Investigating Core Induction Effect on Atmospheric Escape from Rocky Exoplanets and Implications for Habitability

Laura Chin[1], Chuanfei Dong[1], Yuxi Chen[2]

[1] Department of Astronomy, Boston University, Boston, MA
[2] Department of Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, MI

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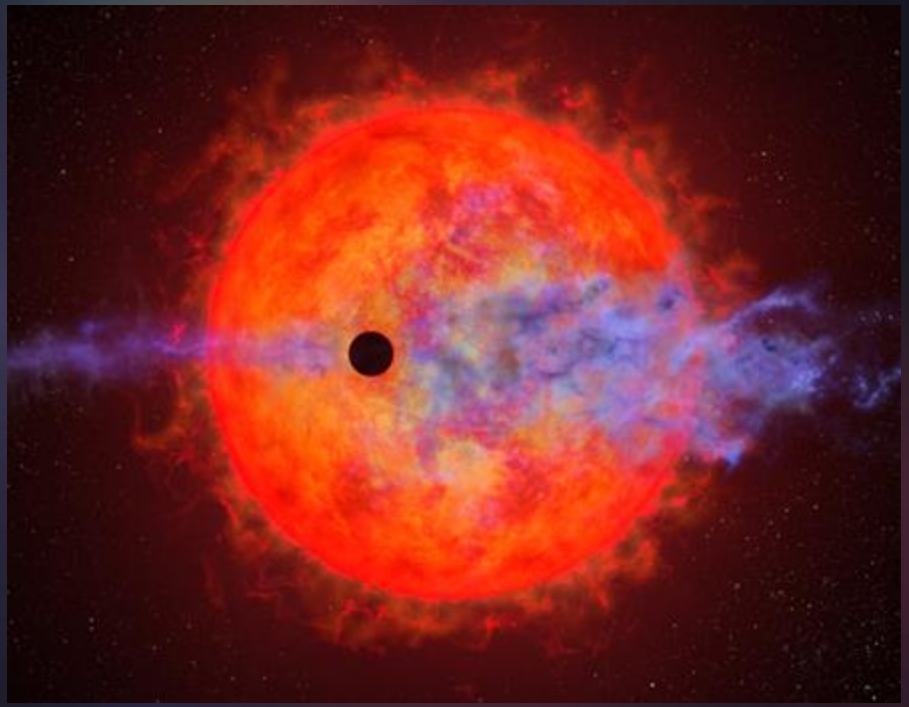
Background & Motivation

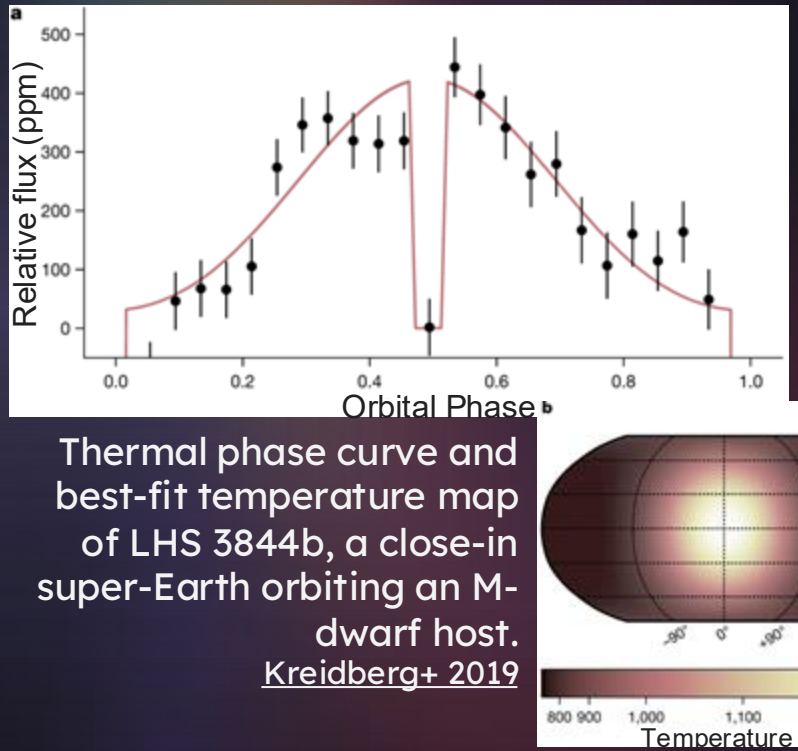
- Atmospheres are a key characteristic of habitable rocky worlds
  - Atmosphere must be sustained over long time periods
- **Nonthermal atmospheric ion escape**
  - Stellar wind erodes ions from upper atmosphere



Artist's concept of atmospheric loss from an exoplanet orbiting an M-dwarf host star. NASA, ESA, Joseph Olmsted (STScI)

Background & Motivation

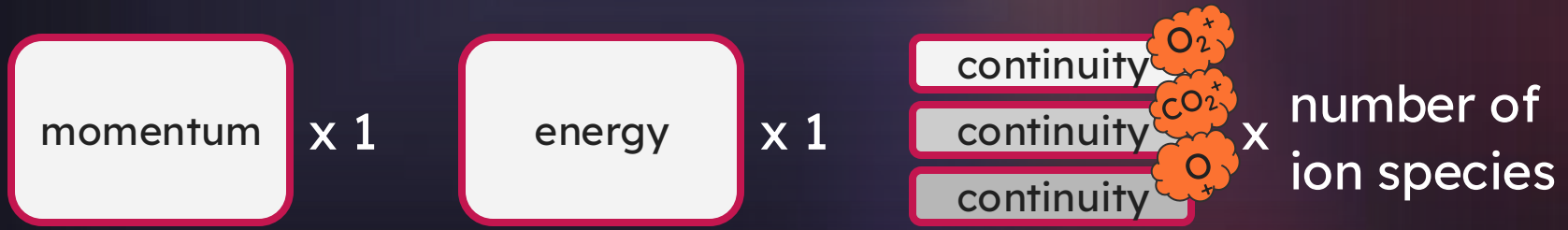
- Statistical trends emerge from 6,000+ confirmed exoplanets
  - Radius valley
  - Trends for terrestrial ($R<2R_E$) planets?
- Campaigns to observe rocky exoplanet atmospheres (JWST)
- **What types of rocky exoplanets are most vulnerable to atmospheric ion loss?**



Thermal phase curve and best-fit temperature map of LHS 3844b, a close-in super-Earth orbiting an M-dwarf host.
Kreidberg+ 2019

Methods

- MHD code: **BATS-R-US**
  - MHD component of Space Weather Modeling Framework (SWMF)
- Multi-species Magnetohydrodynamics (MS-MHD)
  - Chemistry: photoionization, charge exchange, electron recombination
  - Separate ion species
  - Assume same bulk velocity + temperature in all plasma



Planetary System Parameters

Planetary Radius

Conducting Core Size

THE ASTROPHYSICAL JOURNAL LETTERS

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Role of Planetary Radius on Atmospheric Escape of Rocky Exoplanets

Laura Chin[1], Chuanfei Dong[1], and Manasvi Lingam[2,3]

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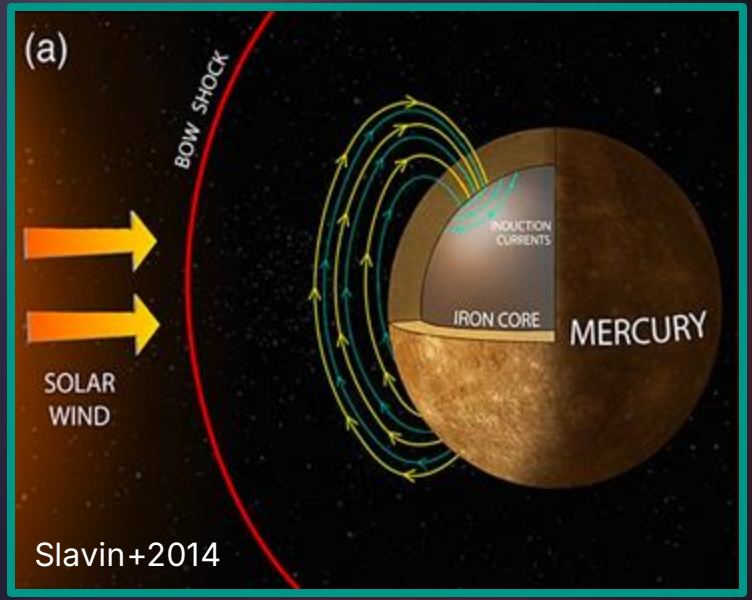
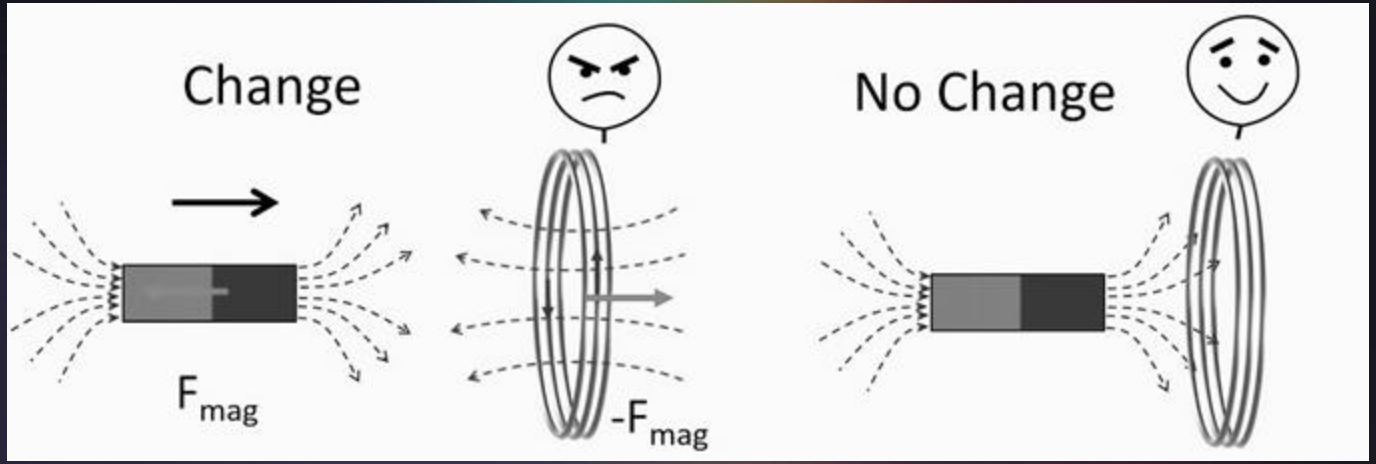


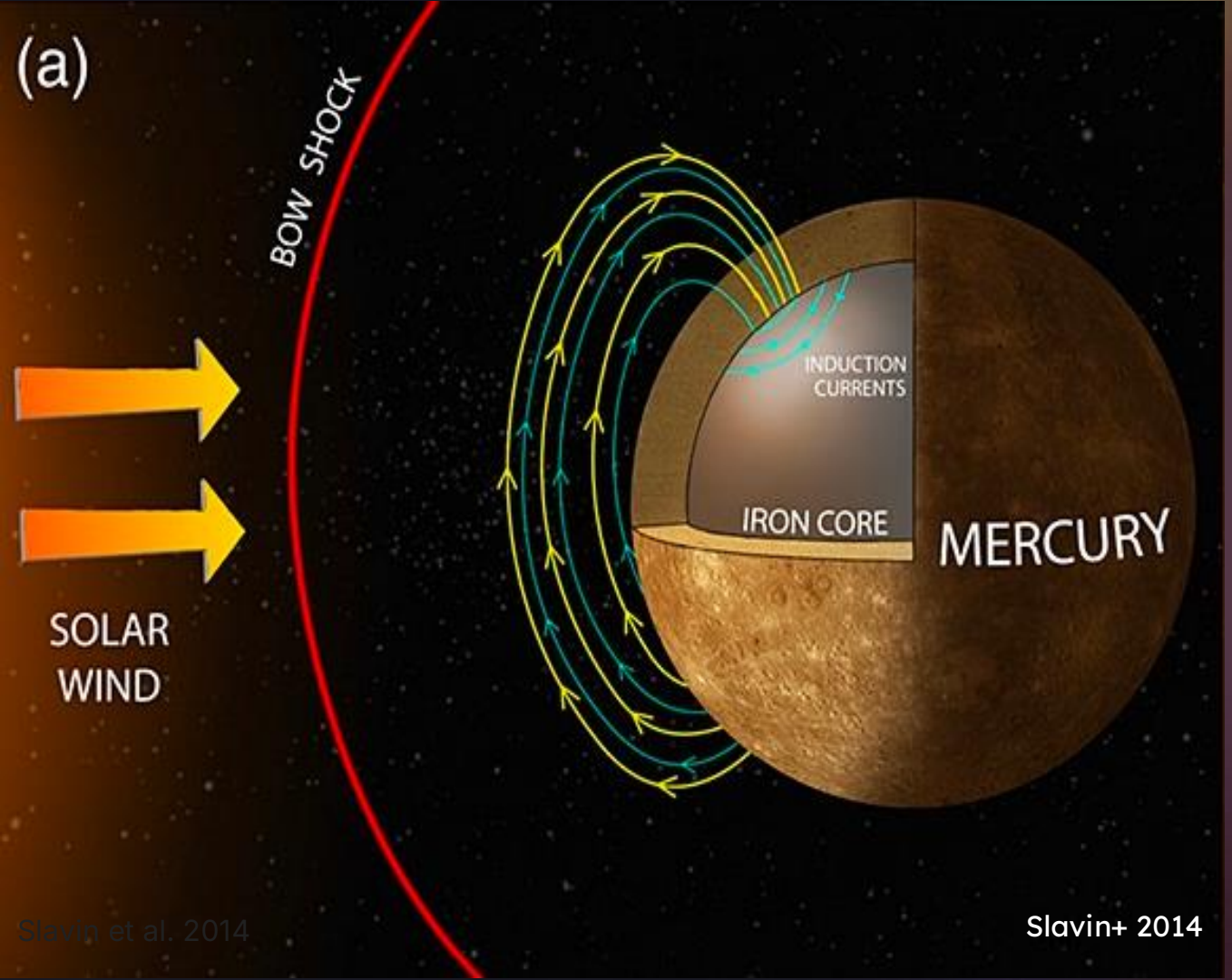
Lenz's Law



loop of conducting material experiences change in magnetic flux → conservation of flux → induced current flows through loop, generates opposing magnetic field

= conducting "loop"

= external magnetic field



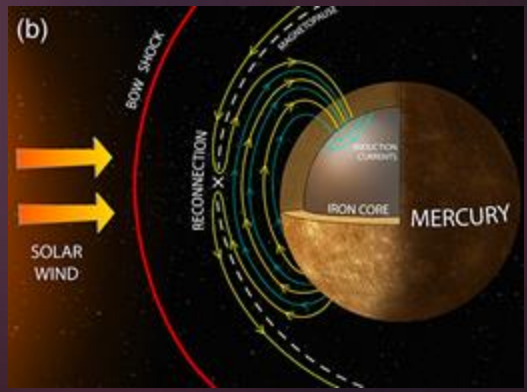
Slavin et al. 2014

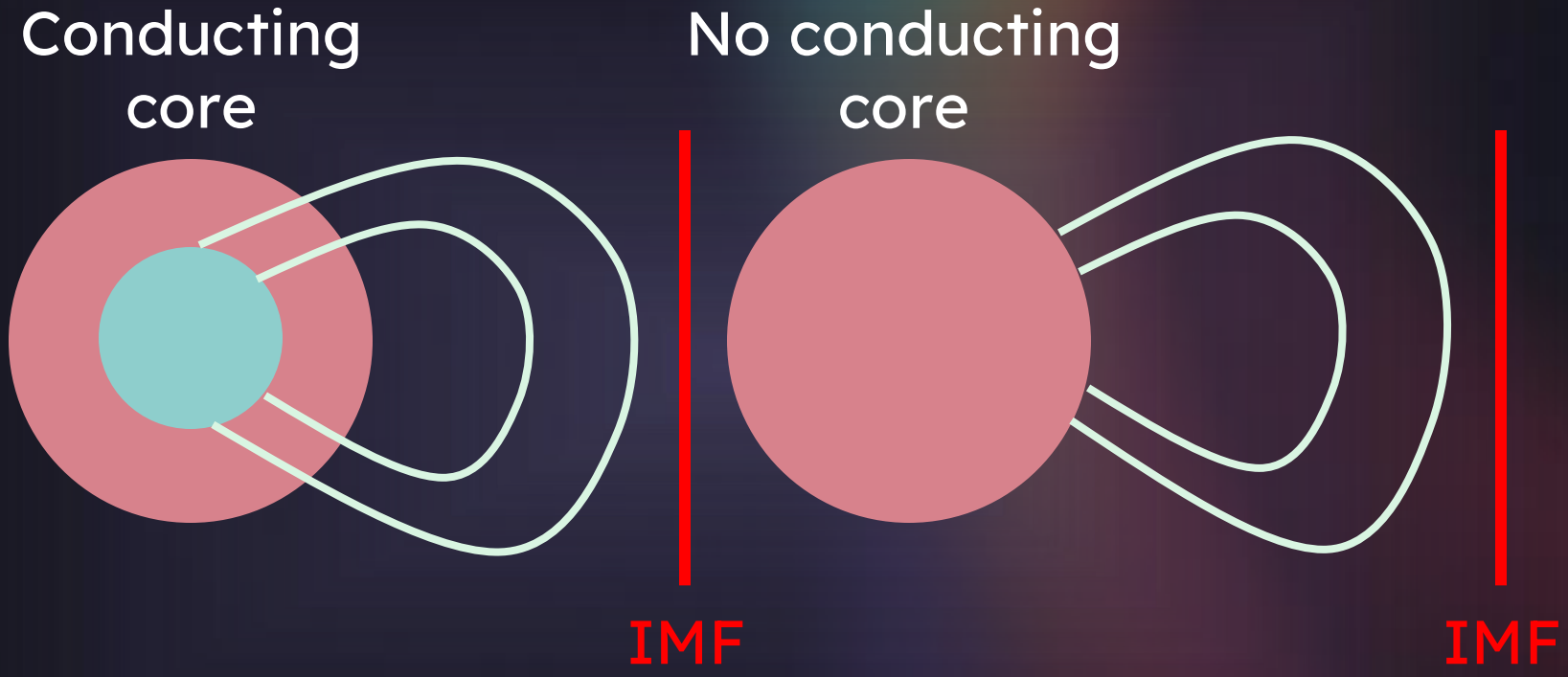
Slavin+ 2014

yellow lines = intrinsic B field

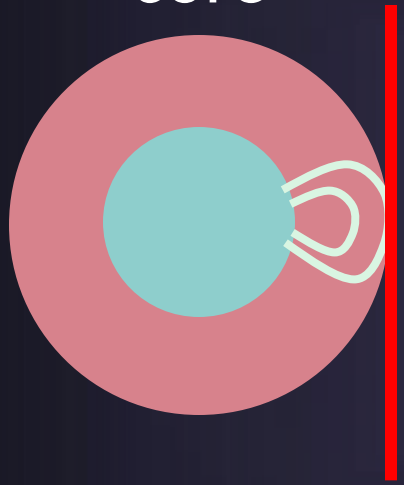
green lines = induced B field

note: reconnection can combat induction effect




Conducting core
No conducting core
IMF
IMF

Conducting core



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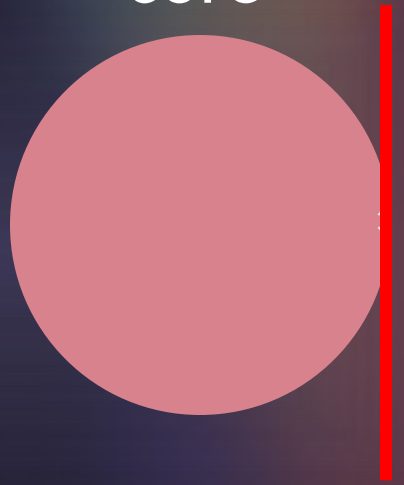
No conducting core



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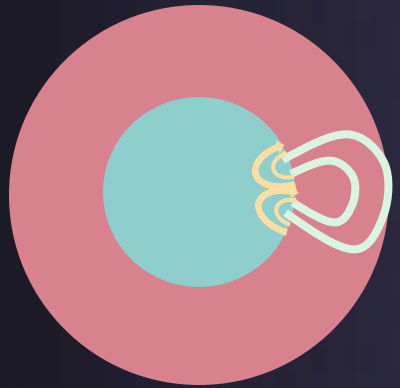
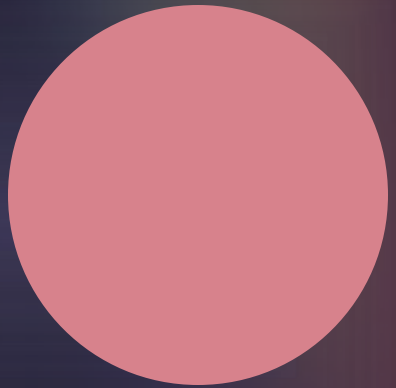
Conducting core



Induced current

No conducting core

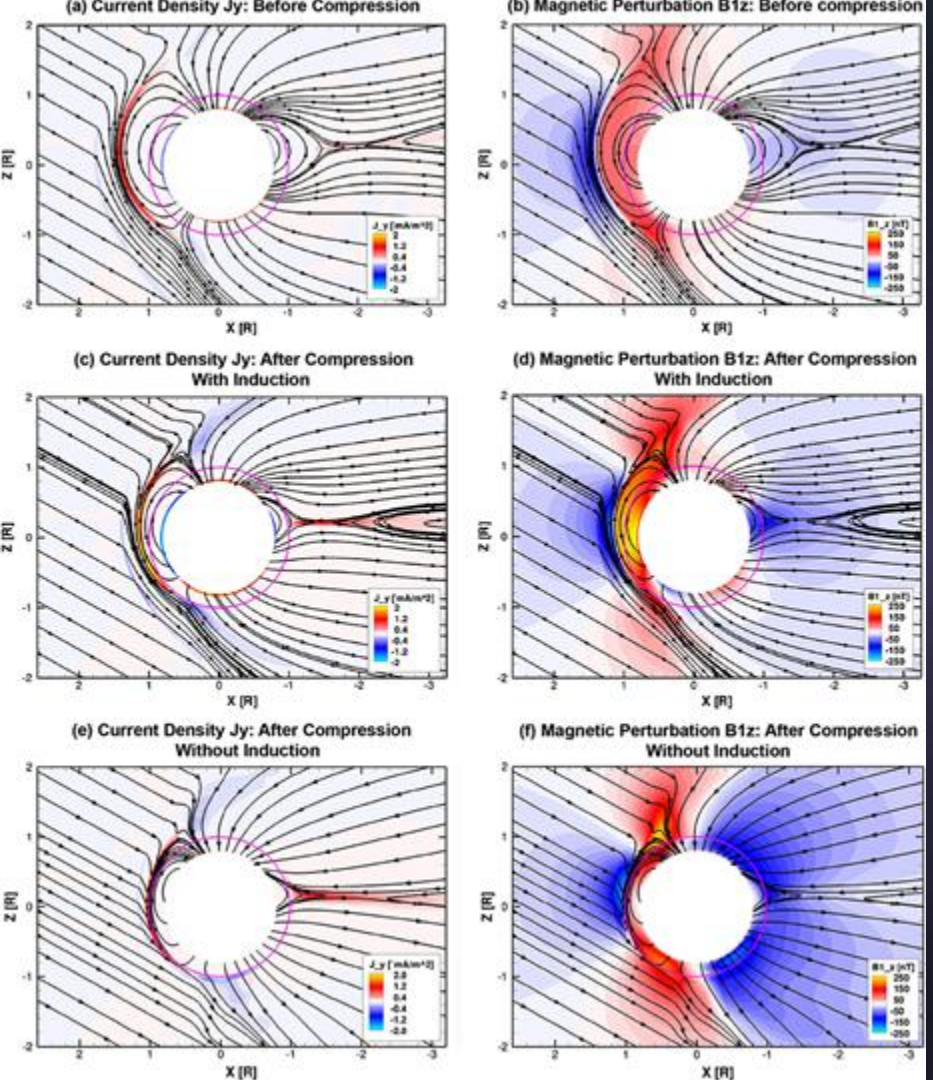


Conducting core

No conducting core

Dayside magnetosphere strengthened

Induced current



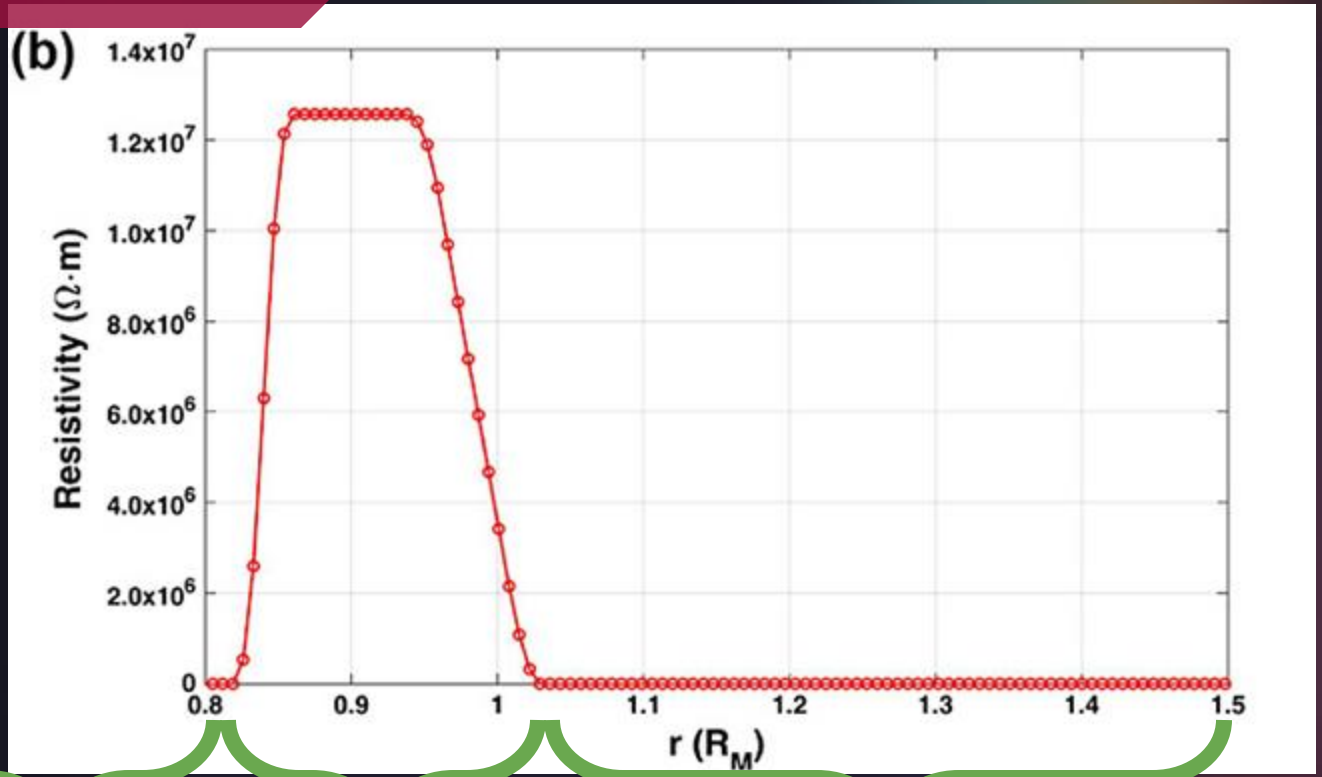
MHD study of induction effect in context of Mercury (no atmosphere)

Result: induction effect enhances magnetosphere in response to solar wind compression

Implications for atmospheric loss: are planets with larger cores better at protecting their atmospheres?

Jia+ 2015

Conducting Core



Resistivity profile

Inside planet (core)

Mantle
high resistivity

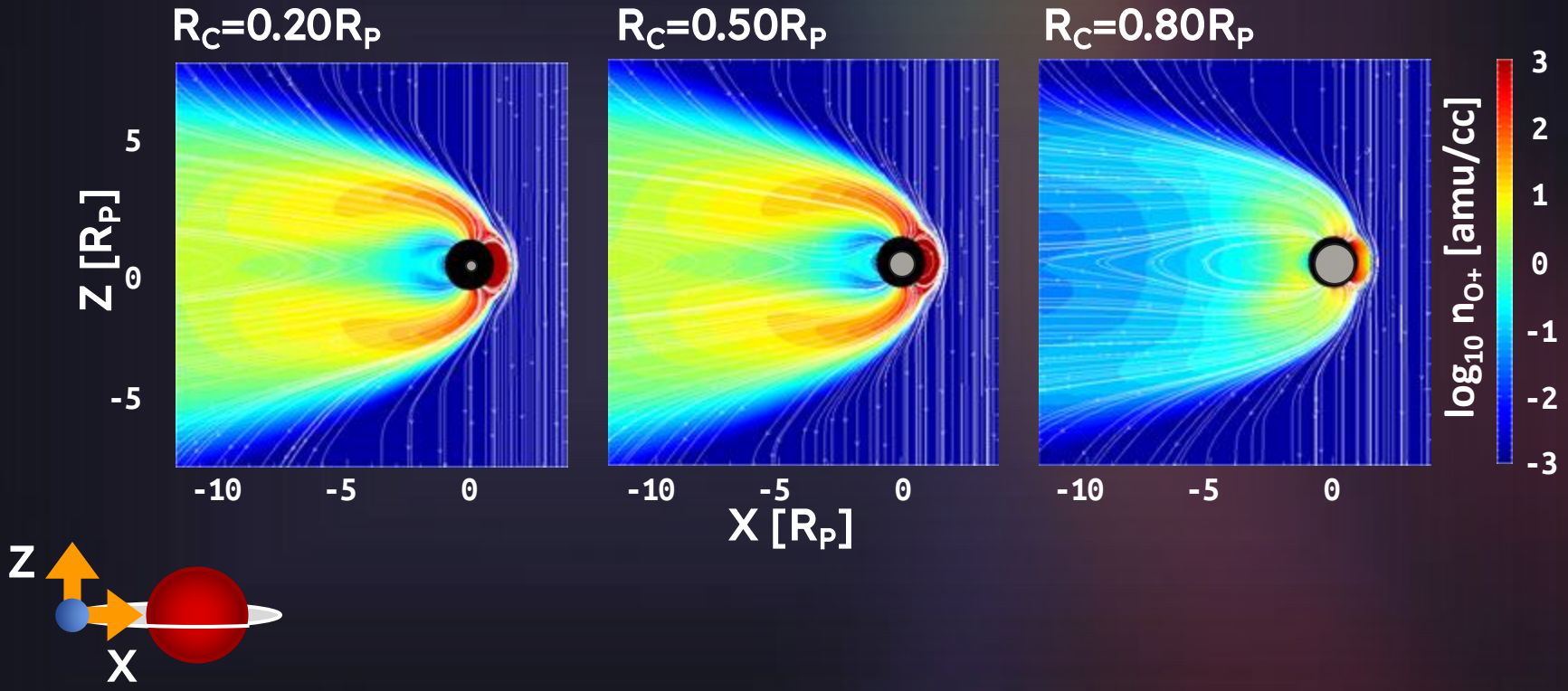
Outside planet

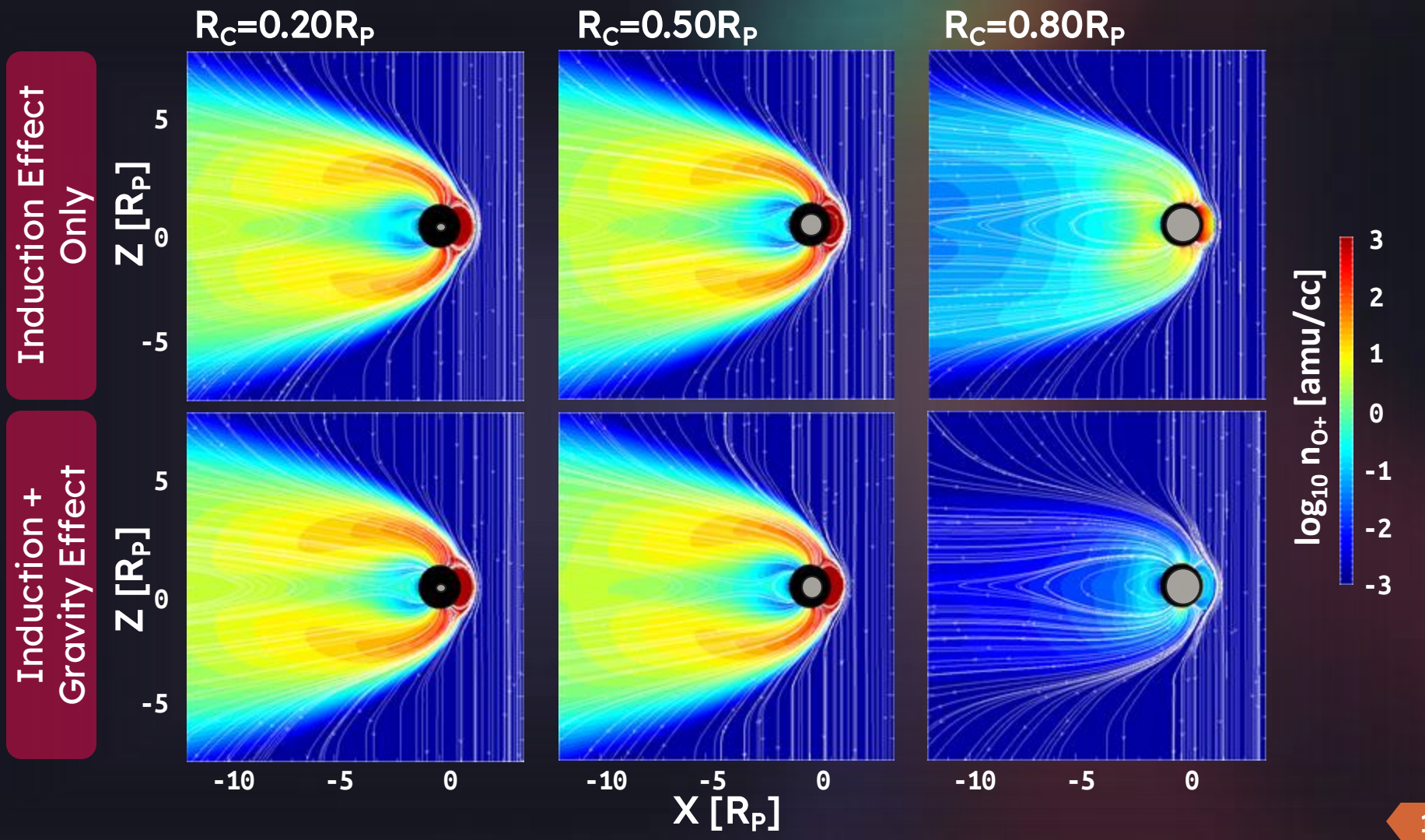
Conducting Core

		(Exo)Planet Analog
Stellar Wind	$n = 4245\ cm^{-3}$ $T = 10.0e5\ K$ $v = (-1937.5, 6.7, -13.0)\ km/s$ $B = (0, 23.0, -194.3)\ nT$	Early (~4 Gya) Solar CME event with 10x higher density
Mass*	$M = 1.29\ M_{Earth}$	Proxima Centauri b (PCb)
Radius	$R = 1.1\ R_{Earth}$	Earth, Venus, PCb
Core	$R_C =$ 20% 50% 80% R_P	Moon, Earth, Mercury
	Dipole = ½ Earth (15000 nT)	Early (~4 Gya) Earth
Atmosphere	Scale height = $0.85H_{Venus}$	PCb
	Composition = CO_2-dominated	Venus

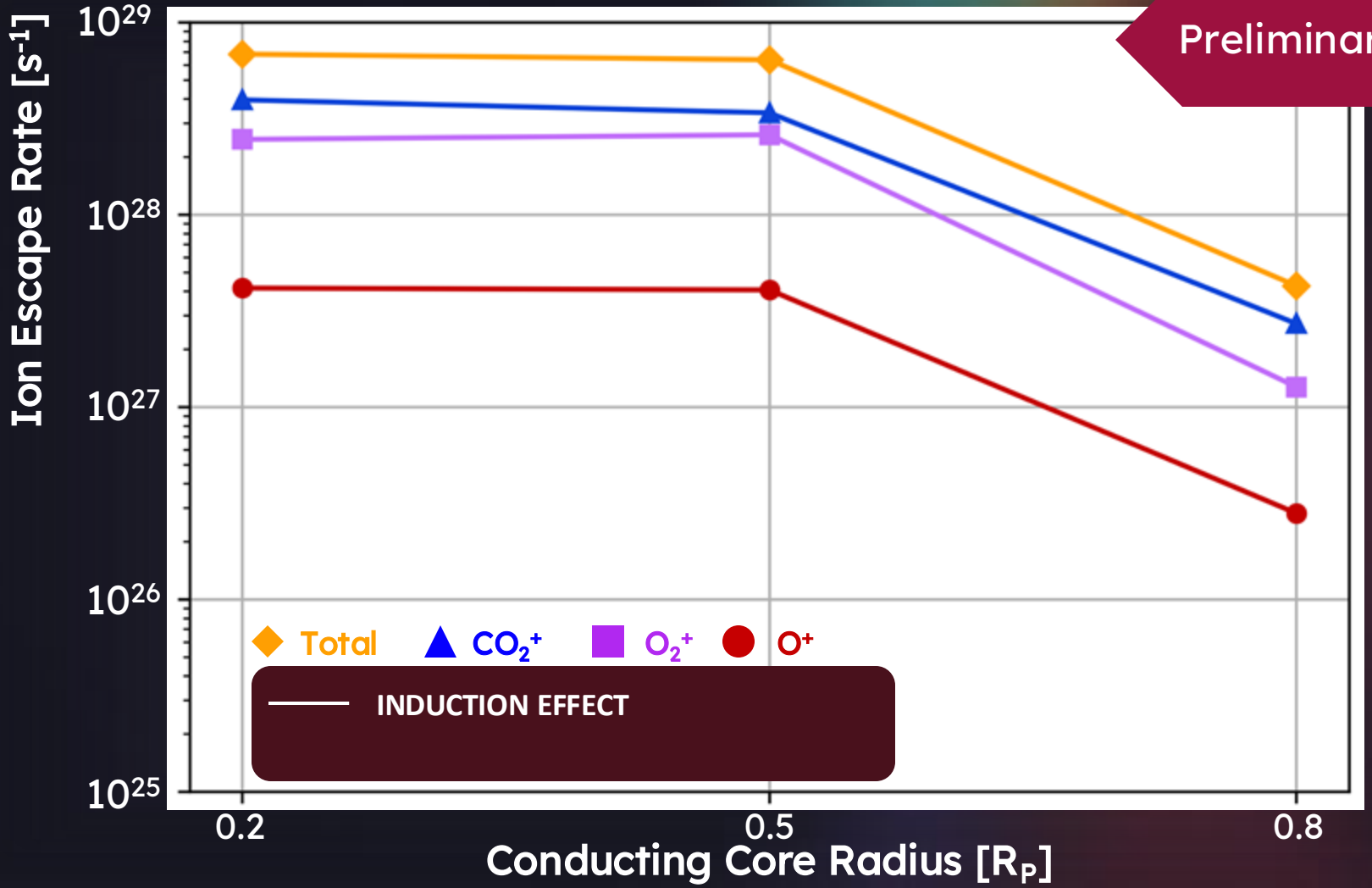
Conducting Core

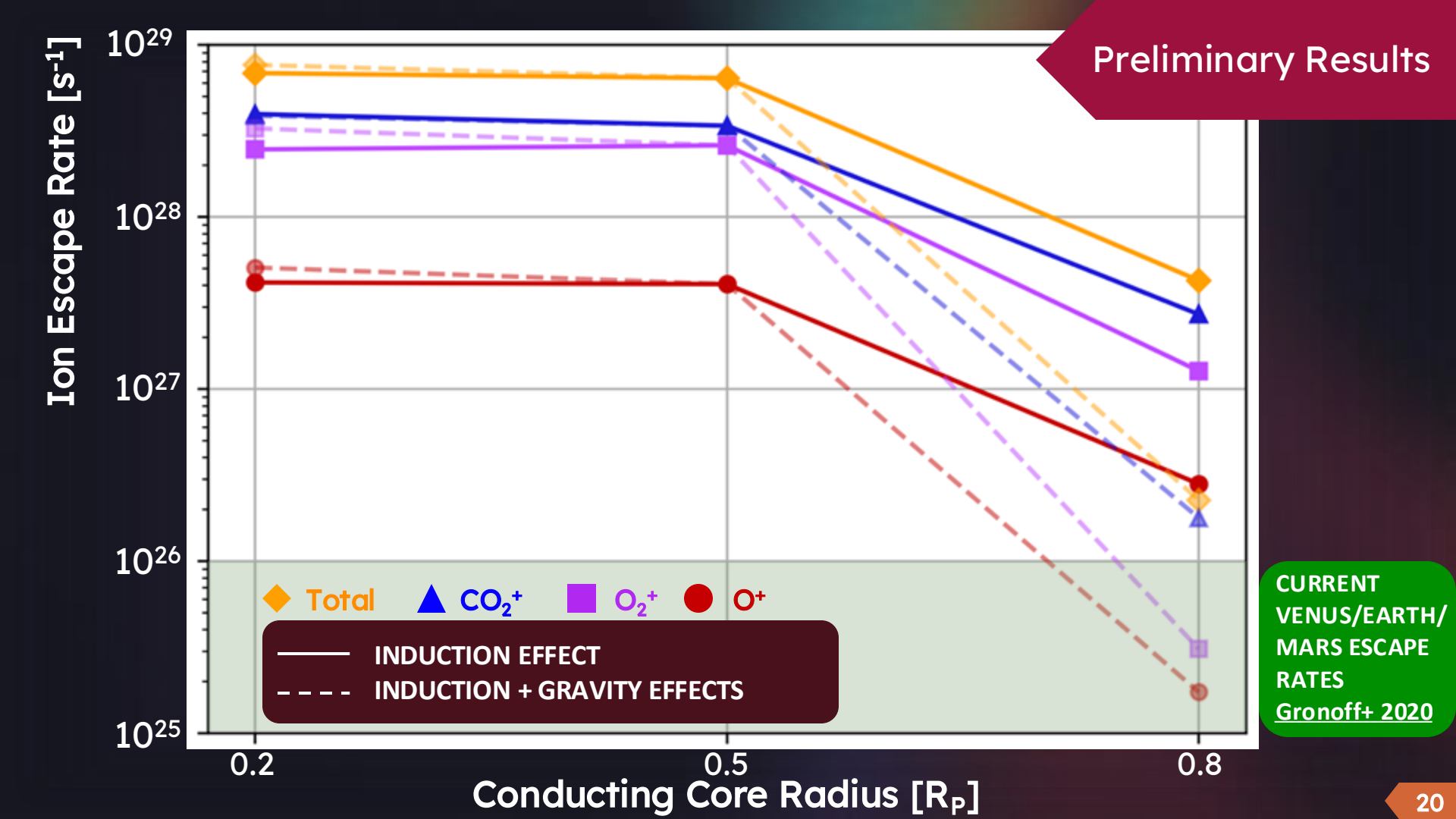
Core	$R_C = 0.20$	0.50	0.80
Induction Effect Only	1.29 M_{Earth}	1.29 M_{Earth}	1.29 M_{Earth}
Induction + Gravity Effect	1.11 M_{Earth} 0.99 H_{Venus}	1.29 M_{Earth} 0.85 H_{Venus}	1.91 M_{Earth} 0.58 H_{Venus}


R_C=0.20R_P
R_C=0.50R_P
R_C=0.80R_P
Z [R_P]
5
0
-5
-10
-5
0
X [R_P]
$\log_{10} n_{O+}$ [amu/cc]
3
2
1
0
-1
-2
-3
Z
X


R_C=0.20R_P
R_C=0.50R_P
R_C=0.80R_P
Induction Effect Only
Induction + Gravity Effect
Z [R_P]
X [R_P]
5
0
-5
-10
$\log_{10} n_{O+}$ [amu/cc]
3
2
1
0
-1
-2
-3

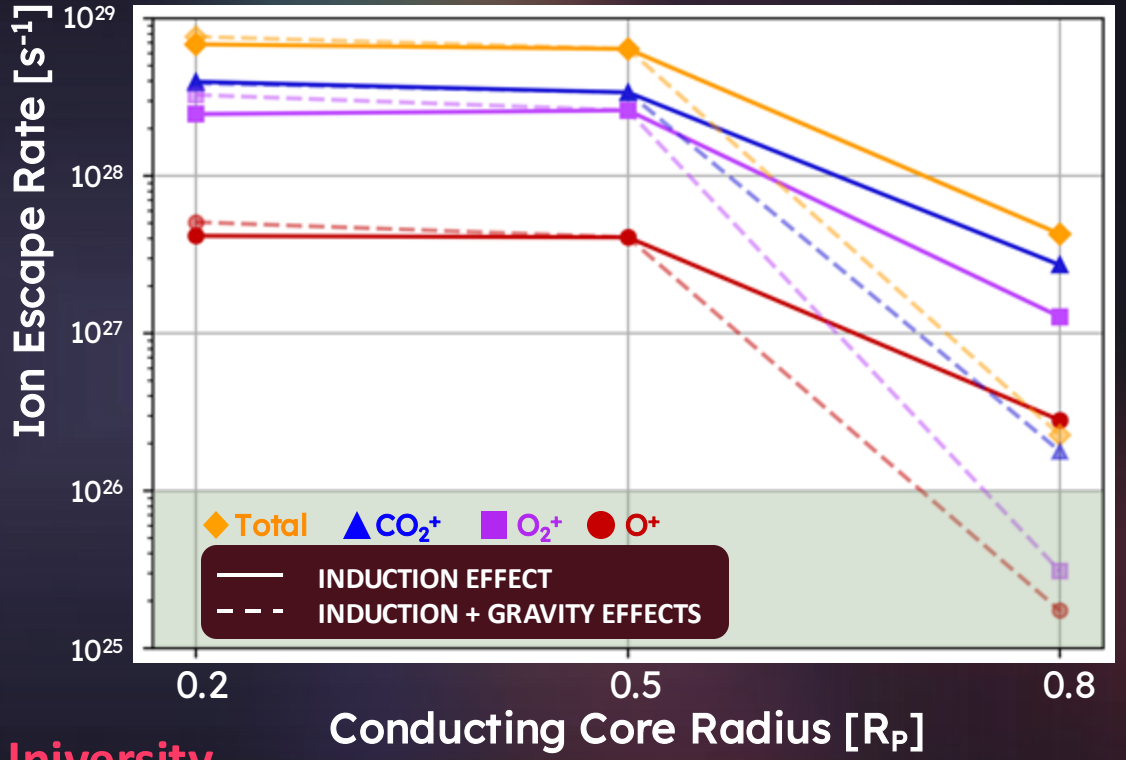
Preliminary Results




Preliminary Results
Ion Escape Rate [s-1]
10^29
10^28
10^27
10^26
10^25
0.2
0.5
0.8
Conducting Core Radius [RP]
Total
CO2+
O2+
O+
INDUCTION EFFECT
INDUCTION + GRAVITY EFFECTS
CURRENT VENUS/EARTH/ MARS ESCAPE RATES
Gronoff+ 2020

Summary

- The planet with the largest conducting core exhibits the lowest atmospheric ion escape rate across all species.
- The induction effect can help protect planets and reduce their atmospheric escape rate by generating additional core-induced magnetic fields.
- Planets with larger conducting cores may have better prospects for habitability.



Laura Chin | Boston University
lrchin@bu.edu