A Critical Look at the Ionization of Protoplanetary Disks: Chemistry in the Presence of an Analogue Heliosphere

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Abstract

Cosmic rays as ionizing agents have important astrochemical and physical consequences in the dense ISM. However, as evidenced by the existence of our own solar Heliosphere, the degree to which CRs are present in the circumstellar environment is unknown. This issue is especially important for low mass pre-main sequence stars with molecular disks, i.e. T-Tauri systems. In these disks the physical and chemical properties, such as ionization fraction, are key in setting the conditions for future planet formation. Within our own Solar System the solar wind shields the inner ~100 AU from galactic cosmic rays with energies below a 300 MeV. T-Tauri stars with relatively high mass loss rates and magnetic activity can likewise power a "T Tauriosphere" that could substantially reduce the galactic CR flux incident on their protoplanetary disks. We find that T-Tauri wind modulation of CRs can be so effective that ionization resulting from short-lived radionuclide decay could dominate the outer disk midplane ionization at typical ISM abundances, if the decay products do not freely escape. We examine implications for both the extent of MRI "dead-zones" as well as for ion chemistry in disks resulting from low CR fluxes. We also provide predictions on how to use observable molecular ions to infer the presence of extrasolar Heliospheres around T-Tauri stars.

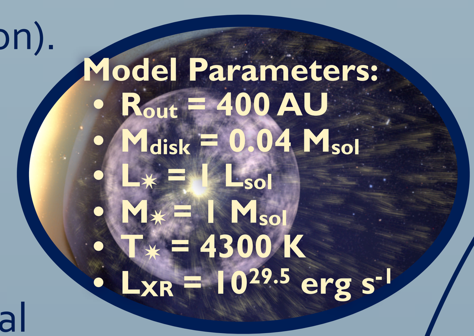
1) Introduction

Ionization is key in driving pathways towards gas phase chemical complexity and disk dynamics such as accretion driven by the magnetorotational instability (MRI; Balbus & Hawley 1991).

Dominant sources of ionization (and stopping distances) in protoplanetary disks are: UV (~10^{-3} g cm^{-2}), X-rays (0.05 g cm^{-2} at 1 keV) and CRs (96 g cm^{-2}; Umebayashi et al 1981) . Thus CRs are most able to ionize the densest gas in disks. ***However, as evidenced by the presence of our own Heliosphere, the degree to which CRs are present in the circumstellar environment is unclear.***

We have examined the effects of the absence of CRs due to wind modulation and magnetic modulation on so-called MRI dead-zones (Cleeves, Adams & Bergin 2013; Paper I) as well as on the chemical nature of disks (Paper II, in preparation).

2) Disk Model



- Disk model computed with *Torus* (Harries 2000). Gas temperatures from X-ray heating and dust collisional cooling (Glassgold & Najita 2001).
- Monte Carlo UV & X-ray R.T. (Bethell & Bergin 2011 a,b).
- Disk chemical calculations of Fogel et al. 2011.
  - ✳ Updated to include a small, 70 reaction deuterium network to make additional predictions for N2D$^+$, H2D$^+$, and HD2$^+$.

3) Cosmic Ray Exclusionary Mechanisms

- Physical mechanisms by which CRs can be reduced are:

  (1) Modulation by stellar winds, i.e., a "T-Tauriosphere,"

  (2) Magnetic mirroring by large scale stellar or environmental, e.g., "hourglass," magnetic field structure (Li & Shu 1996, Padovani et al. 2011), see Fig. 1

- We have investigated incident CR spectra under solar-like and "elevated" wind conditions, using spot coverage as a proxy for magnetic activity and thus wind modulation efficiency. ISM cosmic ray rates from Moskalenko et al. 2002 (grey line) and Webber et al. 1998 (orange line), see Fig 2.

  ✳ Magnetic effects reduce the net flux by ~2x, while ***winds can reduce by more than 1-5 orders of magnitude.***

  ✳ Subsequent CR transport into the disk with the "Continuous Slowing Down Approximation" (Padovani et al. 2009).

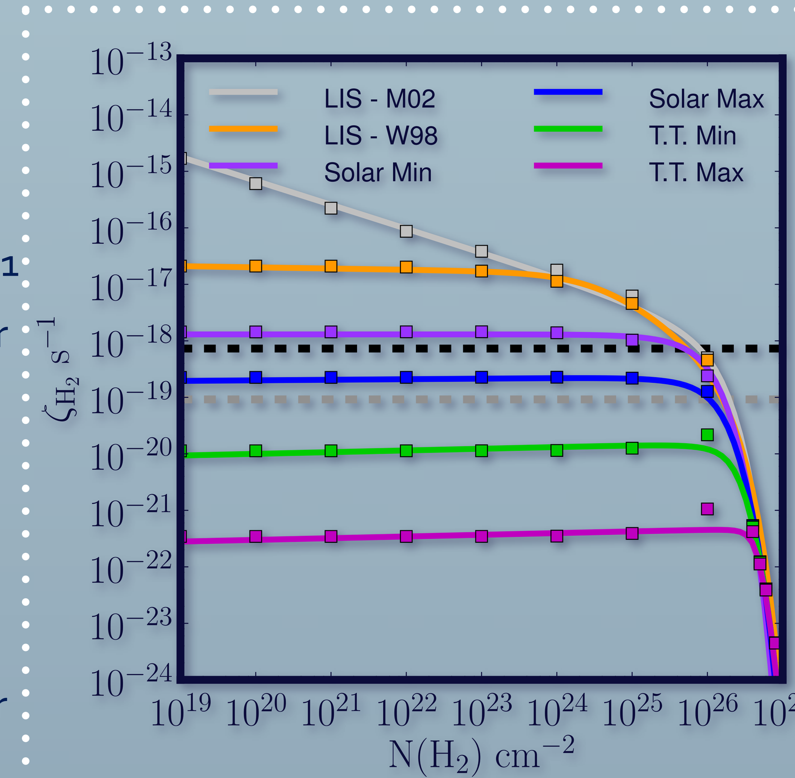


Fig. 2: CR ionization rate vs. column density for different degrees of wind modulation.

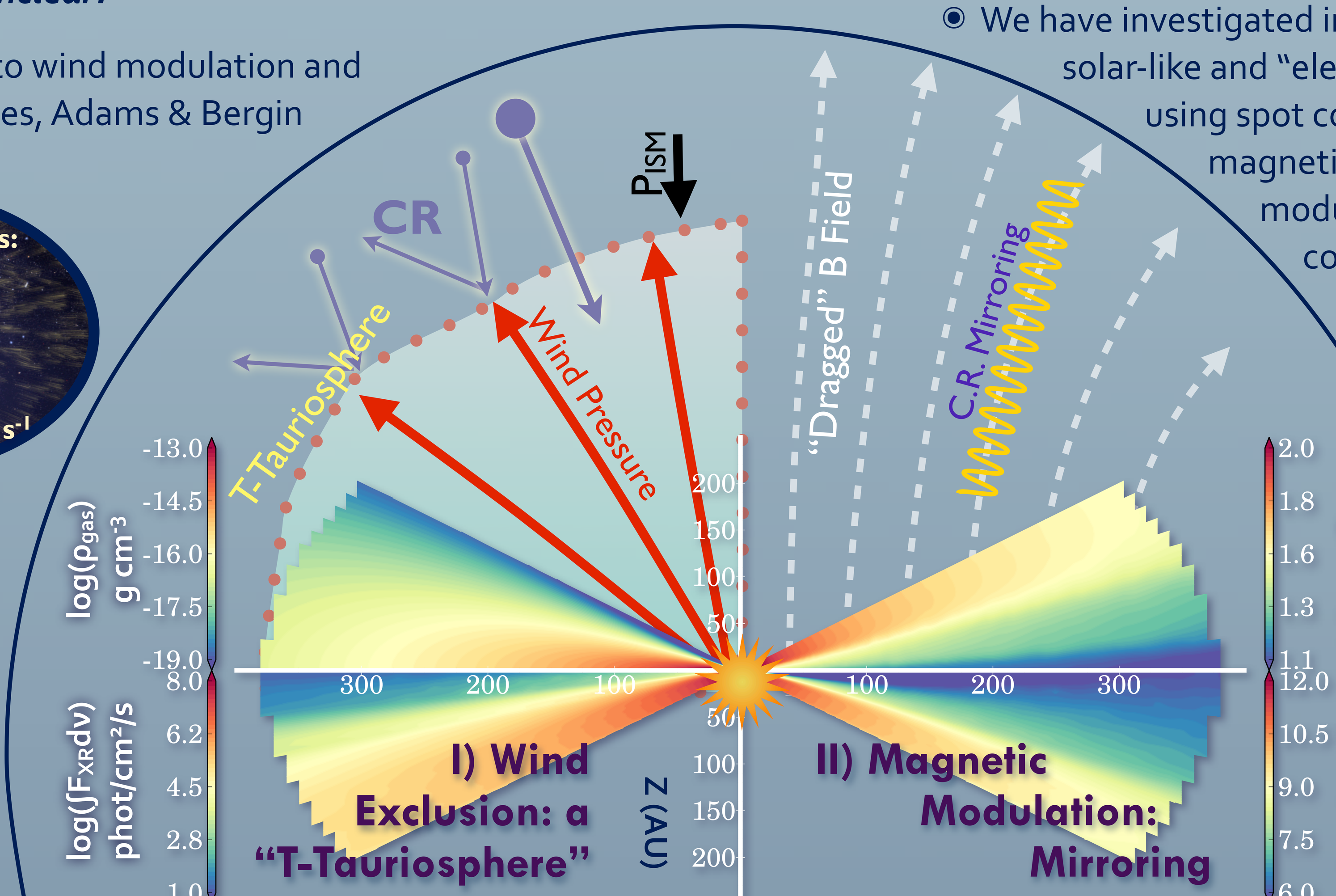


Fig. 1: Basic model framework for wind and magnetic field exclusion.

RESULTS

4) Molecular Ion Abundances

- Molecular ions such as HCO$^+$, DCO$^+$, and N2H$^+$ have been previously detected towards protoplanetary disks (e.g.,van Dishoeck et al. 2003, Qi et al. 2008, Öberg et al. 2010,2011).
  - ✳ Ion abundances trace the ionizing flux as well as environmental factors such as freeze out of parent molecules such as CO.
- We have computed disk chemical models holding other properties fixed and varying only CR ionization. Other sources of ionization are UV, X-rays and (*in progress*) ionization by radionuclide (RN) decay.
- The largest change in abundance occurs between an ISM CR rate ($\zeta_{CR} \geq 10^{-17}$ s^{-1}) and a solar modulated rate (ζ_{CR} ~ (0.1-1) x 10^{-18} s^{-1}).
  - ✳ Molecules such as HCO$^+$ have partial contribution from X-rays, need optically thin isotopologues to determine midplane ionization. Deuterated molecular ions more sensitive to cold gas, but less abundant and thus more difficult to observe.

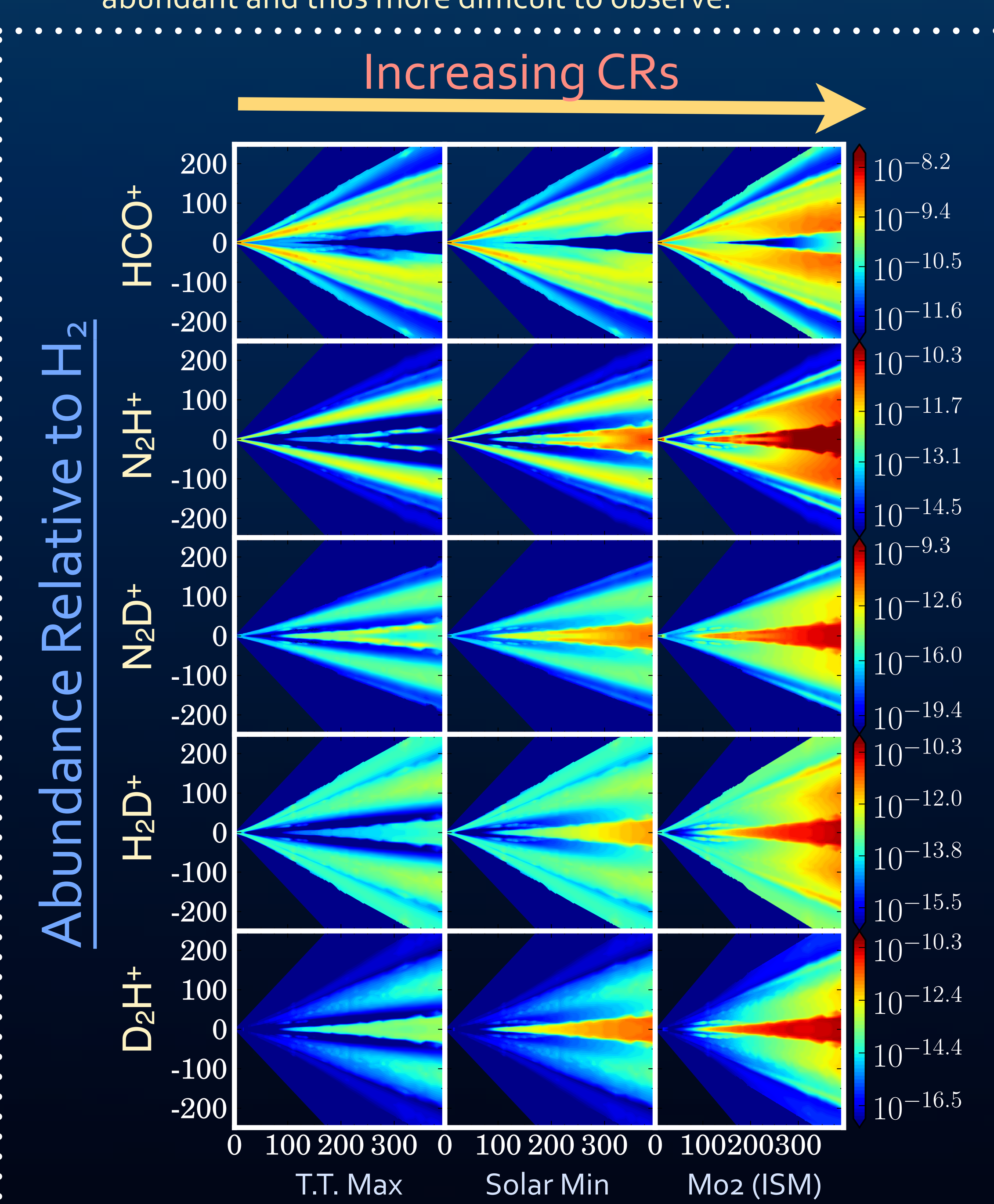
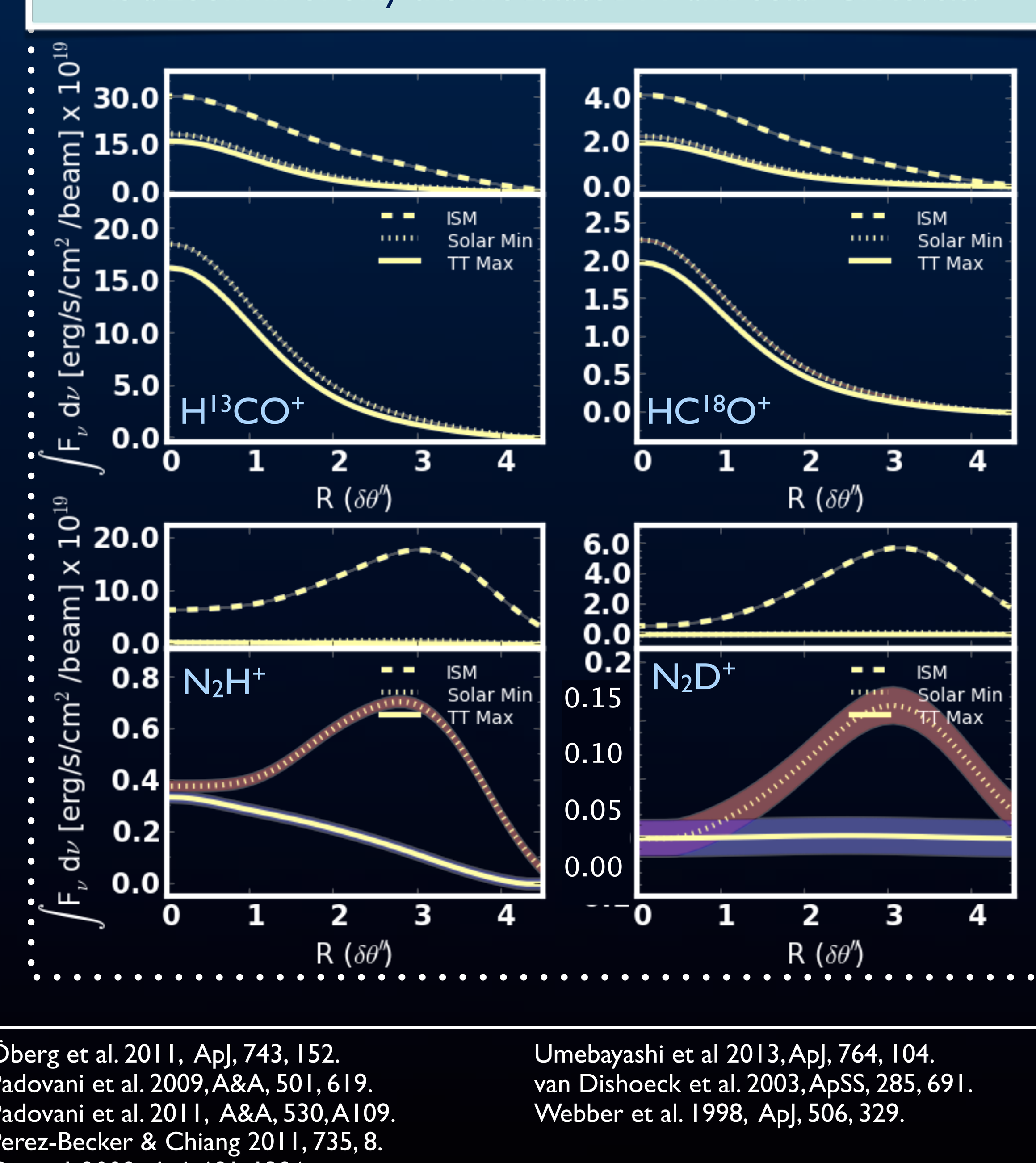


Fig. 3: Chemical modeling results. Low CR to high CR flux from right to left. Abundances are given by n(X)/n(H$_2$).

5) How to Search For a T-Tauriosphere: Observational Constraints from ALMA

- These scenarios can be differentiated by observing rotational transitions of molecular ions that trace the dense midplane gas.
- Because of the high X-ray luminosity of T Tauri stars, it is important to observe optically thin tracers that peer through the ionized gas on the disk surface.
- We have calculated the emergent (non-LTE for deuterium free species) line intensity for ALMA observable transitions with our abundance models using *Lime* (Brinch & Hogerheijde 2010), and simulated ALMA observations using *CASA* for the most compact full ALMA configuration, 66 antennas, and sensitivites from 10h on sky, **Fig. 4**.
- The most sensitive tracers of the midplane ionization are N2H+ (3-2), (4-3) and N2D+ (3-2). H2D+ is detectable for only the ISM (Mo2) ionization case. Usefulness of HCO+ and isotopologues are hindered by significant contribution from X-rays and CO freeze out.

Fig. 4: Radial brightness profile of a selection of emission line models. All species shown at J = 3-2. Top portion of each panel includes: ISM, Solar and T-Tauri CR rates while the bottom portion is a zoom-in of only the modulated TT and Solar CR levels.



6) Dead Zones

- In regions where the ion abundance drops below a critical value (e.g., Perez-Becker & Chiang 2011), the disk cannot sustain MRI turbulence, i.e. be active. Paper I shows that under the influence of elevated CR ("T-Tauri like") wind modulation, the disk would be largely dead to MRI, i.e. accretion cannot proceed in the midplane, Fig. 5.

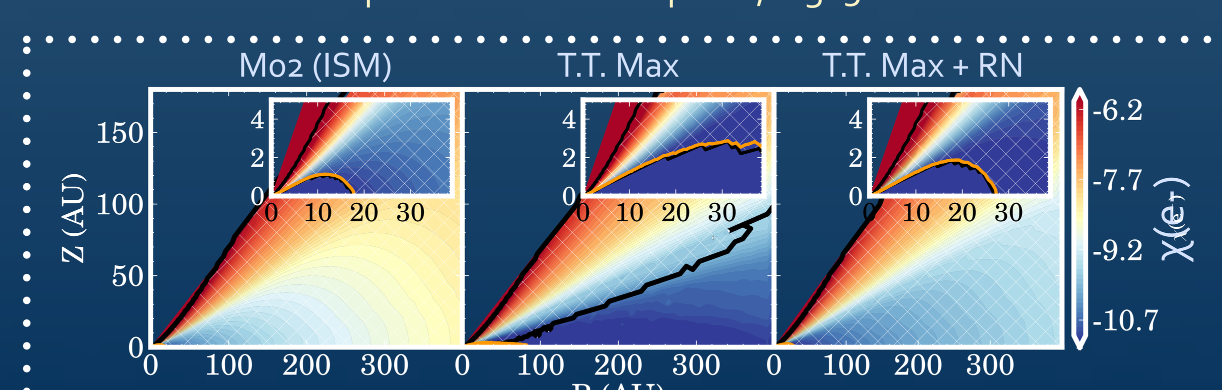


Fig. 5: Dead zones under the influence of a reduced CR flux. Hatched regions: active according to the Magnetic Reynolds #, *Re* and Ambipolar Diffusion Criteria *Am*; orange line: active region defined by *Re*-only. Left to right, MRI dead regions as found under: 1) ISM, 2) T.T. Max and 3) T.T. Max plus uniform ζ_{RN} = 7.3x10^{-19} s^{-1} radionuclide ionization.

- However, a minimal amount of either radionuclide ionization or hard ~7 keV X-ray ionization (L_{XR} > 10^{31} erg/s), which can penetrate to the midplane, can potentially provide a baseline to sustain MRI turbulence and thus power accretion.

7) Radionuclide (RN) Ionization

- Without CRs, decay of short-lived RNs (now extinct) becomes the dominant contributor to the otherwise shielded midplane. The problem has been investigated by Umebayashi et al 1981, 2009, 2013, Finocchi & Gail 1997. In Cleeves, Bergin, Adams & Visser in prep, we are investigating the vertical ionization rate (Fig. 6) including the significant effects of energy/process dependent particle loss, previously untreated.

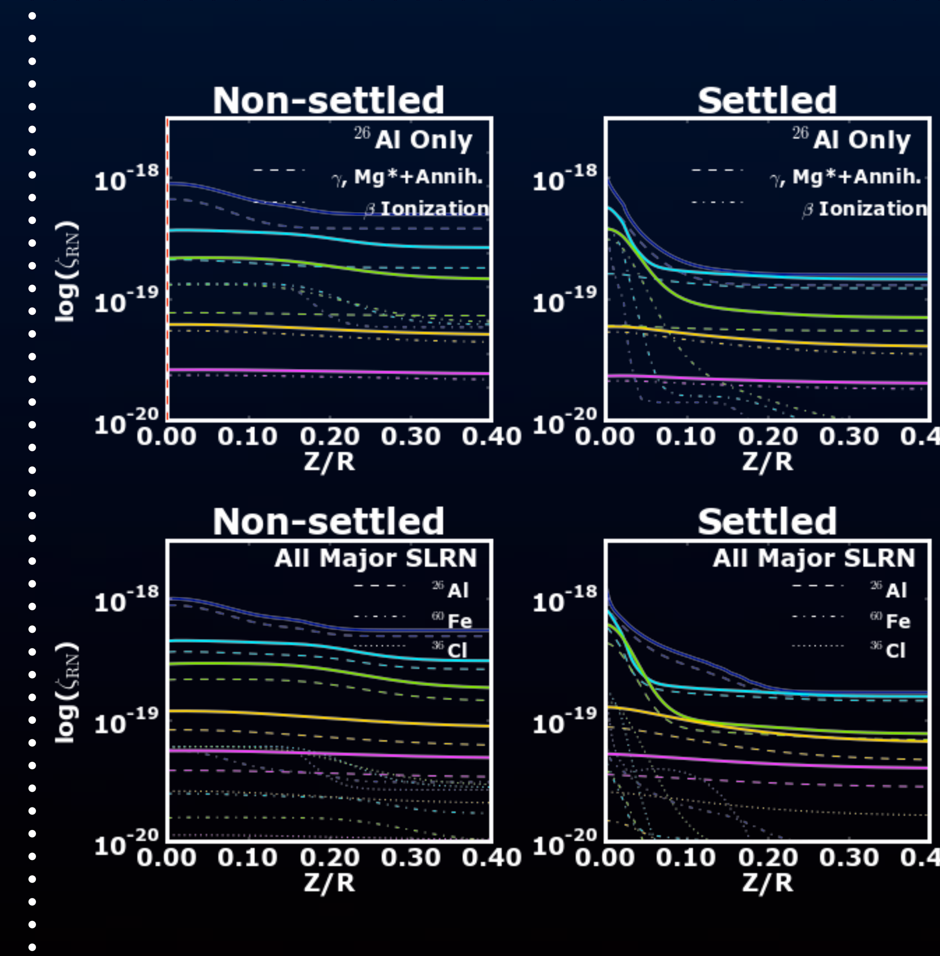


Fig. 6: RN ionization rates, ζ_{RN} in s^{-1} H$_2^{-1}$ versus height from the midplane at the indicated radii. Top panels are ^{26}Al-derived; bottom panels also include ^{60}Fe ^{36}Cl decay. Left panels assume gas & dust are well mixed while the right include dust settling.

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