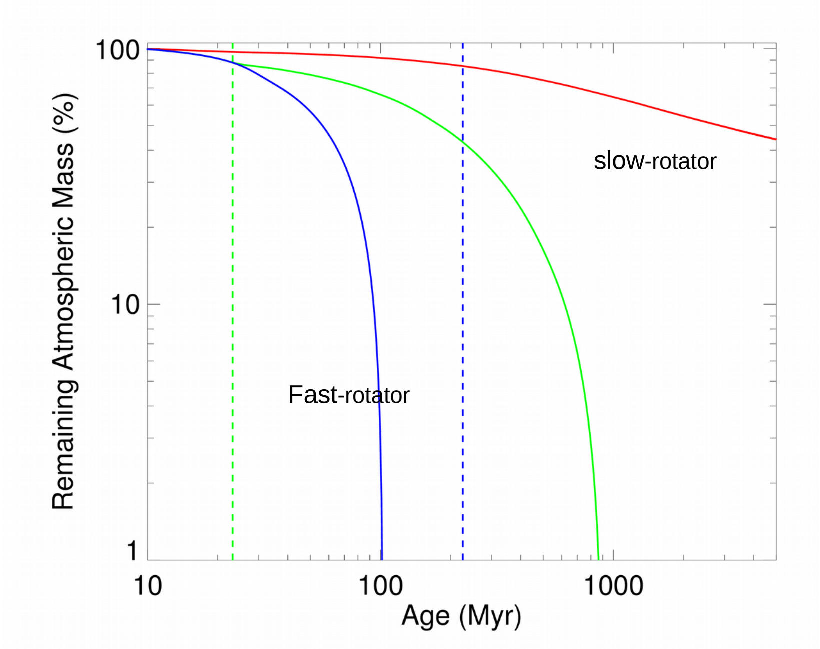
specifying an externally applied electric field (assumed

constant with height) and calculating the Pedersen conduc-

tivity.

Evolutionary Atmospheric Loss

- The vertical lines show the stellar saturation times.



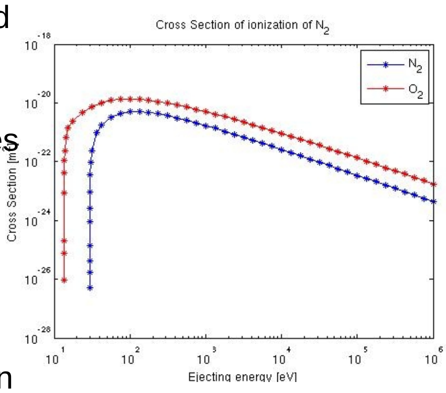
Current Status of PhD program

- The extreme ultraviolet and X-ray Sun in Time: High-energy evolutionary tracks of a solar-like star
- Charge exchange and Photoionization production rate calculation causing by different stellar wind condition
- Gui system

Goals and Future Work

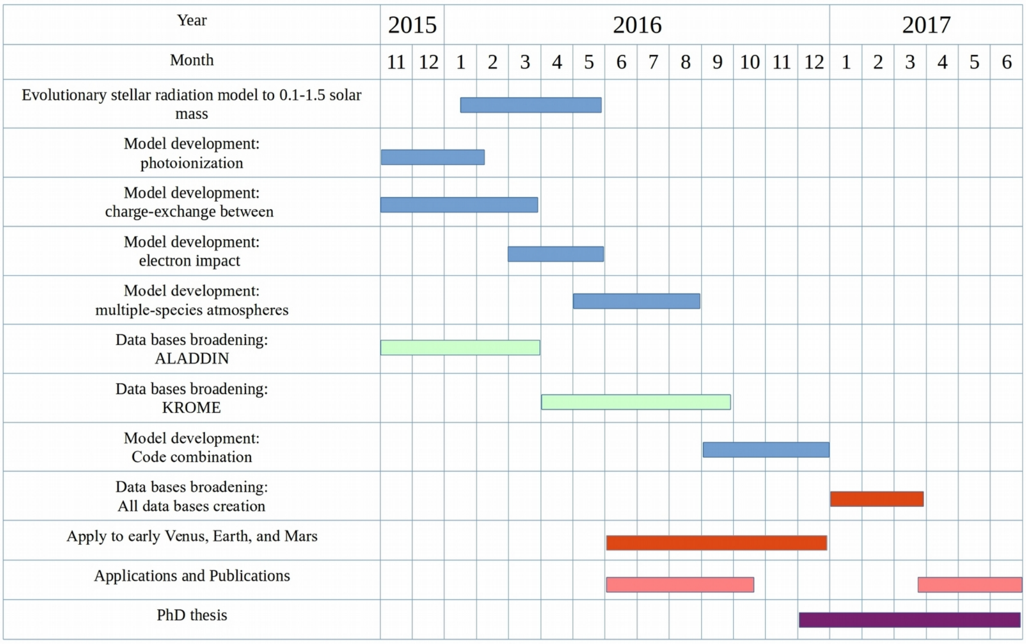
- High-energy evolutionary tracks of stars with masses between 0.1 and 1.5 solar masses
- Interaction between stellar winds and atmospheres under protection of magnetosphere
- Include multiple-species atmospheres
- Broaden ionization data bases:

  ALADDIN and KROME
- Apply this methodology to early Venus, Earth, and Mars
- Apply different EUV heating condition which causes expanding atmospheres



Cross section variation with different electron energy; from ALADDIN

Time Plan


Year
2015
2016
2017
Month
11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6
Evolutionary stellar radiation model to 0.1-1.5 solar mass
Model development: photoionization
Model development: charge-exchange between
Model development: electron impact
Model development: multiple-species atmospheres
Data bases broadening: ALADDIN
Data bases broadening: KROME
Model development: Code combination
Data bases broadening: All data bases creation
Apply to early Venus, Earth, and Mars
Applications and Publications
PhD thesis

Financial Aspects

- The described PhD-project is funded by the Emerging Fields grant from FGGA faculty with
- support from the FWF NFN project 'Pathways to Habitability'. The grant includes personal
- costs for the PhD position (three years) and also a generous amount of travel money, which
- allows visits to the already mentioned collaborators and especially to Dr. Lammer.
- The official project start was 1.7.2014 and the funding period ends at 30.6.2017 which is
- also the expected end date for this PhD-project.

Thank you!