Stellar high-energy luminosity evolution for pre-main sequence and main-sequence stars

Tu, L., Johnstone, C.P. , Güdel, M. , Lüftinger, T. , Lichtenegger, H., Kislyakova, K.G., Lammer, H.

XUV & magnetic activities

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- Ratio of X-ray to bolometric luminosity

$$R_x = \frac{L_x}{L_{bol}}$$

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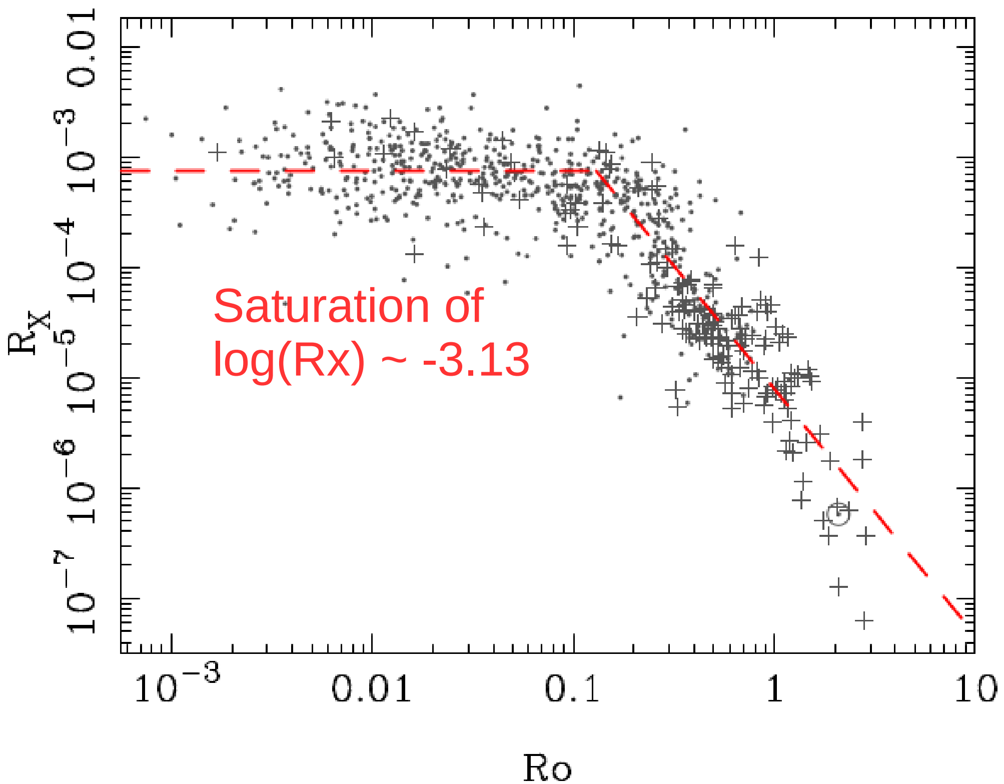
β = −2.70 ± 0.13 (Wright et al., 2011)



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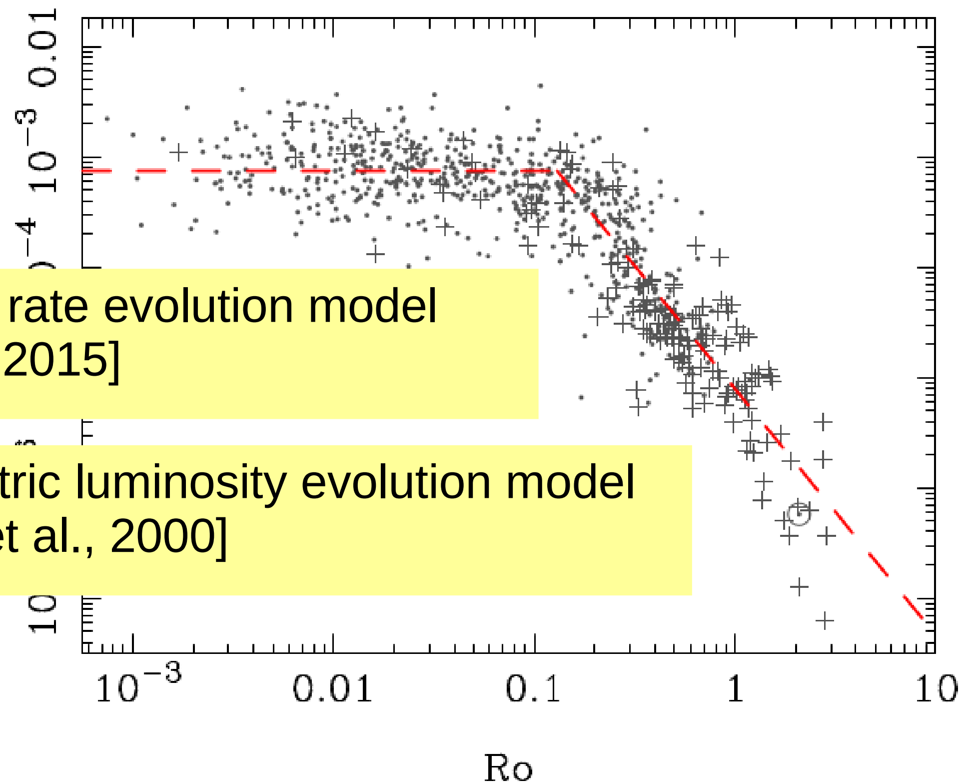

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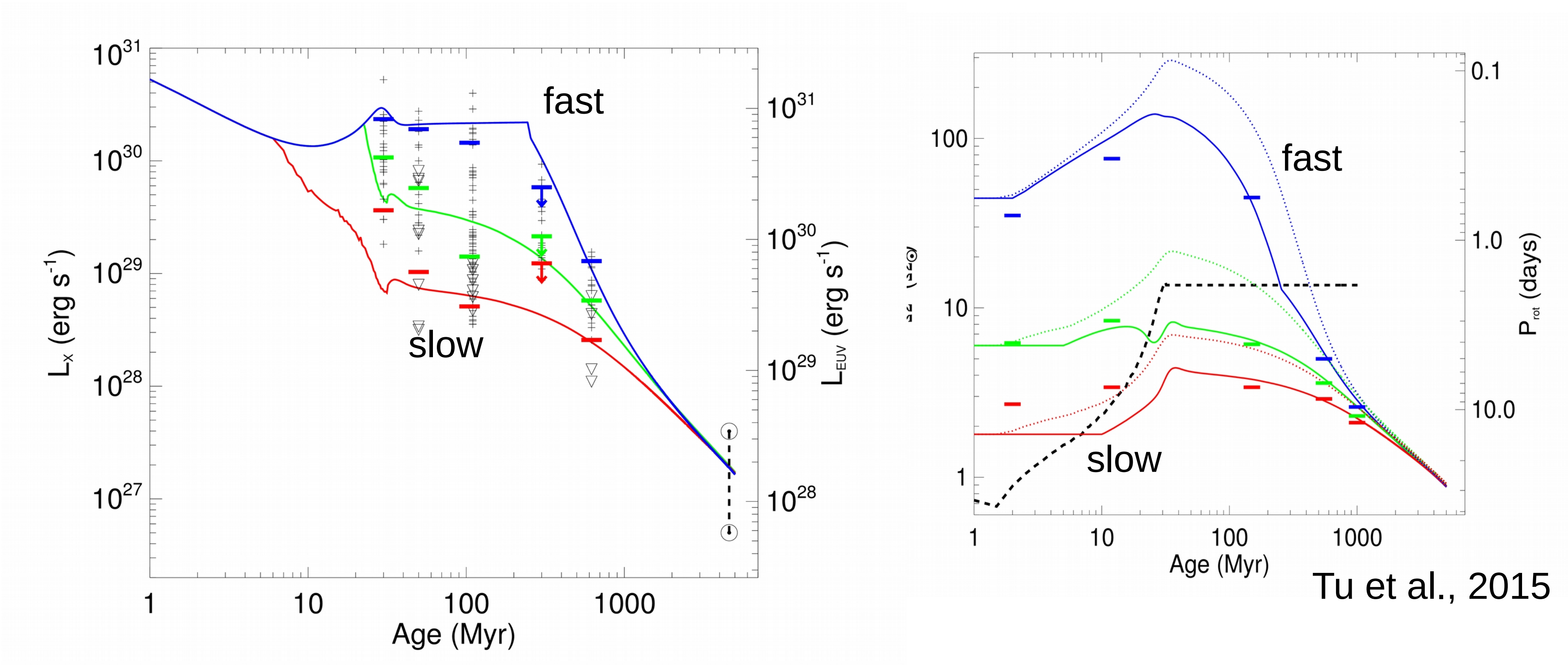
Bolometric luminosity evolution model [Siess et al., 2000]

Magnetic convective turnover timescale evolution model [Spada et al., 2013]

Solar radiation evolution



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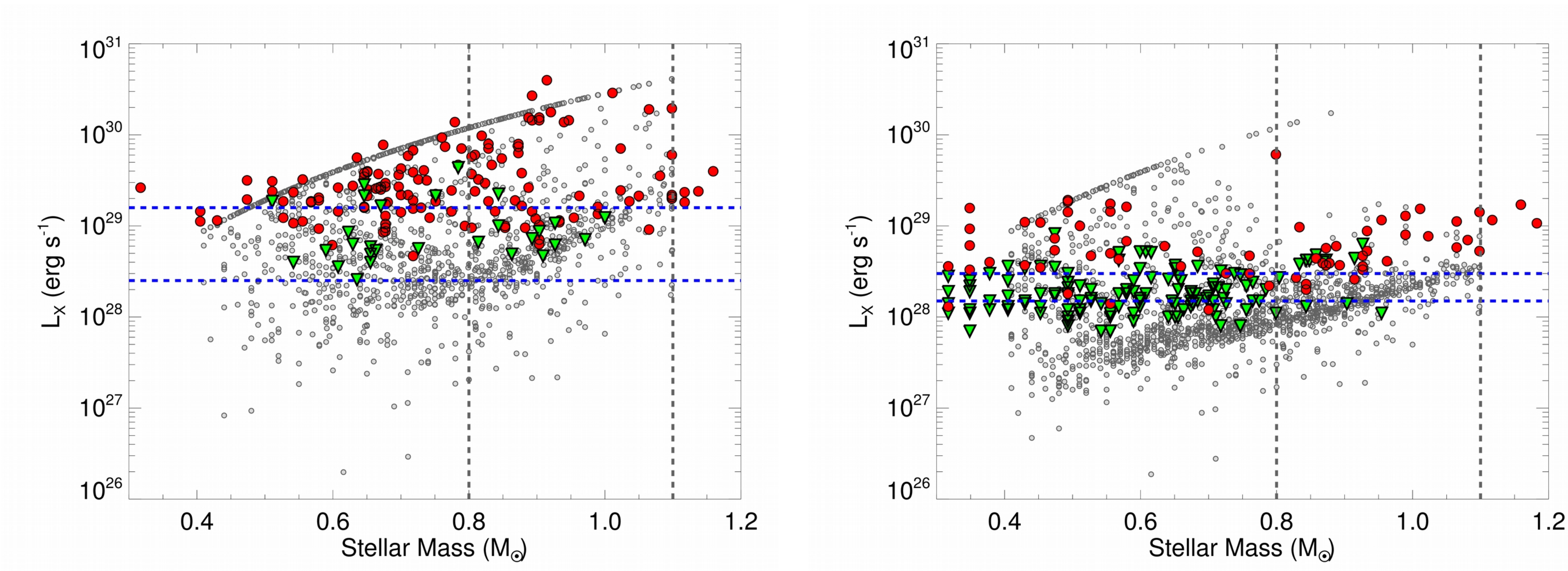

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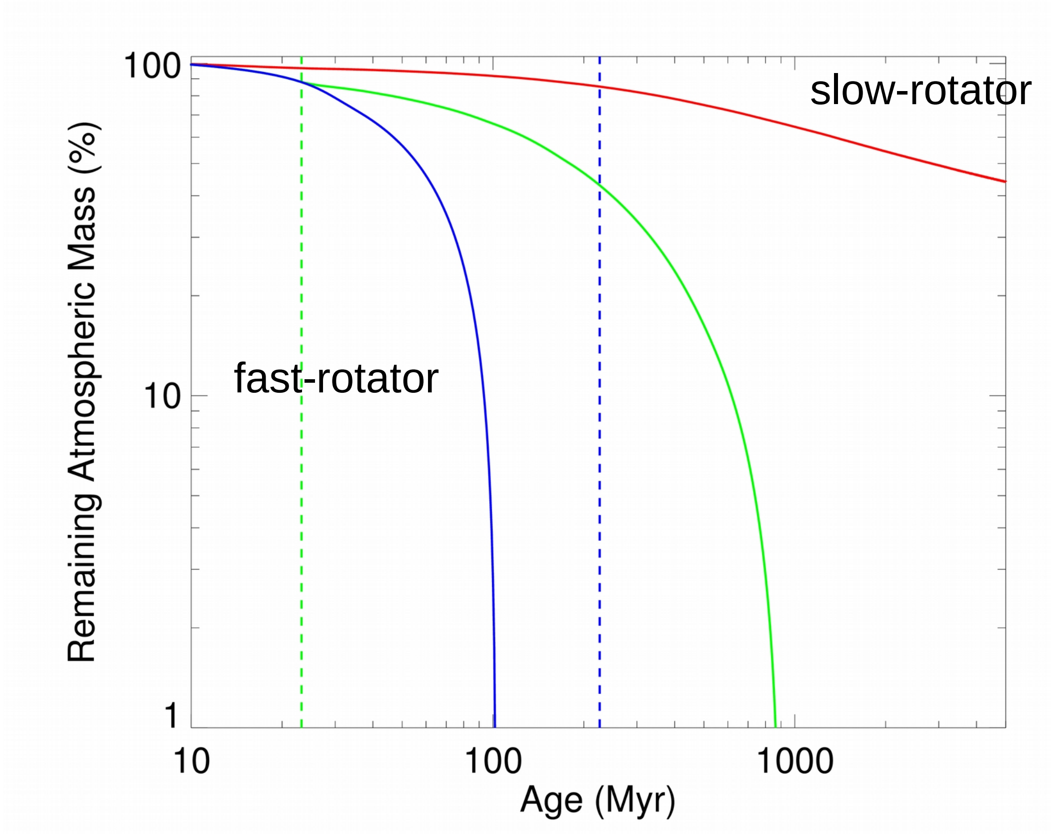

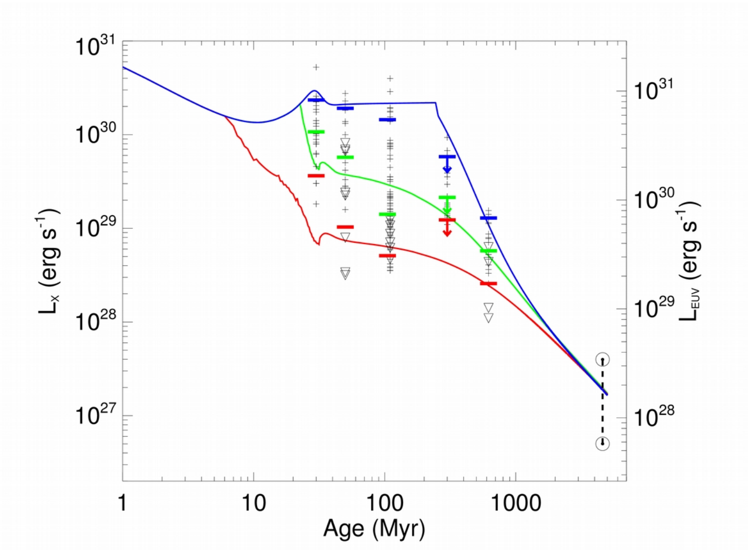

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  → Jeans parameter

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→ Hydrodynamic flow regime

→ Blowoff criteria

$\lambda_c < 1.5$

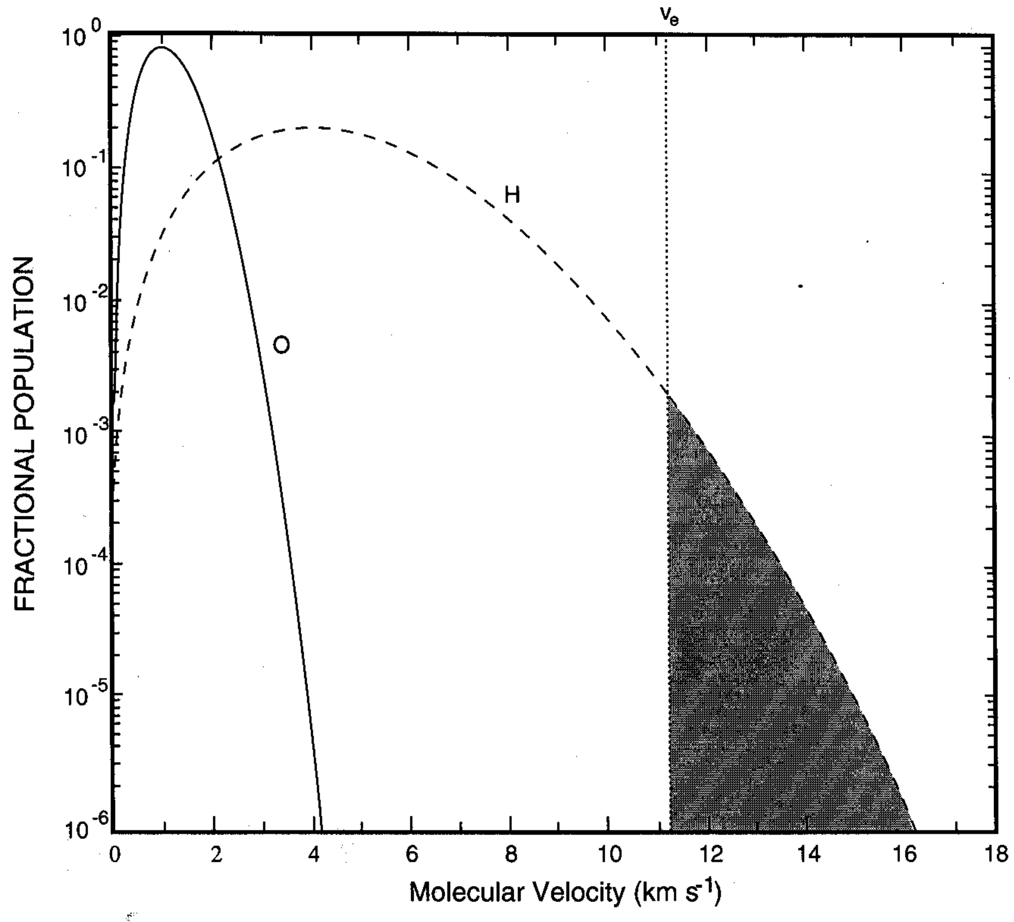

Figure 1.6 Boltzmann distribution of velocities for a molecular ensemble of oxygen atoms and hydrogen atoms. Escape velocity v_e for earth also indicated.

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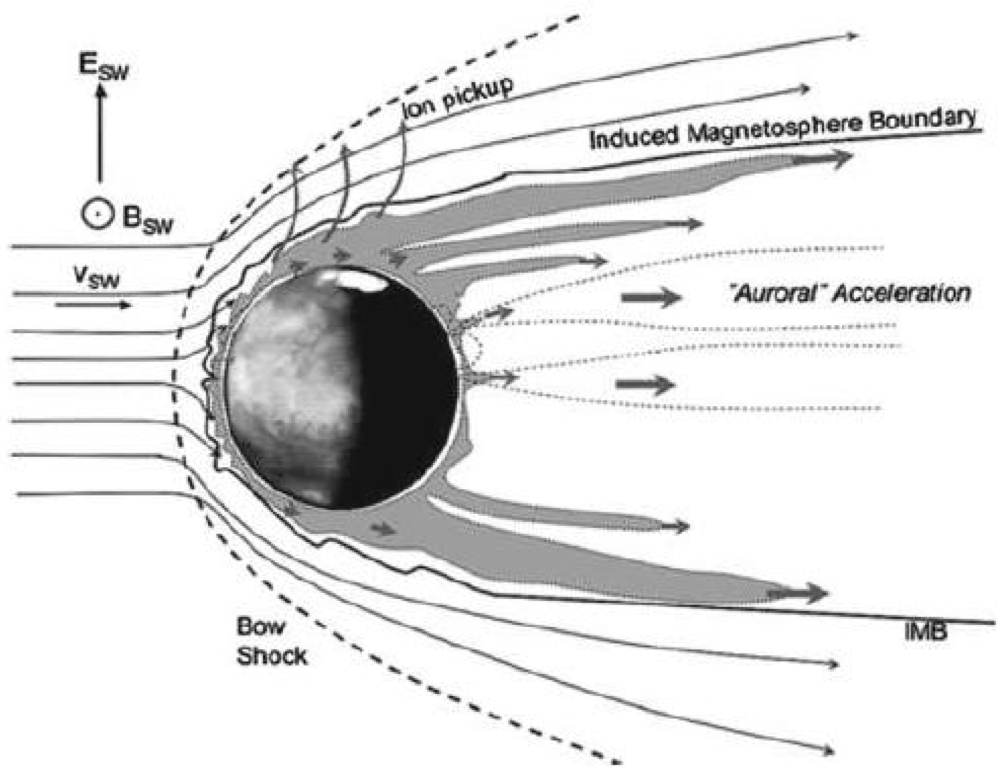

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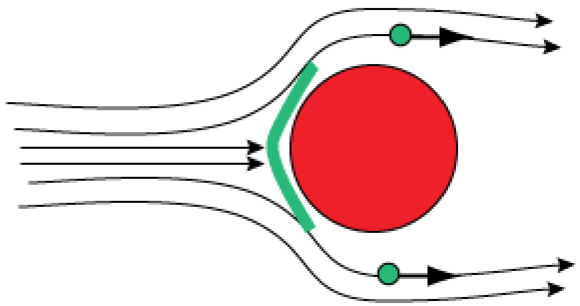
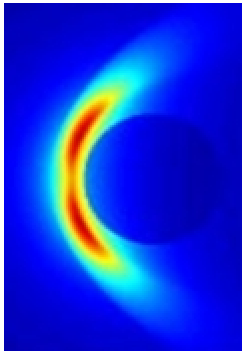

Solar wind hits high-altitude particles of a planet with no magnetic field

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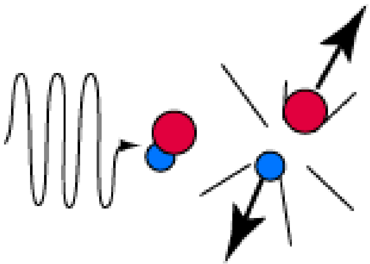
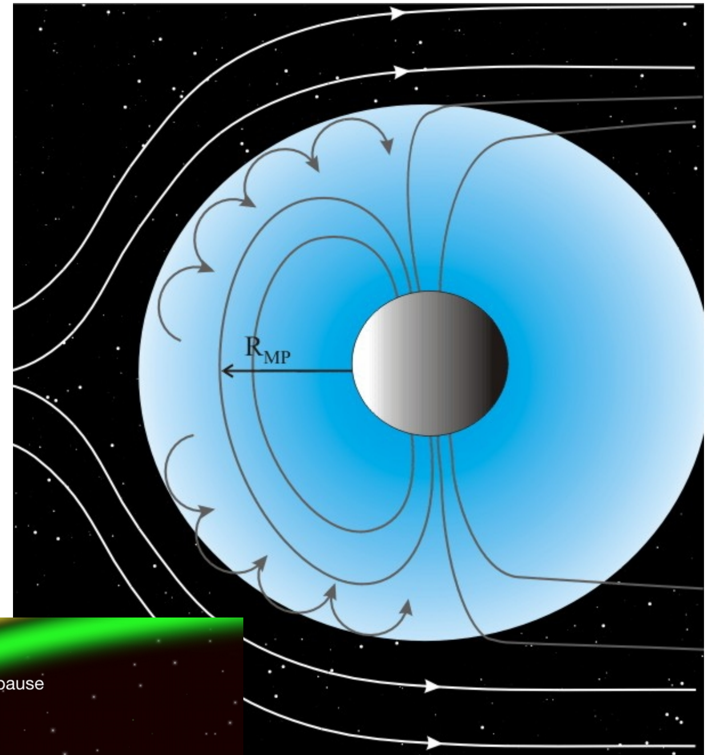


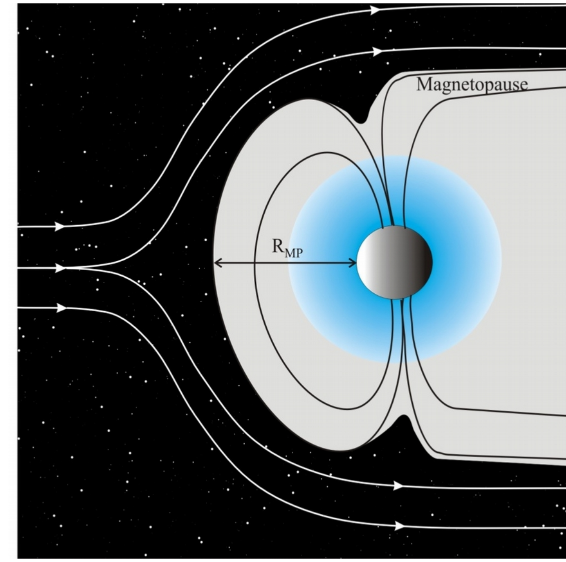
High-energy sunlight breaks apart molecules into higher-speed atoms

Comparison of Venus, Mars, and Earth

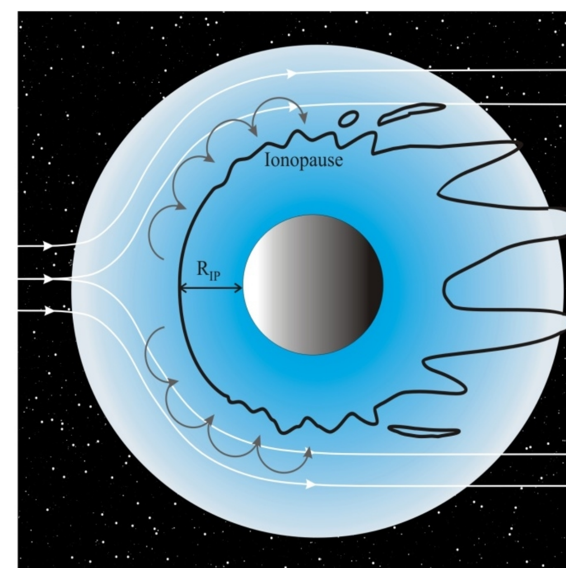
Early Earth



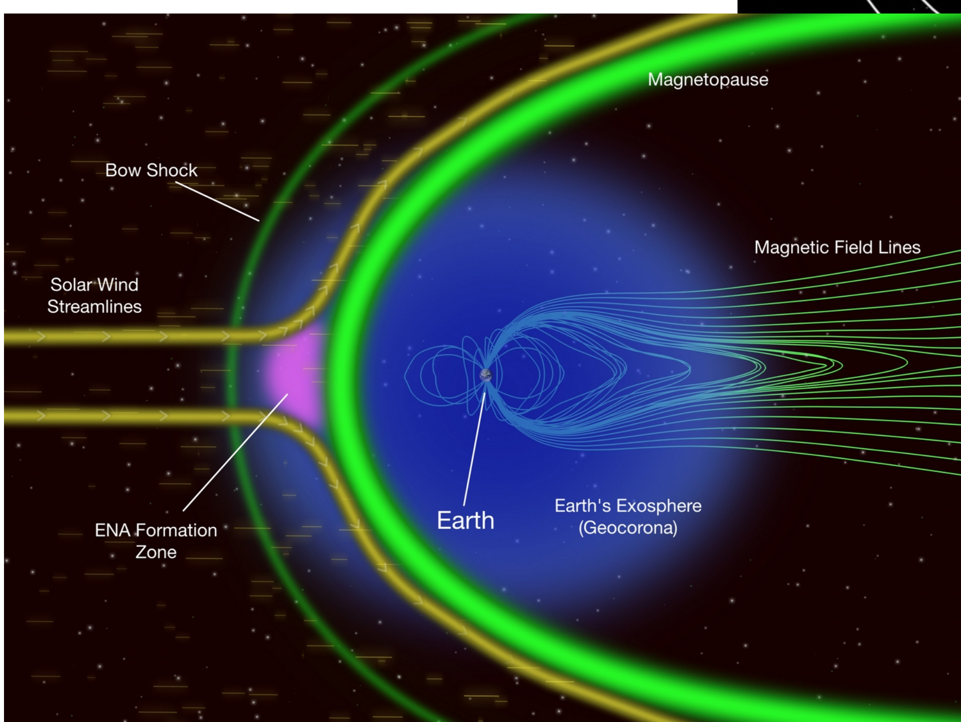
Present Earth



Present Venus, Mars



Lammer et al., 2011



History of Martian and Venus atmosphere

- First epoch (~500 Myr)

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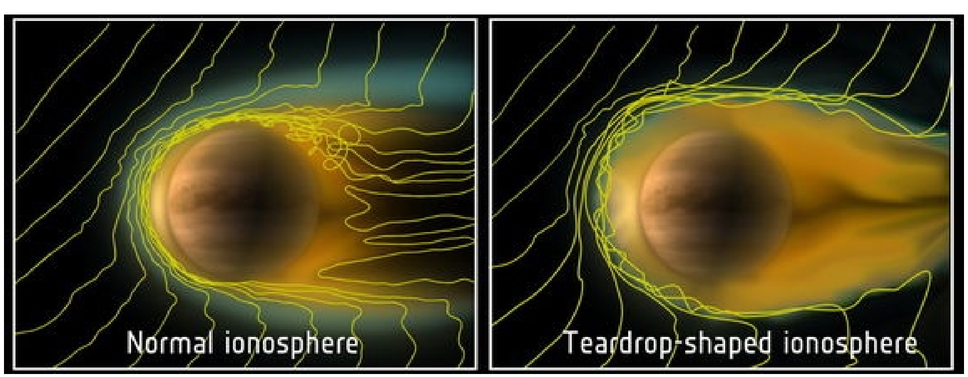

Heating & Cooling processes

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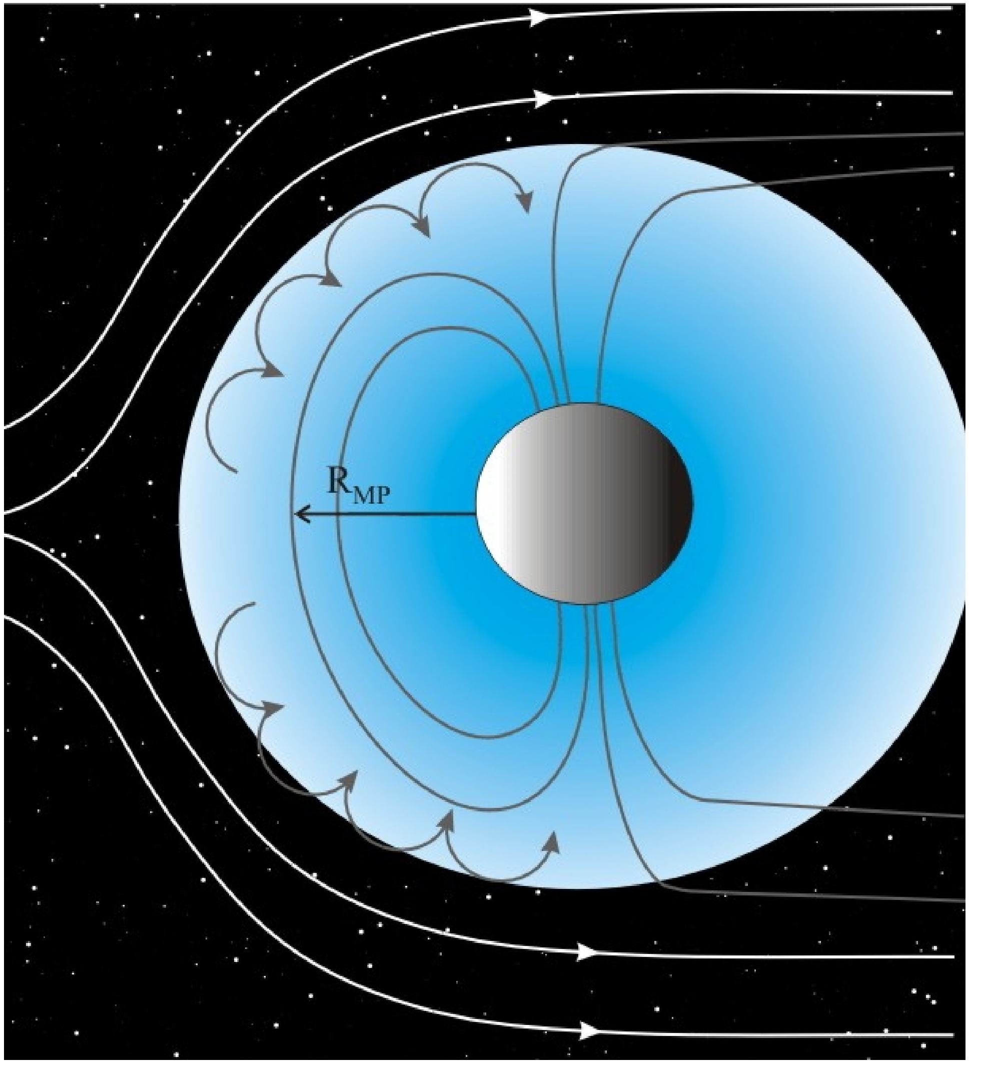

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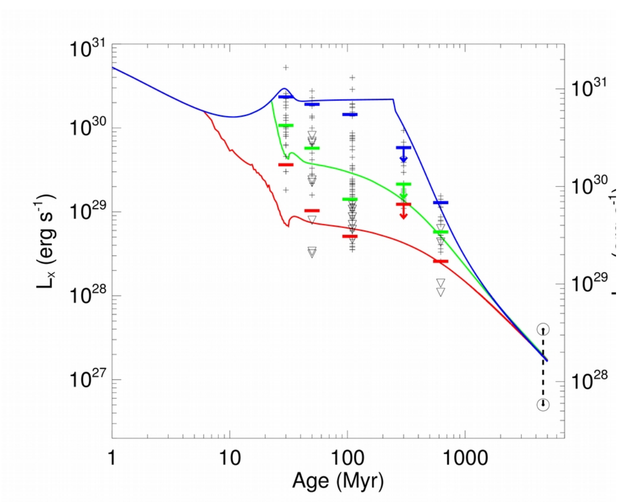
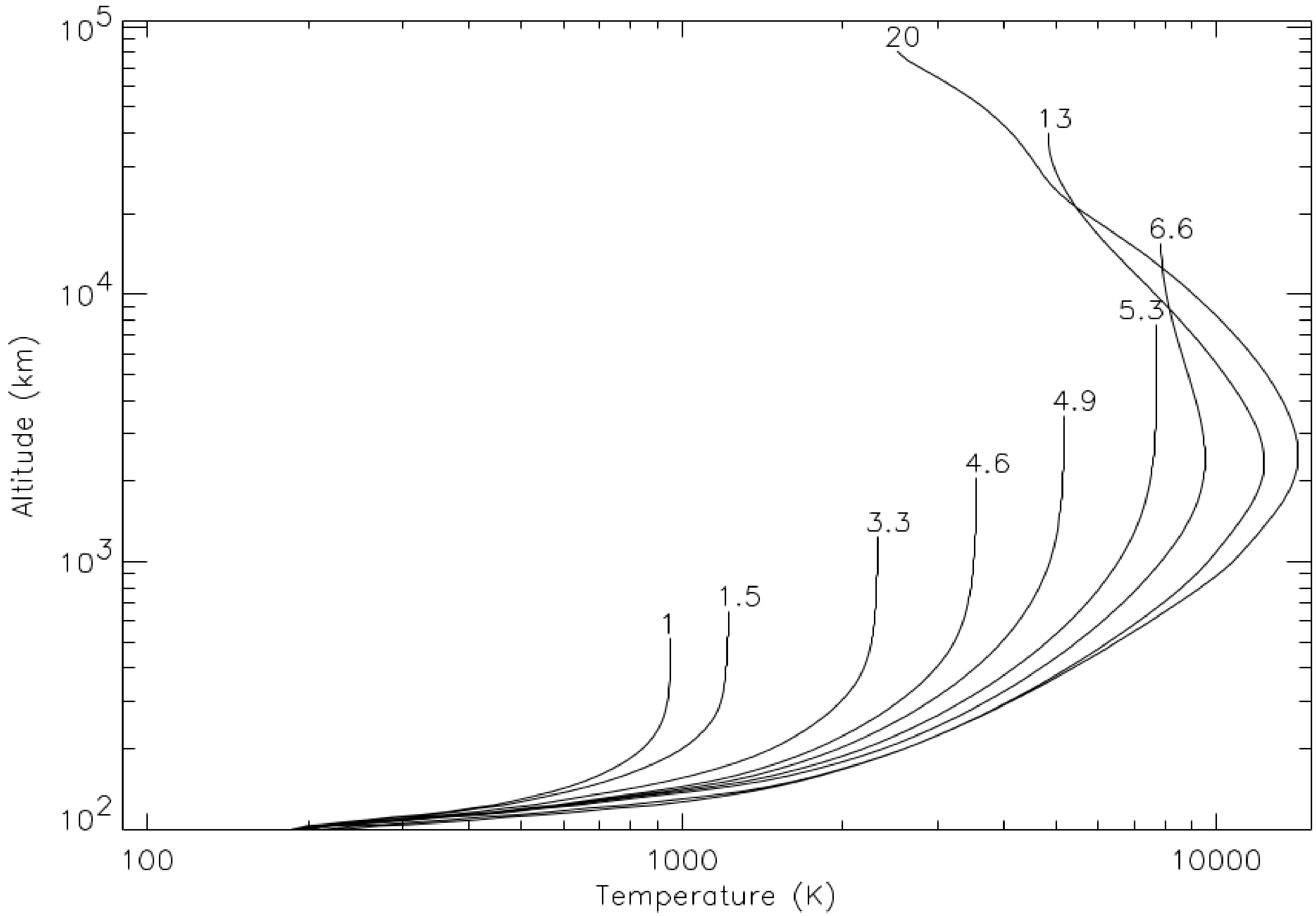
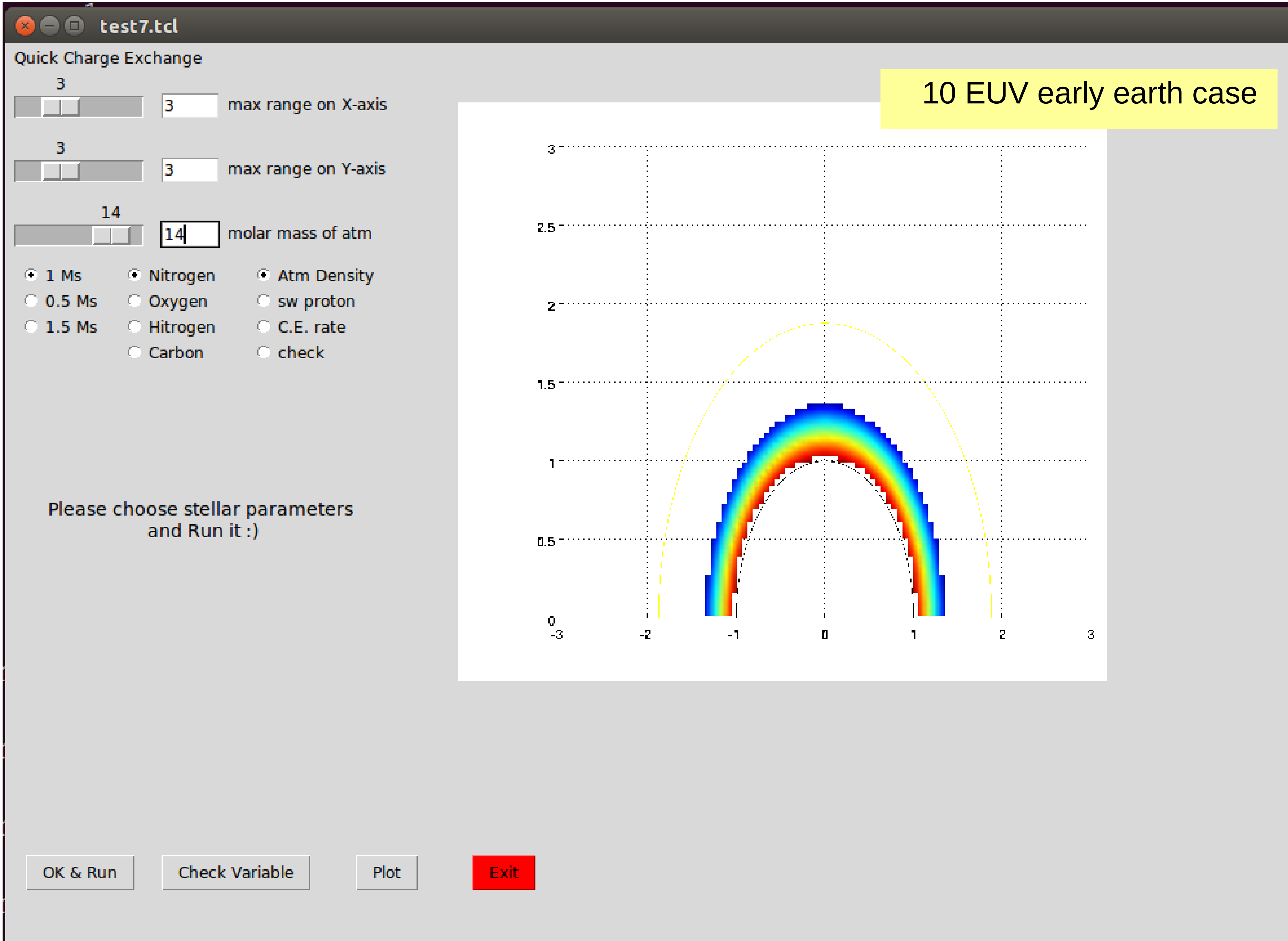




Tu et al., 2015

Tian et al., 2008

10 EUV early earth case



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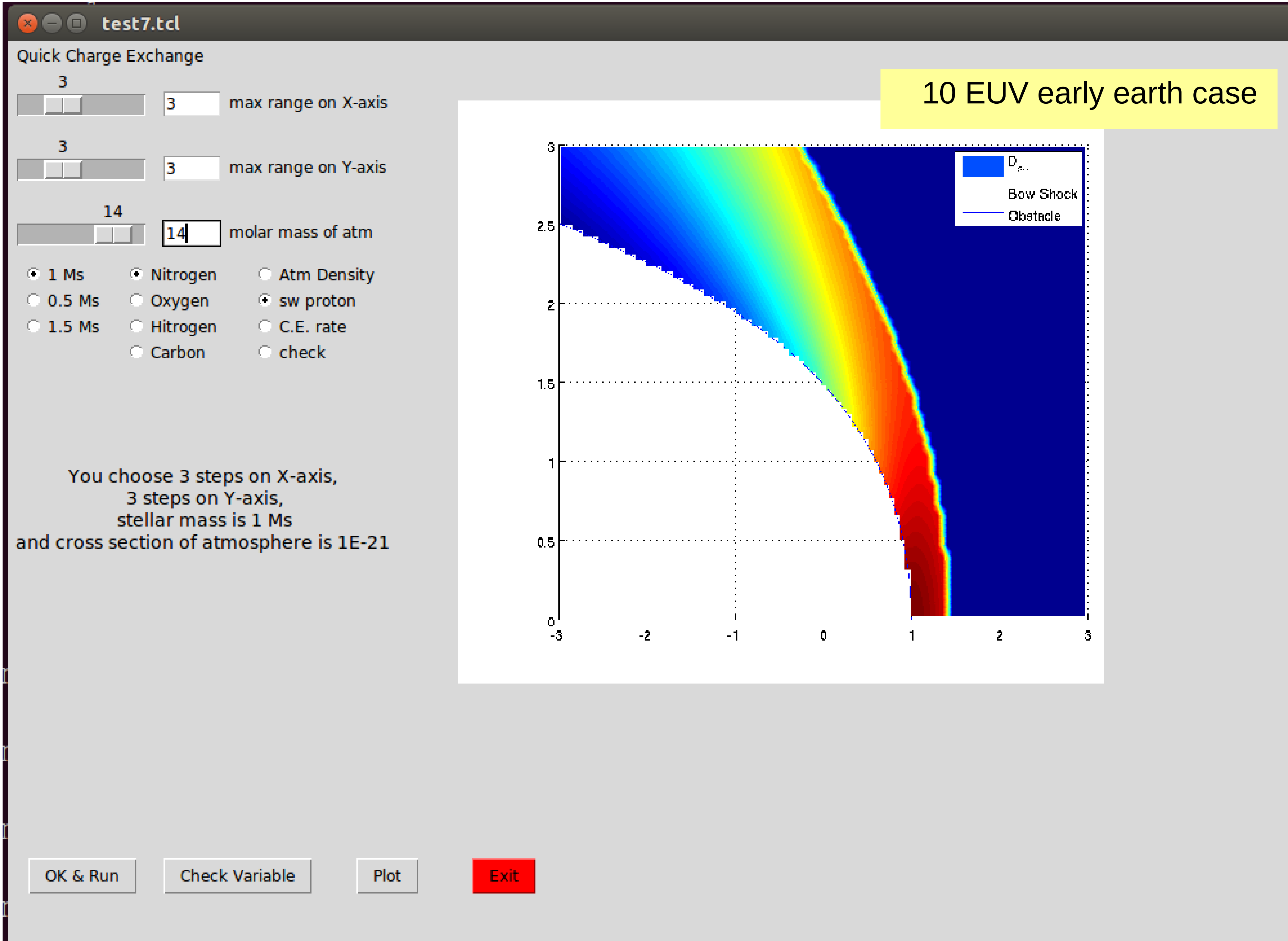

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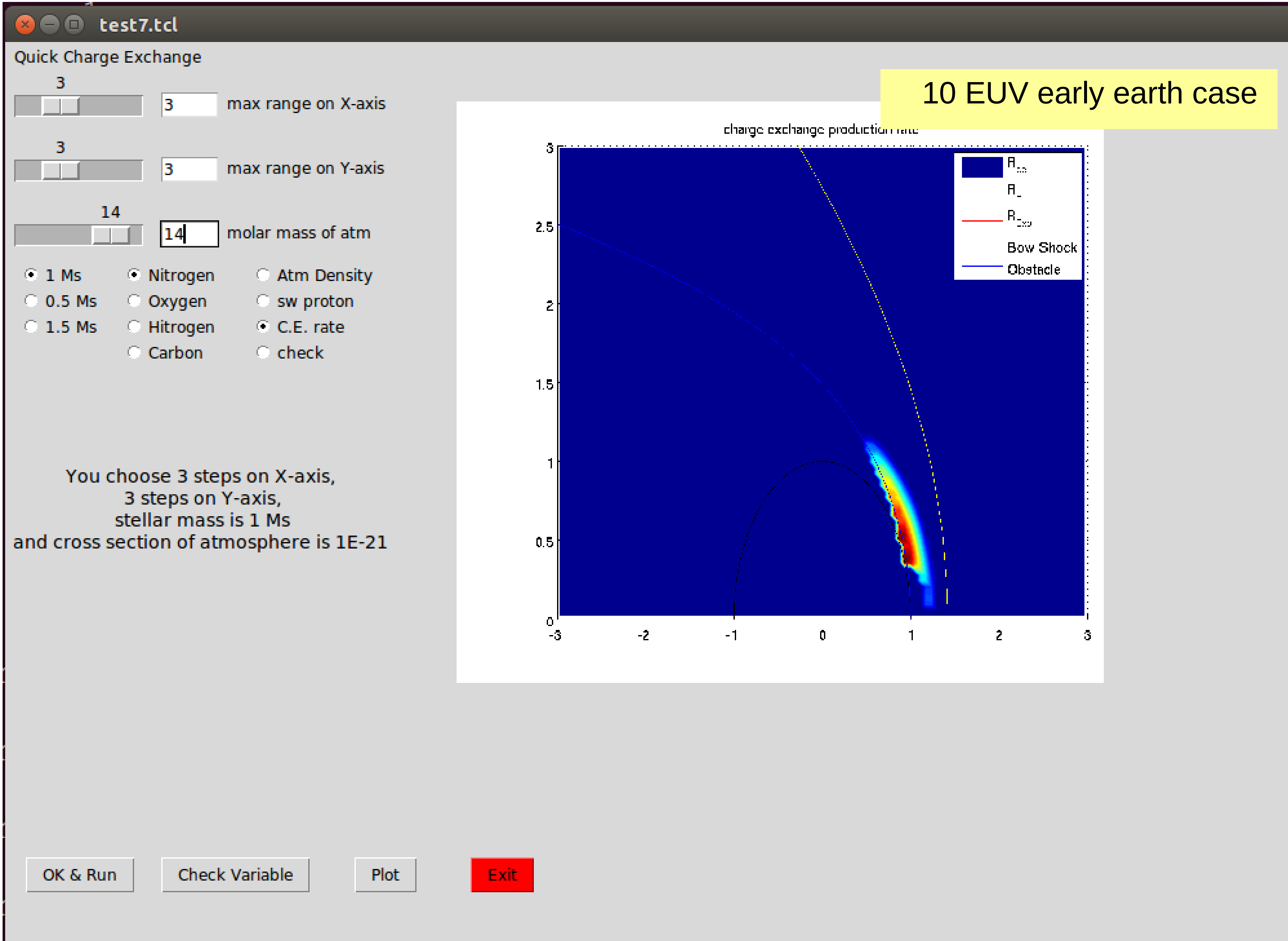

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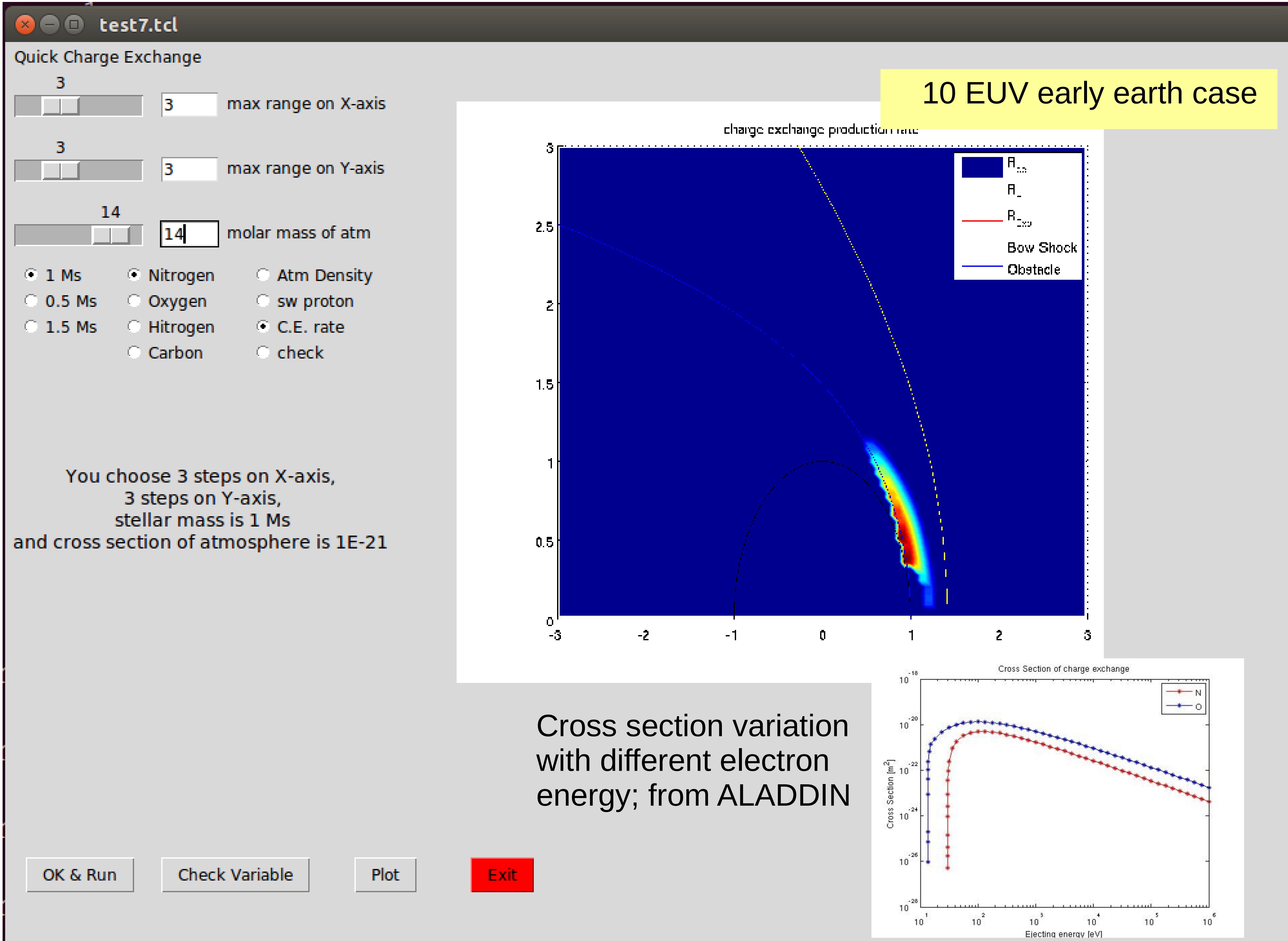
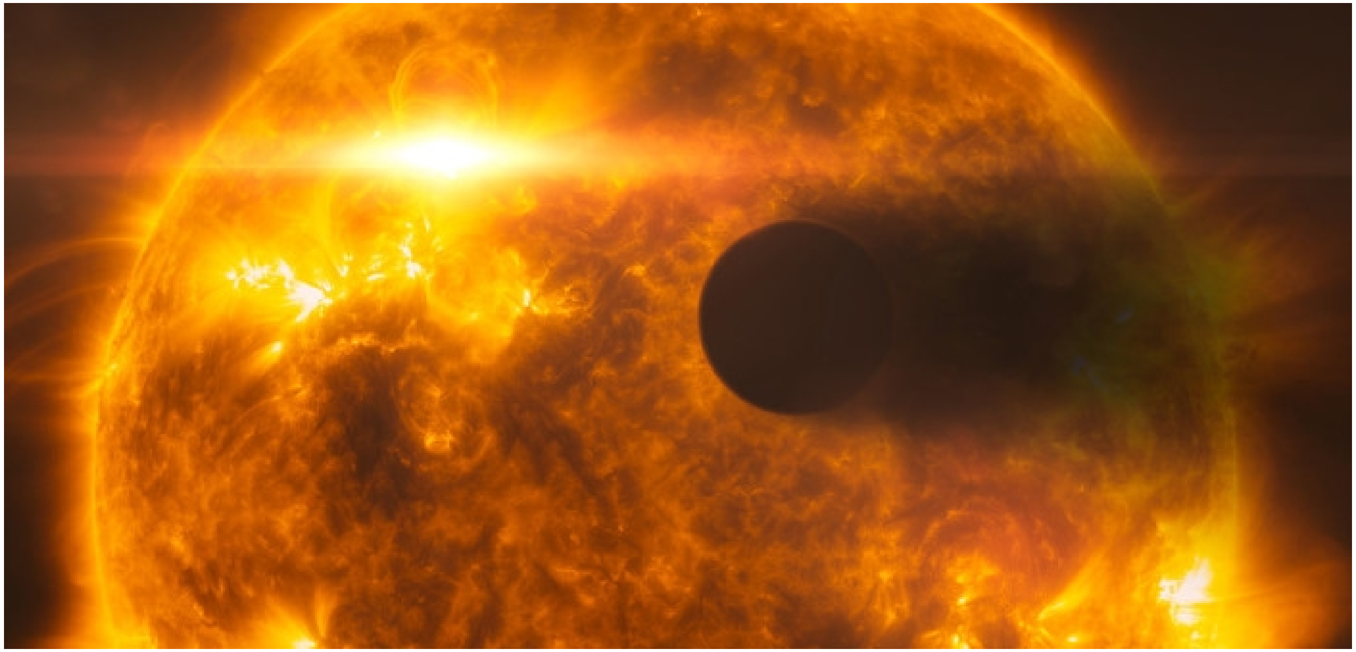


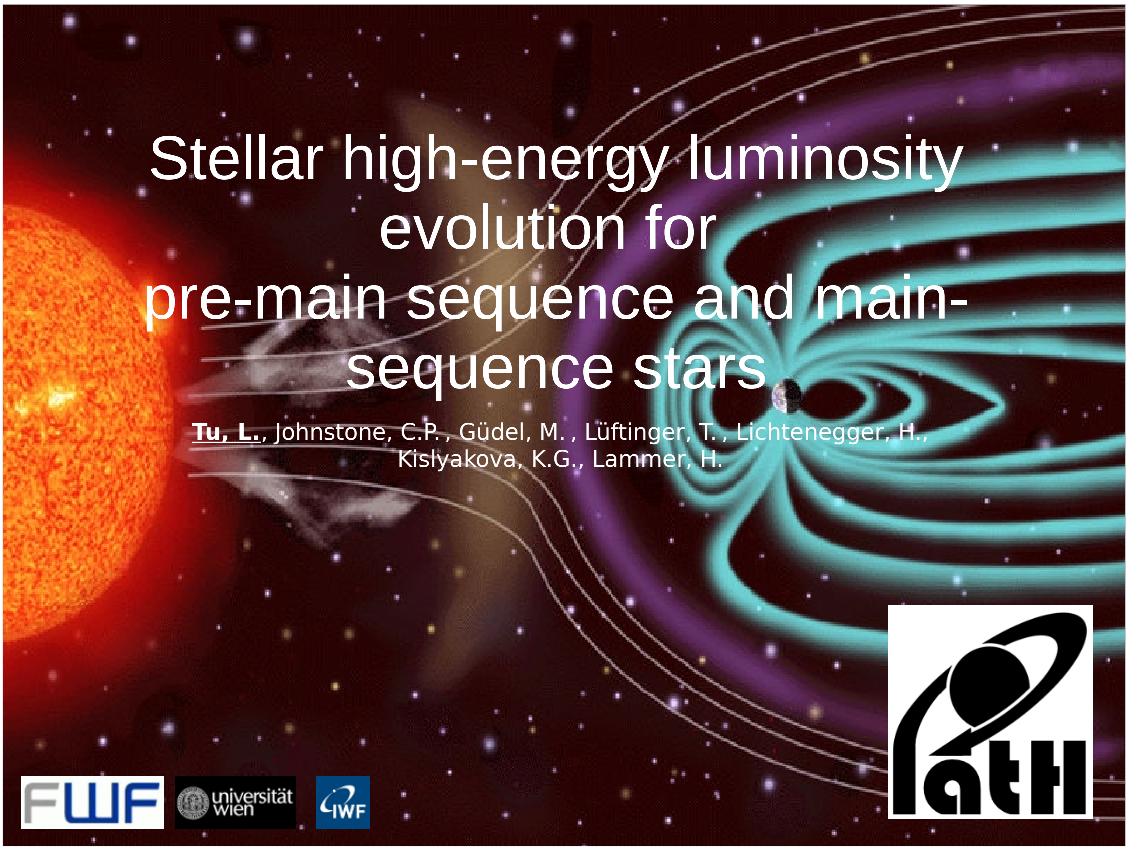
Cross section variation with different electron energy; from ALADDIN

Conclusions

- X-ray and EUV are believed to be driven by dynamo motion, which is thought to be driven by differential rotation.
- Rotation, stellar activities, and stellar wind all decay with stellar age.
- Non-thermal loss on terrestrial planetary upper atmosphere relates to the environment. Star’s initial rotation rate –and the subsequent rotational evolution– is an important aspect that needs to be properly considered when studying the evolution of the atmospheres of terrestrial planets.

Thank you for attention!

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FWF
universität wien
IWF

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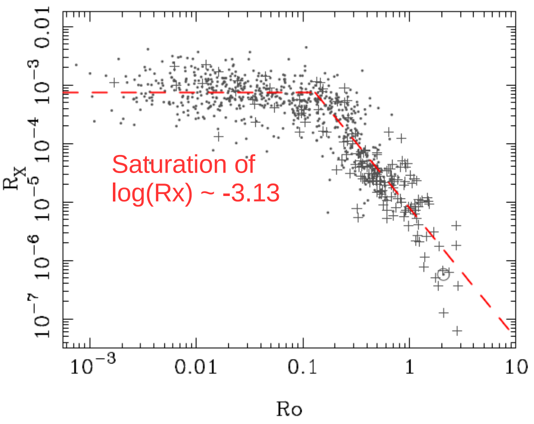

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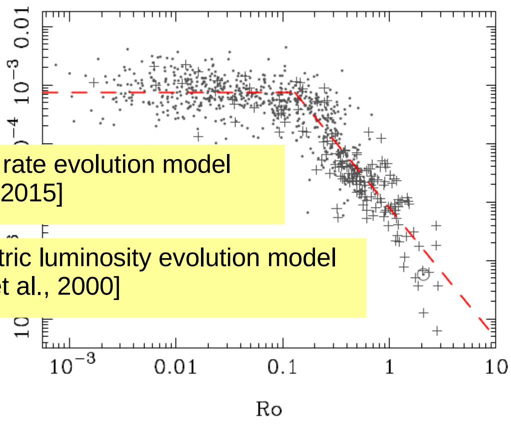
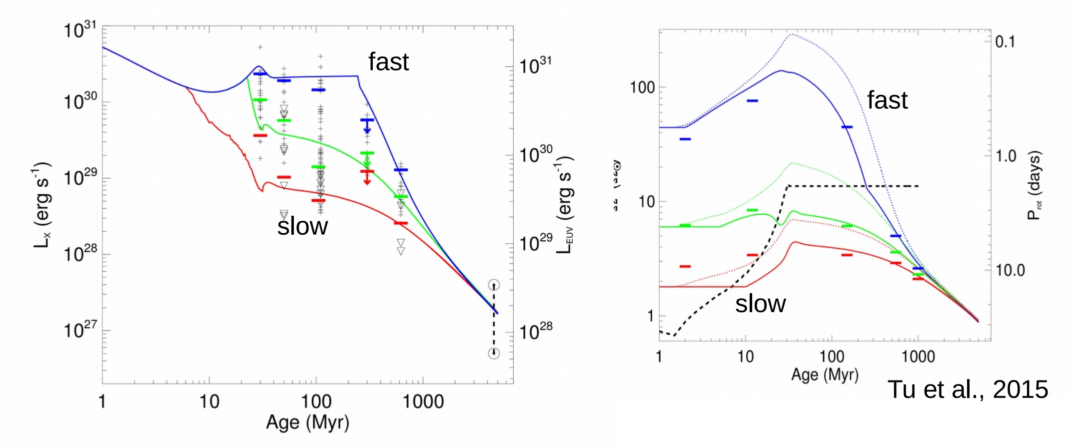


Solar radiation evolution



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- 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

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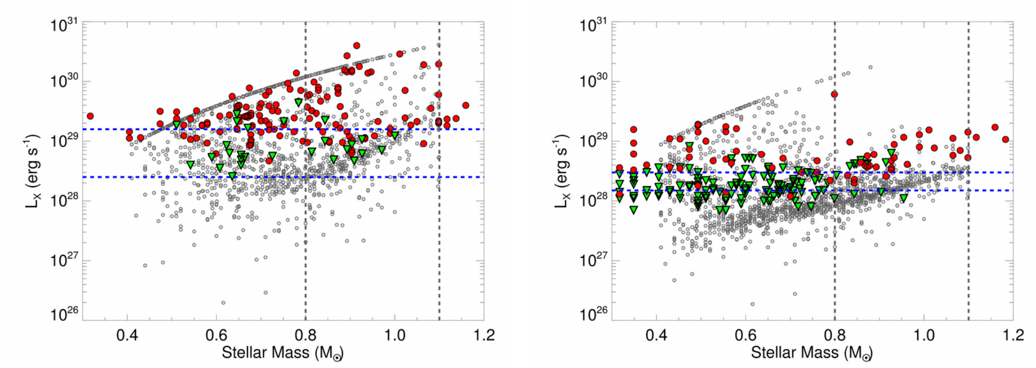

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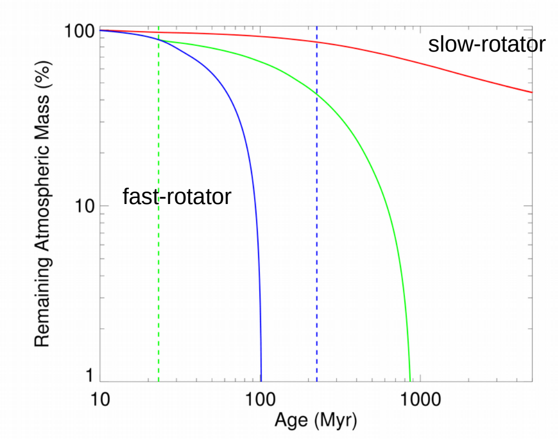

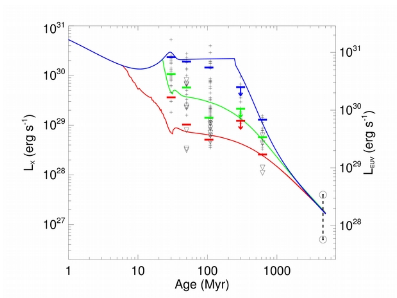

Escape mechanisms

- Thermal escape
  - → Jeans escape
  - → Jeans parameter

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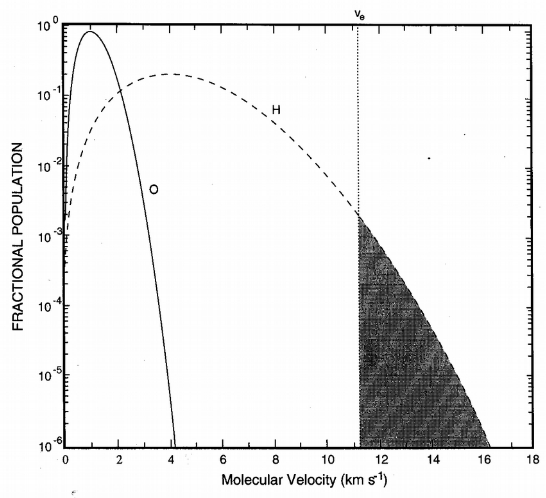


Figure 1.6 Boltzmann distribution of velocities for a molecular ensemble of oxygen atoms and hydrogen atoms. Escape velocity v_e for earth also indicated.

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:

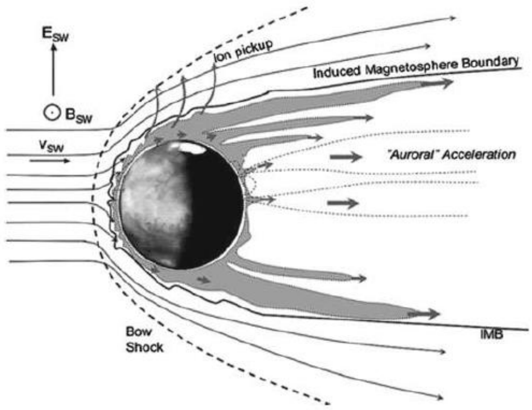
represents the ratio of the gravitational energy to the mean thermal energy of the particle, along with the number

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

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

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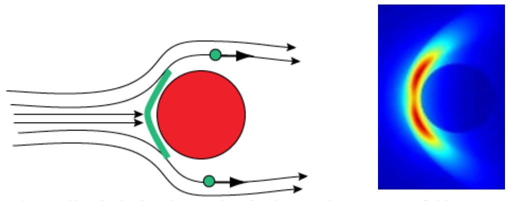

Solar wind hits high-altitude particles of a planet with no magnetic field

$$O^+ + O \rightarrow O + O^+$$
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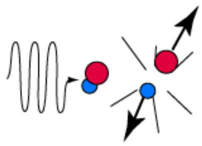
Charge exchange on Venus

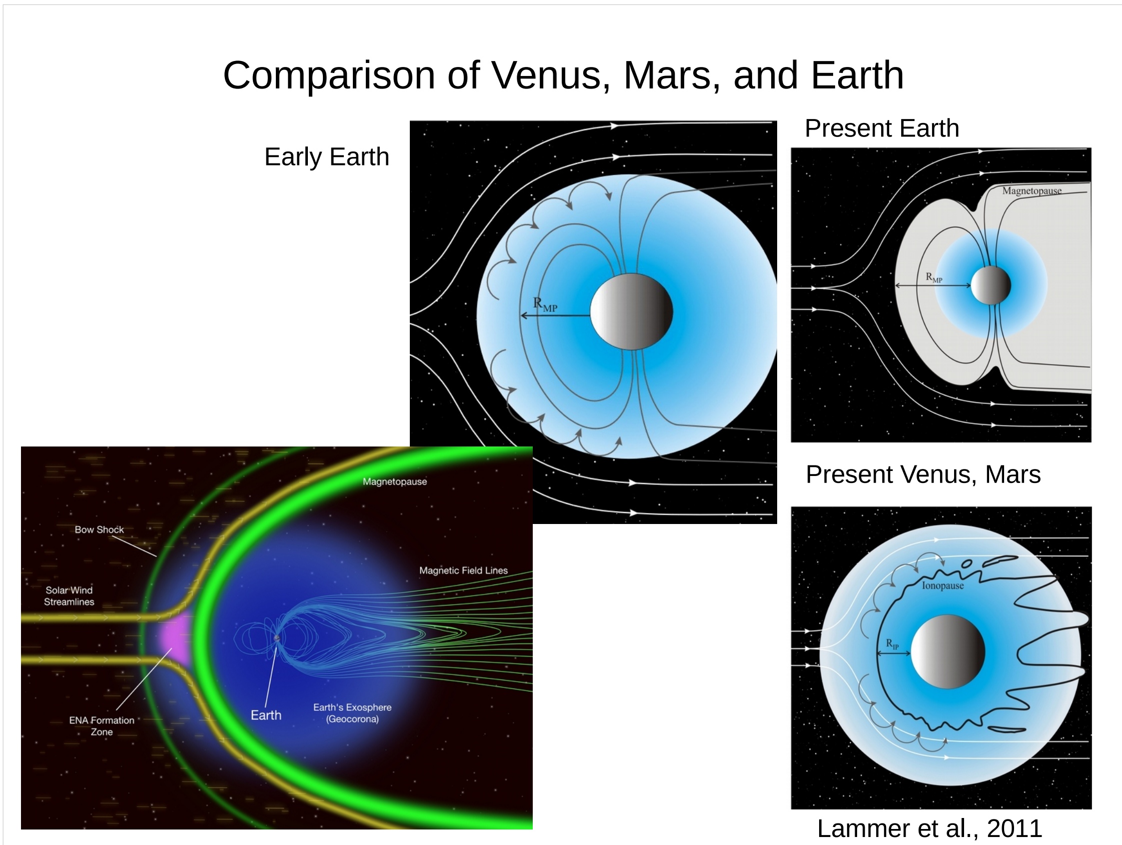


High-energy sunlight breaks apart molecules into higher-speed atoms

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



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 (~500 Myr)
  - -high EUV
  - -low gravity
  - -Hydrodynamic flow regime
  - -dragged heavier species such as O and C atoms
- Second epoch (~4–4.3 Gyr ago)
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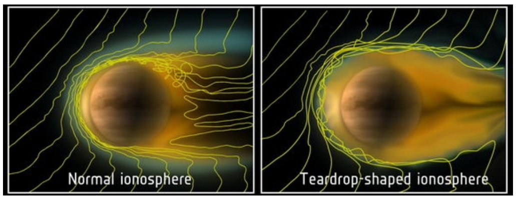

The evolution and escape of the martian atmosphere and the planet's water inventory can be separated into an early and late evolutionary epoch. The first epoch started from the planet's origin and lasted ∼ 500 Myr. Because of the high EUV flux of the young
Sun and Mars' low gravity it was accompanied 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

Heating & Cooling processes

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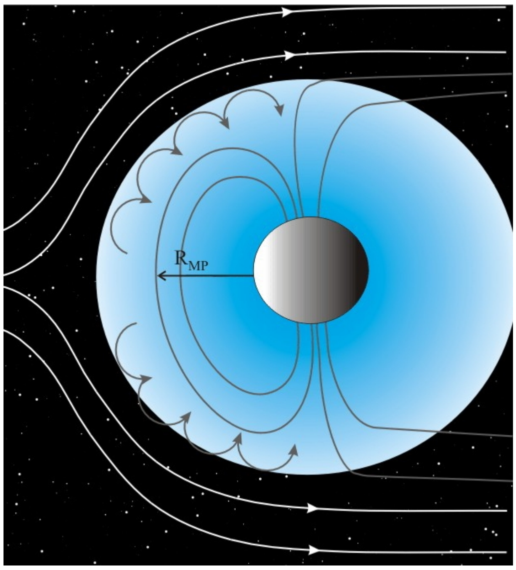
  → vibrational-rotational bands of atmospheric ions



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

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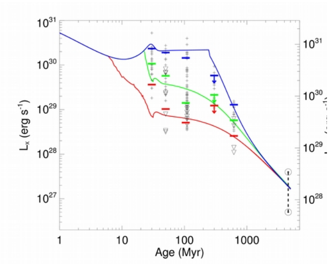
- Adiabatic cooling after 5 EUV



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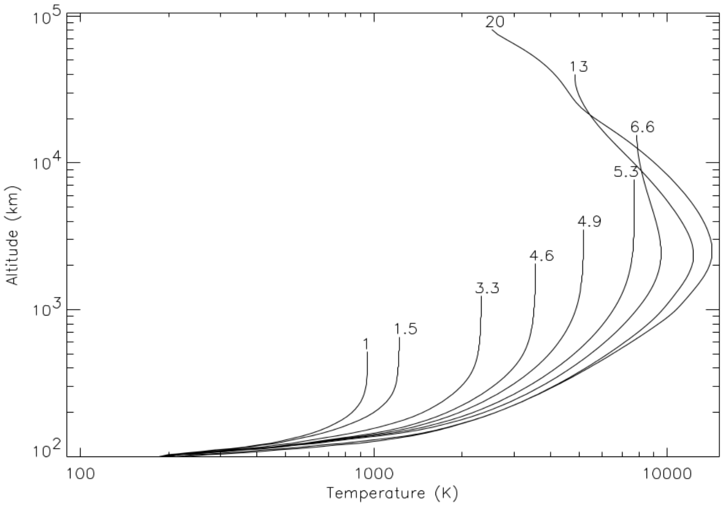


Tian et al., 2008

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

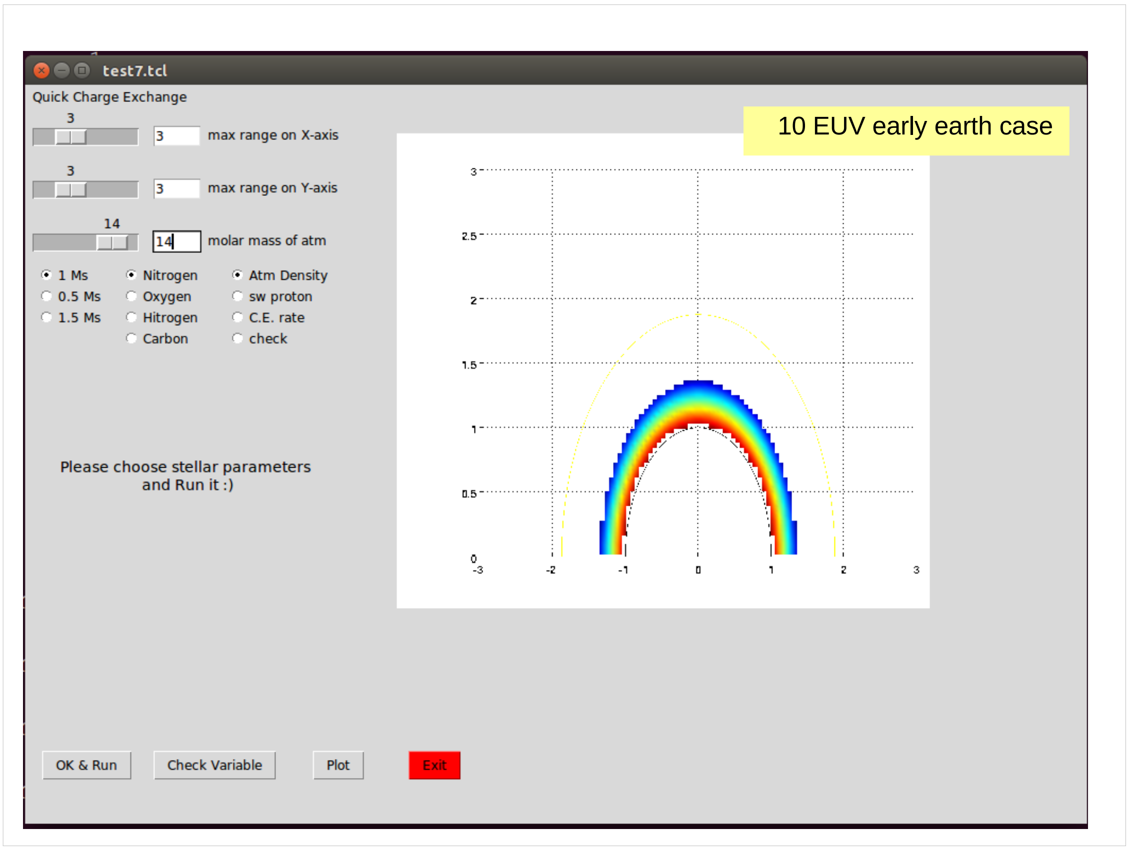
the entire thermosphere should have experienced hydrodynamic flow.

The Joule heating term in the model is included by

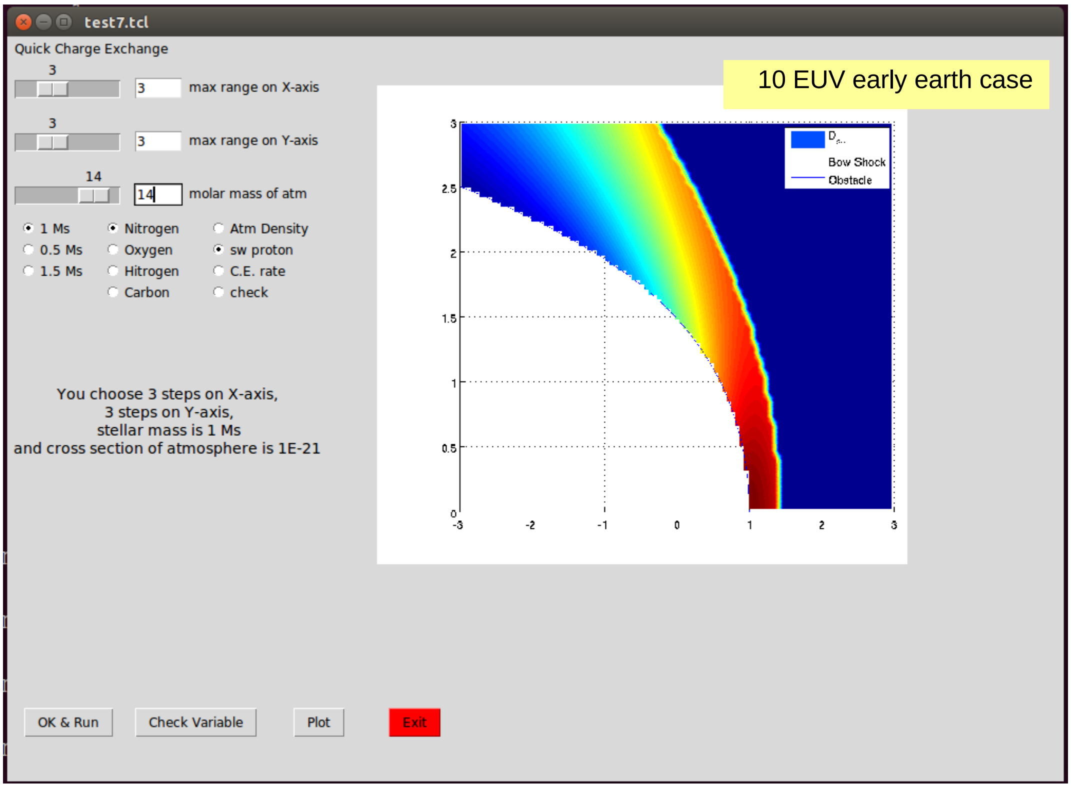
specifying an externally applied electric field (assumed

constant with height) and calculating the Pedersen conduc-

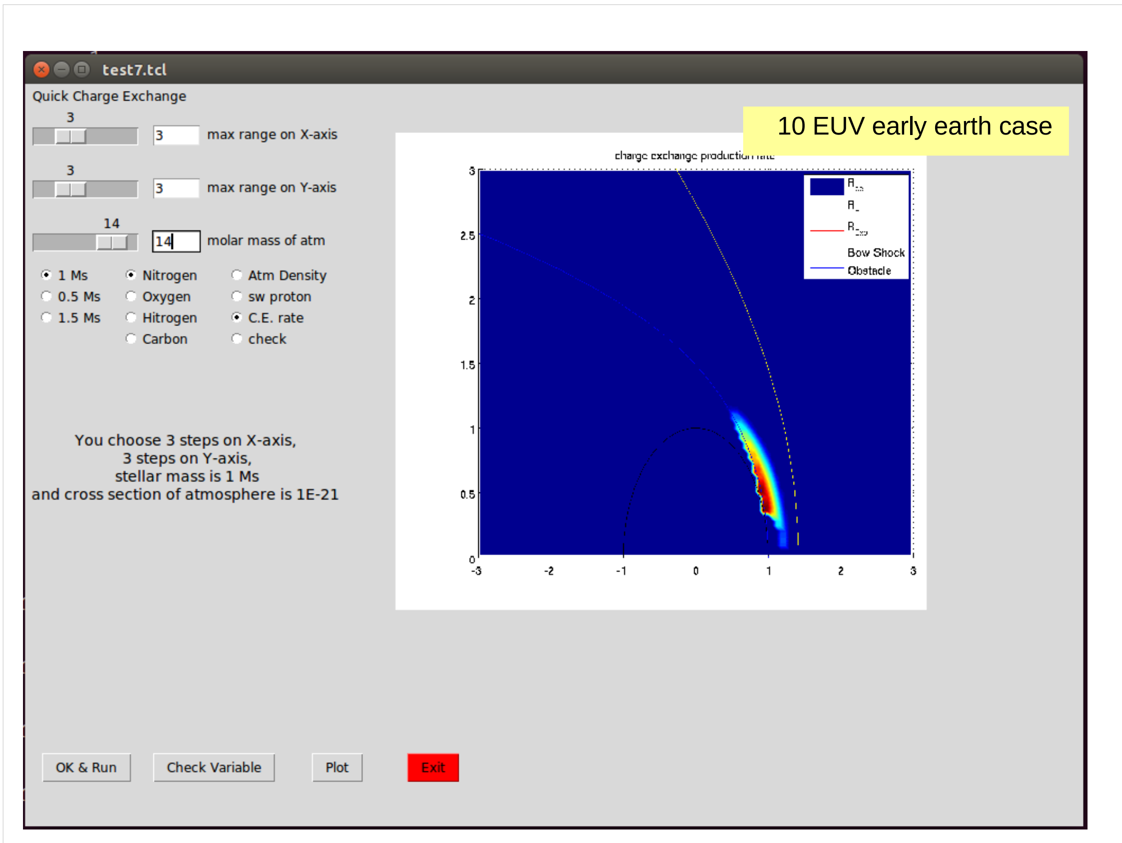
tivity.



test7.tcl
Quick Charge Exchange
3
3
max range on X-axis
3
3
max range on Y-axis
14
14
molar mass of atm
1 Ms
0.5 Ms
1.5 Ms
Nitrogen
Oxygen
Hitrogen
Carbon
Atm Density
sw proton
C.E. rate
check
Please choose stellar parameters
and Run it :)
10 EUV early earth case
OK & Run
Check Variable
Plot
Exit



test7.tcl
Quick Charge Exchange
3
max range on X-axis
3
max range on Y-axis
14
molar mass of atm
1 Ms
0.5 Ms
1.5 Ms
Nitrogen
Oxygen
Hitrogen
Carbon
Atm Density
sw proton
C.E. rate
check
You choose 3 steps on X-axis,
3 steps on Y-axis,
stellar mass is 1 Ms
and cross section of atmosphere is 1E-21
10 EUV early earth case
Bow Shock
Obstacle
OK & Run
Check Variable
Plot
Exit


test7.tcl
Quick Charge Exchange
3
3
max range on X-axis
3
3
max range on Y-axis
14
14
molar mass of atm
1 Ms
0.5 Ms
1.5 Ms
Nitrogen
Oxygen
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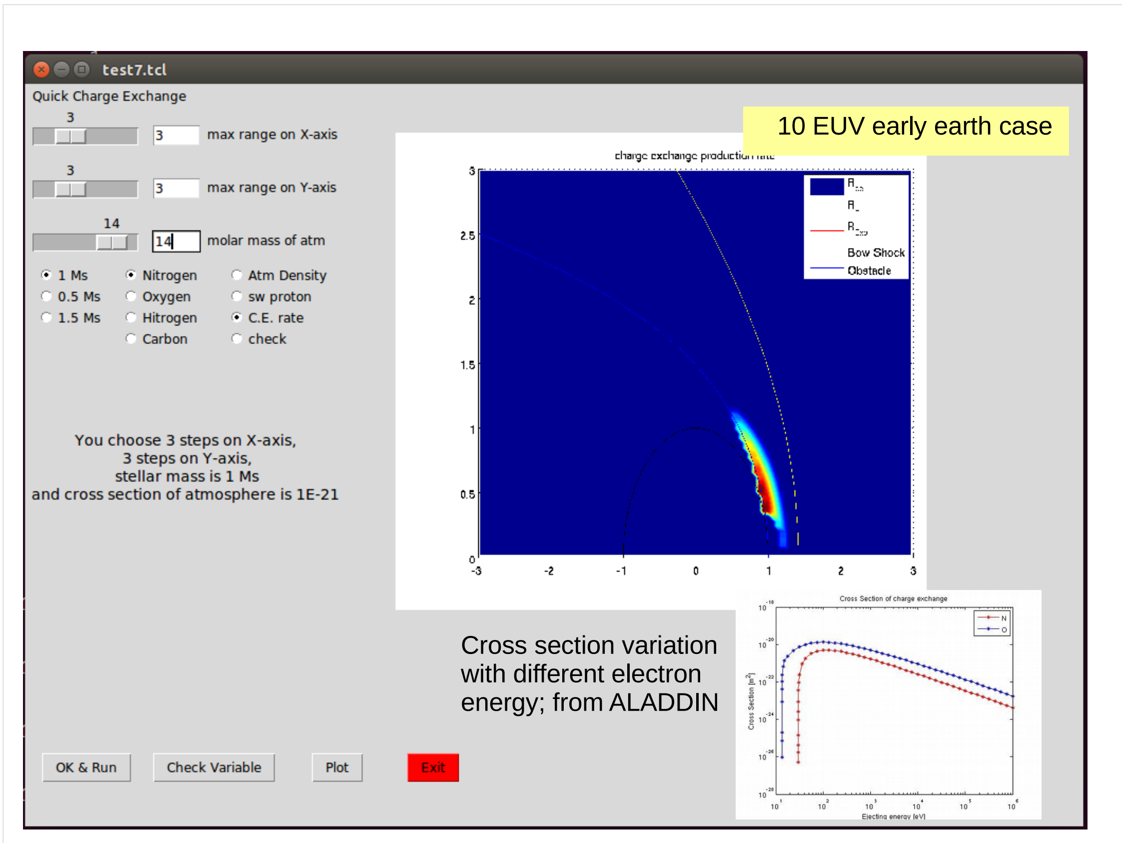
C.E. rate
check
You choose 3 steps on X-axis,
3 steps on Y-axis,
stellar mass is 1 Ms
and cross section of atmosphere is 1E-21
10 EUV early earth case
Bow Shock
Obstacle
OK & Run
Check Variable
Plot
Exit


test7.tcl
Quick Charge Exchange
3
3
max range on X-axis
3
3
max range on Y-axis
14
14
molar mass of atm
1 Ms
0.5 Ms
1.5 Ms
Nitrogen
Oxygen
Hitrogen
Carbon
Atm Density
sw proton
C.E. rate
check
You choose 3 steps on X-axis,
3 steps on Y-axis,
stellar mass is 1 Ms
and cross section of atmosphere is 1E-21
OK & Run
Check Variable
Plot
Exit
10 EUV early earth case
Bow Shock
Obstacle
Cross section variation
with different electron
energy; from ALADDIN
Cross Section of charge exchange
N
O
Electing energy [eV]

Conclusions

- X-ray and EUV are believed to be driven by dynamo motion, which is thought to be driven by differential rotation.
- Rotation, stellar activities, and stellar wind all decay with stellar age.
- Non-thermal loss on terrestrial planetary upper atmosphere relates to the environment. Star’s initial rotation rate –and the subsequent rotational evolution– is an important aspect that needs to be properly considered when studying the evolution of the atmospheres of terrestrial planets.

Thank you for attention!