MAGNETIZED ACCRETION AND DEAD ZONES IN PROTOPLANETARY DISKS

N. Dzyurkevich[1,3], N. J. Turner[2,3], Th. Henning[3], W. Kley[4]
1. Laboratoire de Radioastronomie ENS-LERMA UMR 811, rue Lhomond 24, 75005 Paris, France;
2. Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA;
3. Max Planck Institute for Astronomy, Königstuhl 17, 69117 Heidelberg, Germany; 4. University of Tuebingen, Auf der Morgenstelle 10, 72076 Tuebingen, Germany.

Abstract. The edges of magnetically-dead zones in protostellar disks have been proposed as locations where density bumps may arise, trapping planetesimals and helping form planets. Magneto-rotational turbulence in magnetically-active zones provides both accretion of gas on the star and transport of mass to the dead zone. We investigate the location of the magnetically-active regions in a protostellar disk around a solar-type star, varying the parameters like dust-to-gas ratio. The dead zone is in most cases defined by the ambipolar diffusion. In our maps, the dead zone takes a variety of shapes, including a fish-tail pointing away from the star and islands located on and off the midplane. The corresponding accretion rates vary with radius, indicating locations where the surface density will increase over time, and others where it will decrease. We show that density bumps do not readily grow near the dead zone's outer edge, independently of the disk parameters and the dust properties. Instead, the accretion rate peaks at the radius where the gas-phase metals freeze out. This could lead to clearing a valley in the surface density, and to a trap for pebbles located just outside the metal freeze-out line. Here, we provide the fitting formula for the metal line and consider the cojoint impact of metal and snow lines on the shape of the dead zone.

I. Fiducial Disk Model & Method.

Disk Parameters:
1-200 AU disk with gradual edge, 1 solar mass star;
Surface density: 1700 g cm^{-2} at 1 AU, $\sim r^{-0.9}$;
Temperature: 280 K at 1 AU, $\sim r^{-0.5}$;

Dust and Chemistry Parameters:
Consider only dust grains $<10^{-5}$ cm, organized into fractal 'fluffy' aggregates, solid density 1.4 g cm^{-3};
Main ions are HCO^+ and Mg^+ (representative metal);
$n(Mg)/n(H) = [10^{-6},.., 10^{-8}]$;

Magnetic fields: Plasma beta is 400.

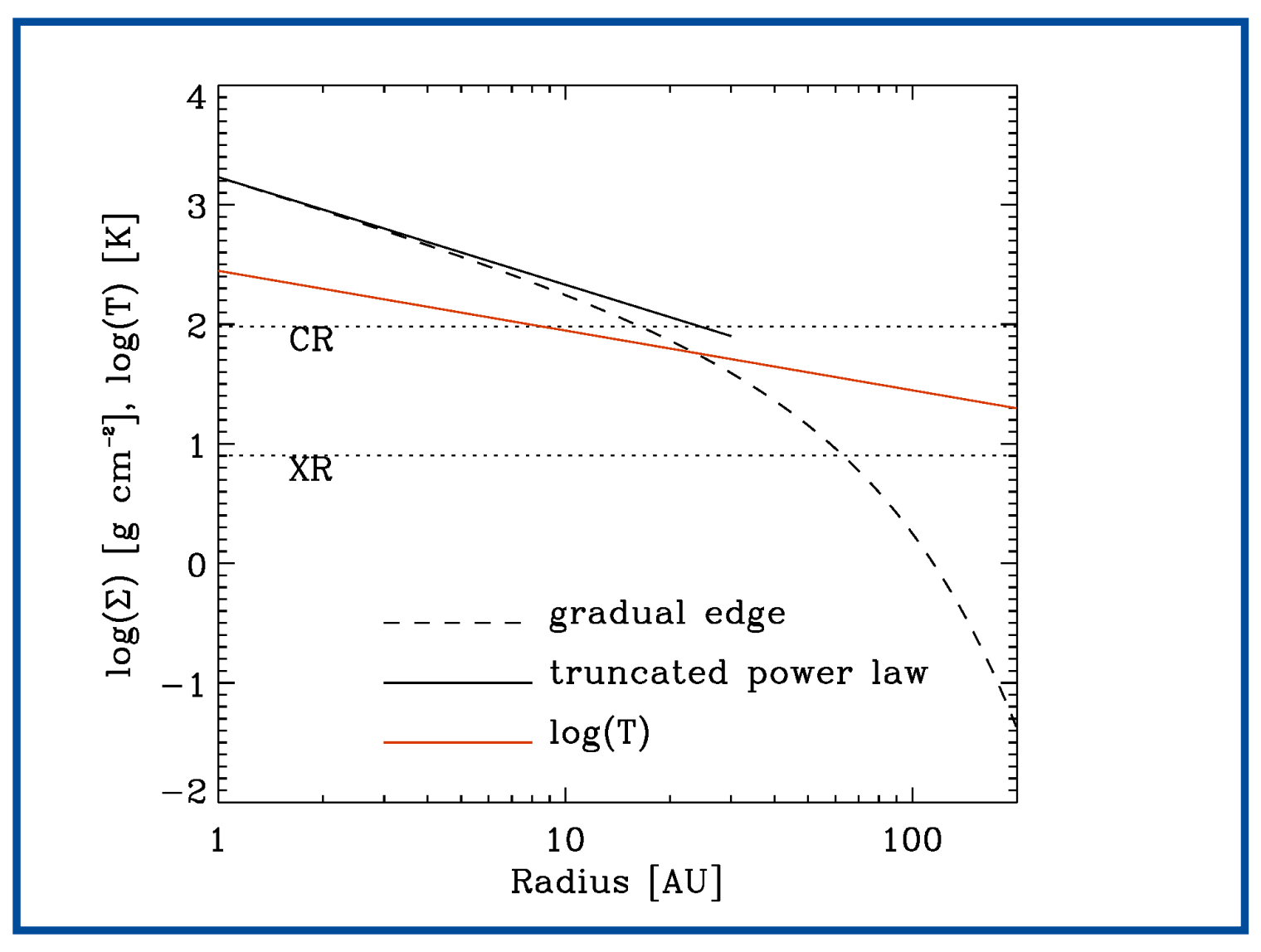


Fig. 1. Gas surface density of our model (dashed) and MMSN (solid), shown together with XR and CR penetration depth and temperature.

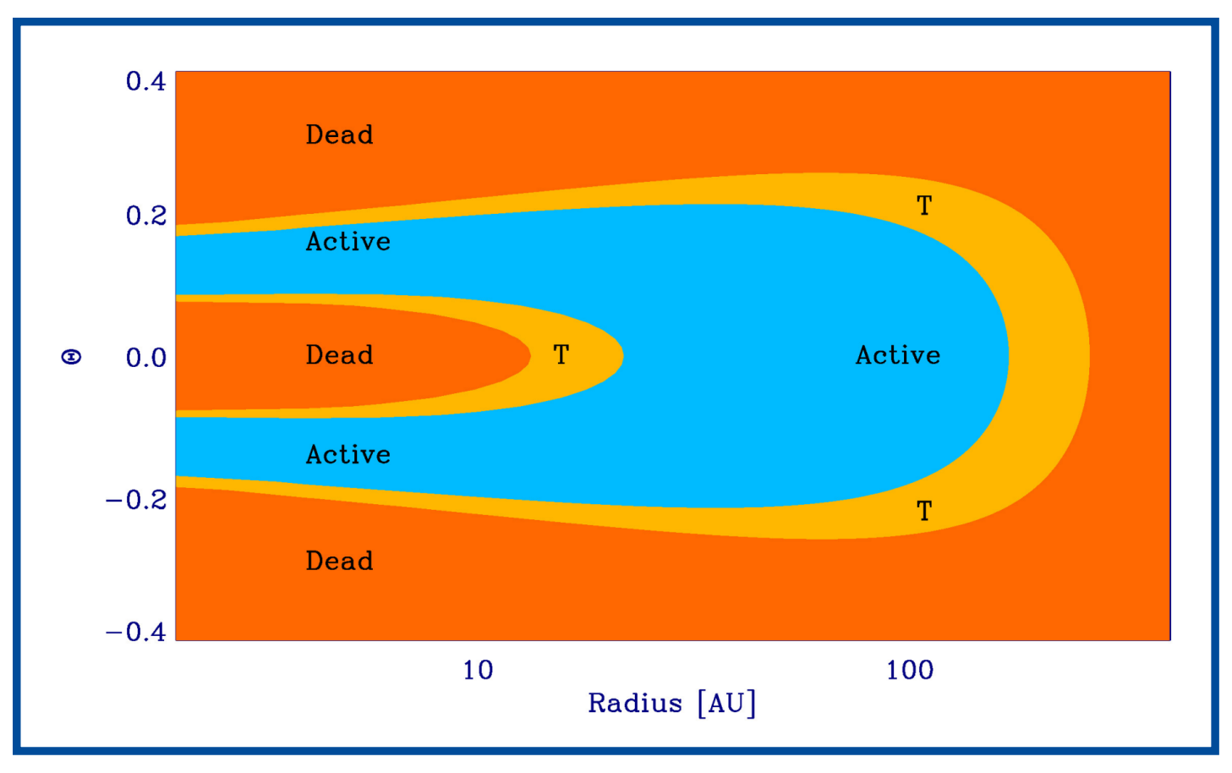


Fig. 2: Color coding: Active-Transitional-Dead zones

The aim is to obtain a realistic radial profile of mass accretion rate in a protoplanetary disk, and to make a prediction where the density rings can be built. The production steps are following:
(1) Choose the ionization mechanisms like CR, XR and radionuclides;
(2) Derive equilibrium ionization state of the disk using recipe in Okuzumi (2009) for given ionization rate, dust abundance, gas density and temperature;
(3) Calculate Ohmic, Pederson and Hall conductivities using the densities and charges of dust, ions and electrons (see also Wardle 2007);
(4) Assume plasma beta and calculate the MRI-activation criterium (Elsasser number);
(5) To translate 2D MRI-criterium map in radial-dependend mass accretion rate, we use the scaling relation between turbulent stress and Elsasser number (Bai & Stone 2011).

II. Results for constant dust-to-gas ratio.

(1) Size of MRI-dead zone vs. dust-to-gas ratio (Dzyurkevich et al 2013). The channels of high MRI activity ('1' contours in blue active regions) are due to volatile Mg. Freeze-out of metals lead to sudden **drop** in accretion rate (r~7-8 AU in fiducial model).

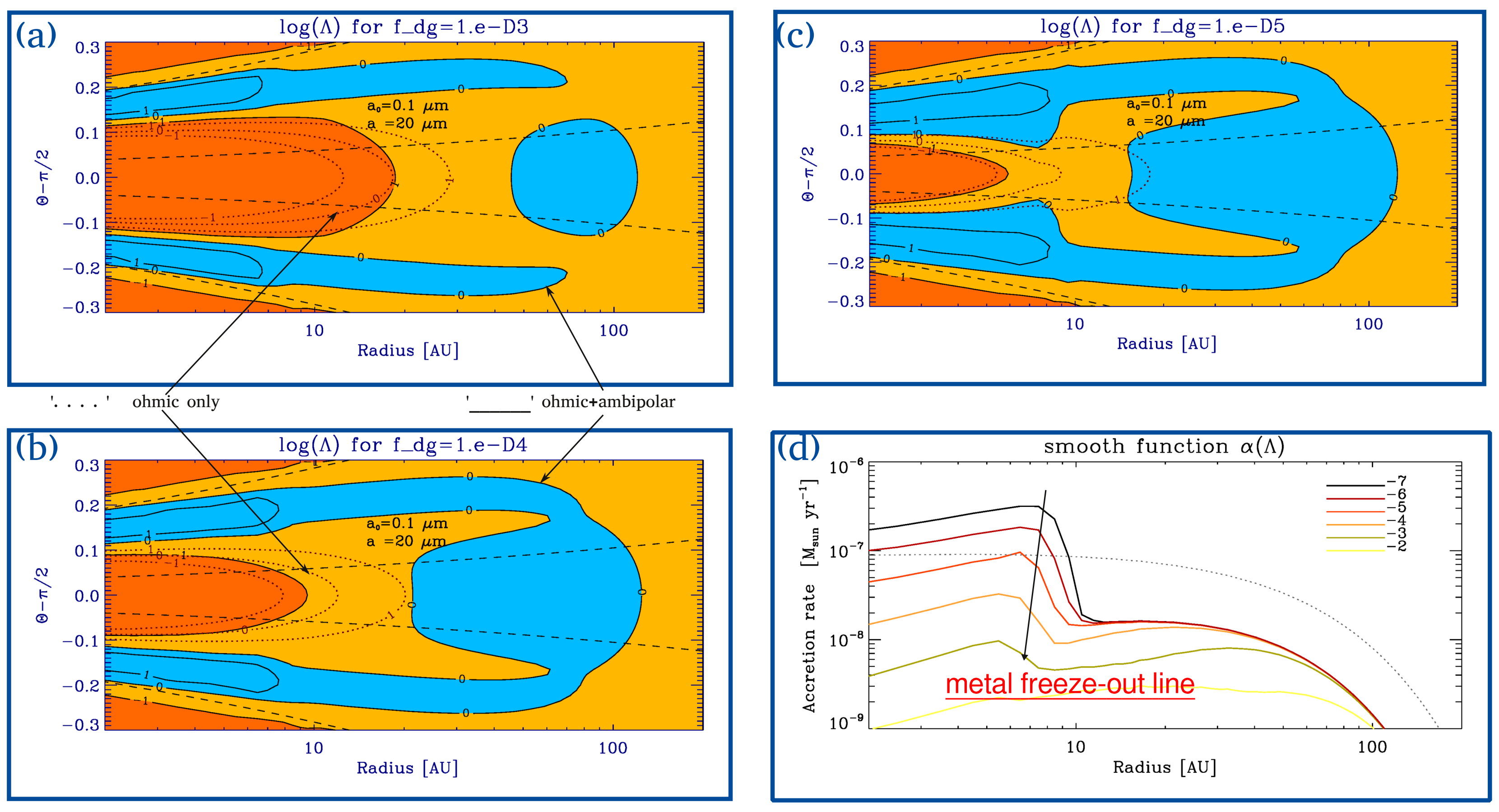
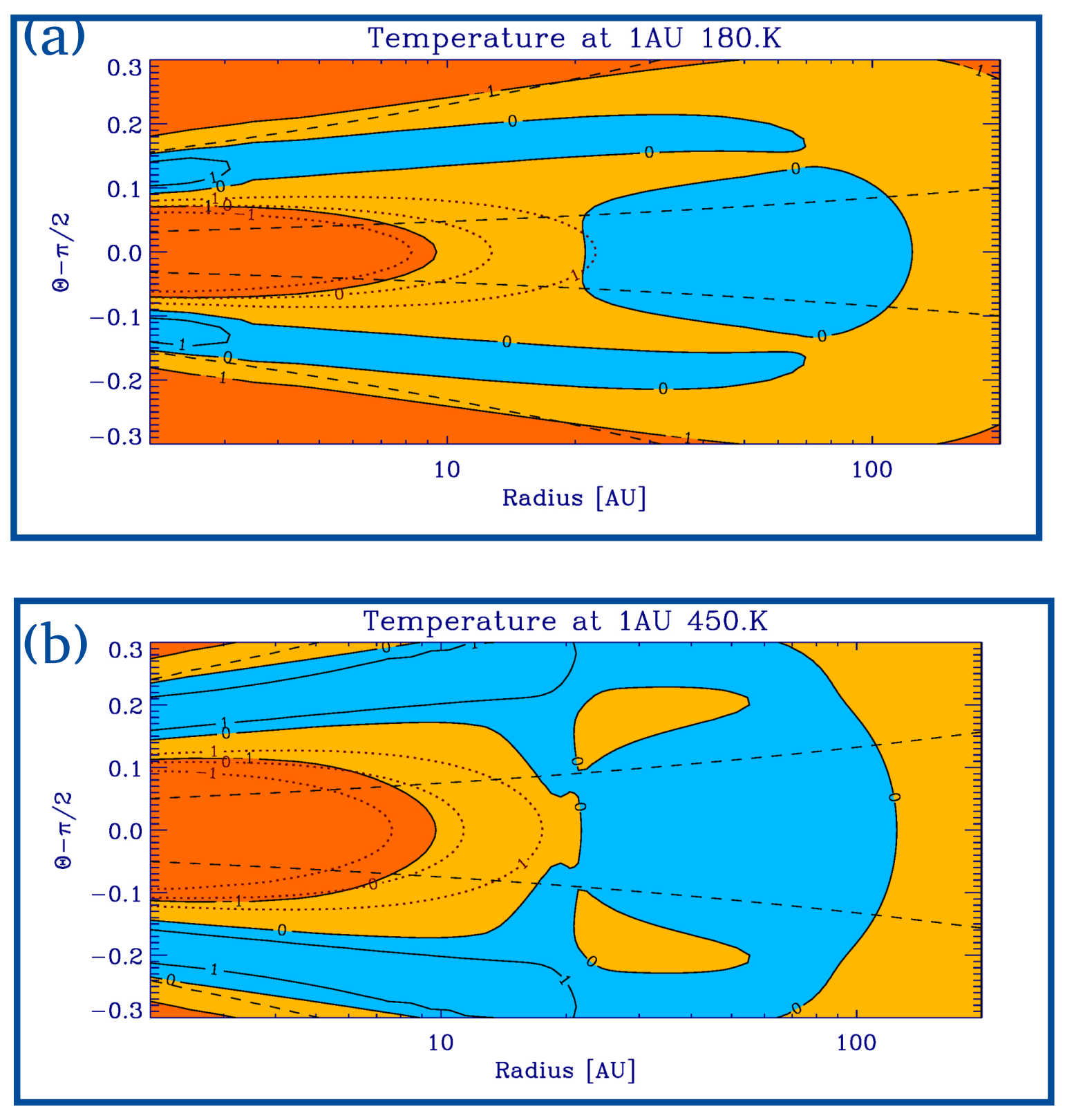


Fig. 3. (a-b-c) MRI criterium: log(Λ)<0 for dead, 0<log(Λ)<1 transitional, log(Λ)>1 active zones. **Fig 3 (d)** shows corresponding accretion rates for $\log(f_{dg})$=-7...-2.

Ionization increases smooth with radius, thus there is no gas accumulation at the outer edge. Instead, there is a clear peak in accretion rate at the metal line. This is a robust feature, common for the disks with any set of parameters (Dzyurkevich et al 2013).



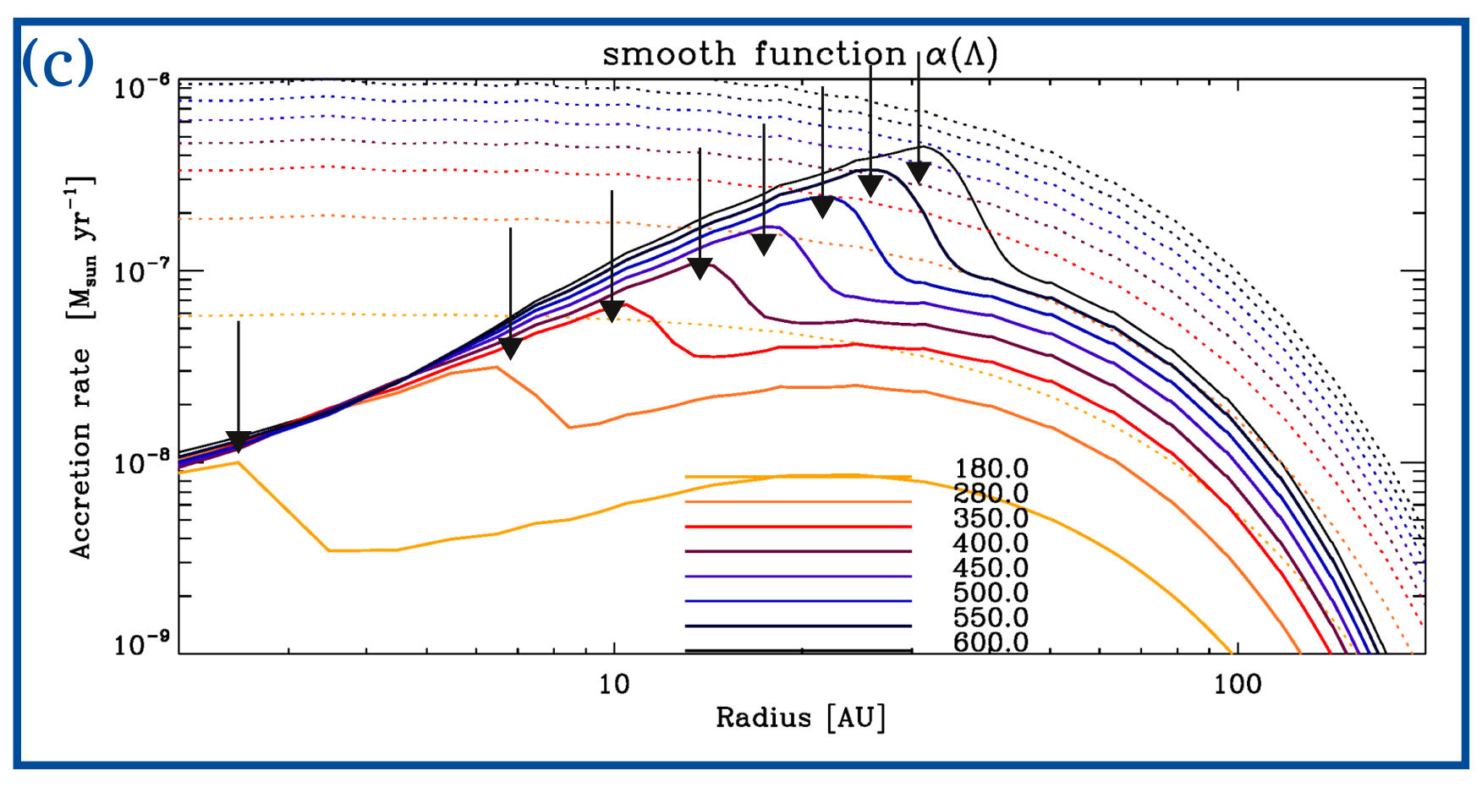


Fig. 4 (a-b) MRI criterium: log(Λ)<0 for dead, 0<log(Λ)<1 transitional, log(Λ)>1 active zones. **Fig 3 (c)** Migration of the metal line with the disk temperature (180K - 600K at 1 AU).

The ratio $n(Mg^+)/n(HCO^+)$ depends on the disk temperature and on the dust abundance. The metal line is at 100K in the disk corona, or for very low f_{gd}. For high f_{dg}, the metal line shifts to 150K. **Metals control the gas recombination rate for $T>T_{metal}$,**

$$T_{metal} = \frac{T}{T_{\rm mid}}\left[A + B\left(\frac{\rho}{\rho_{\rm mid}}\right)^{0.15}\frac{1}{\log_{10}(10^{-2}/f_{dg}+1)}\right]$$

Constants are A=100K, B=50K, factor T/T_{mid} takes into account the vertical variation in the temperature. The **fitting formula** is derived from our models.

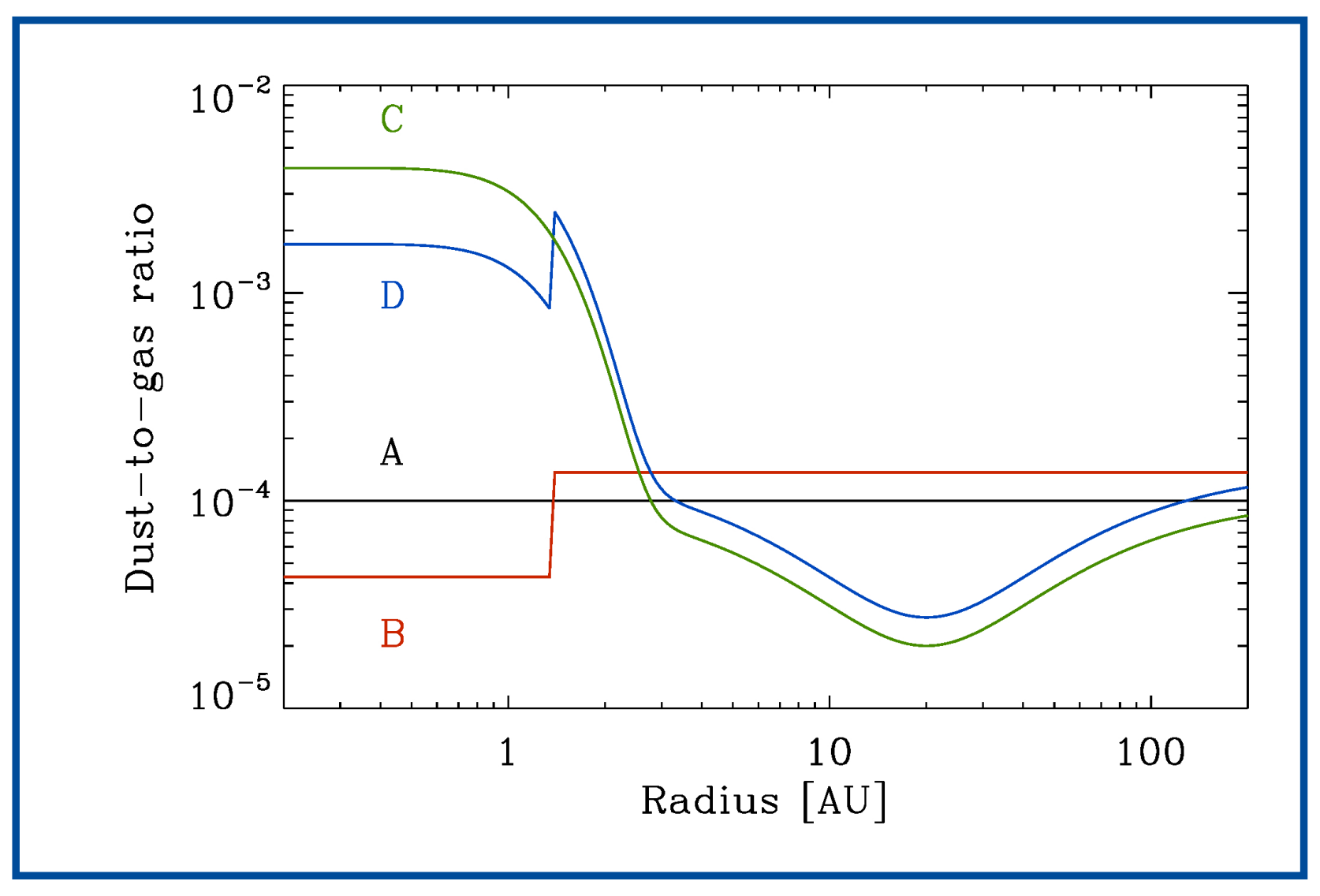


Fig.5. Variations in dust-to-gas ratio across the snow line.

III. Dead zone shapes for various radial profiles in dust-to-gas ratio.

This set of models has T=196 K at 1 AU. **Case A.** Dust is a 'dirty ice' with homogenious dust-to-gas ratio everywhere, material density 1.4 g cm^{-3};
Case B. Radial jump in dust-to-gas ratio because of grain composition change: Si-rich 'dry' grains inside and the 'dirty ice' outside of snow line. The material densities are assumed as 3.3 (for Si-rich grains) and 0.92 g cm^{-3} (for ice mantles);
Case C. Change in radial profile of dust-to-gas ratio after 10^5 years of dust evolution, following the model of Birnstiel et al (2010). All dust has 1.4 g cm^{-3}, but 'ice' can survive higher fragmentation velocities, drift and accumulate inside of snow line (Fig. 5);
Case D. Combination of Case B and Case C.

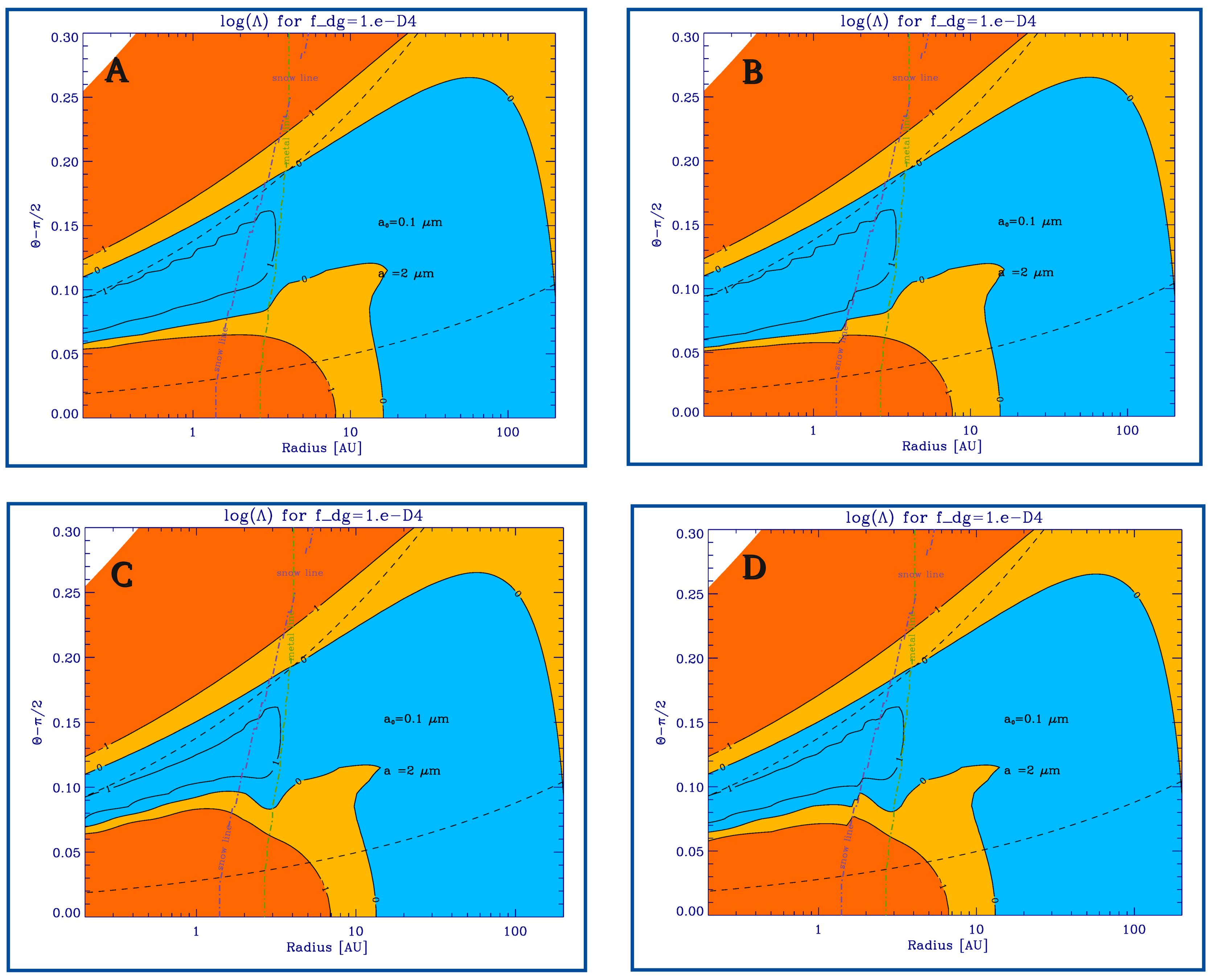


Fig. 6. (A-D) Dead zone shape and MRI-active layers for models A-D. Snow and metal line have ~1 AU radial separation at the midplane. Dashed lines are 1H and 5H from bottom to top.

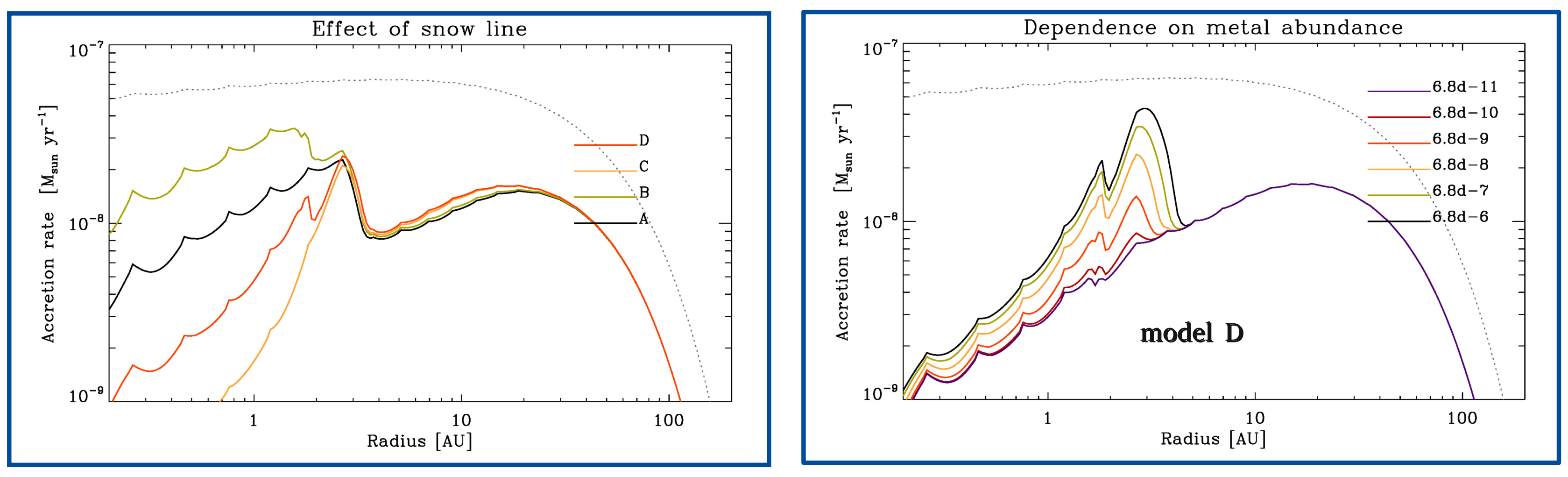


Fig 7. Left: Effect of snow line on gas accretion rate for models A-D. Right: Effect of various abundances of volatile metals such as Mg or Fe on the peak in accretion rate at the metal line (model D only).

Abundance of volatile metals shall be **n[Mg]/n[H] > 1.d-8 for a substantial jump** in the accretion rate at the metal line. Metal and snow lines are at ~150K and 169 K in MMSN. 'Dry' grains have significanly smaller volume and are less efficient in adsorbing free electrons - this makes MRI-active channels to carry more mass. After 10^5 years, dust is accumulated in the inner region and reduces (or even shuts off) the accretion through the MRI-channels.

Conclusions:
We consider the metal line to be the location to form a ring of enhanced density, which would provide the birthplace for planets. Long-term effects of snow and metal lines seem to be converse: while MRI-channels inside of metal line drain the inner disk, the dust growth and its radial migration makes the disk inside of snow line more 'dusty' and thus reduces the accretion there. It has to be clarified with 2D-viscous disk and dust simulations, which process will win and whether the ring of gas can be formed at the metal line.

References:
Bai, X.-N., Stone, J., ApJ 2011, 736,144
Dzyurkevich, N., Turner, N.J.,Henning, Th., Kley, W., ApJ 2013, 765,114
Okuzumi, S., ApJ 2009, 698, 1122
Wardle, M., Ap&SS 2007, 311, 35