Disk chemical and dynamical evolution at subsolar metallicity

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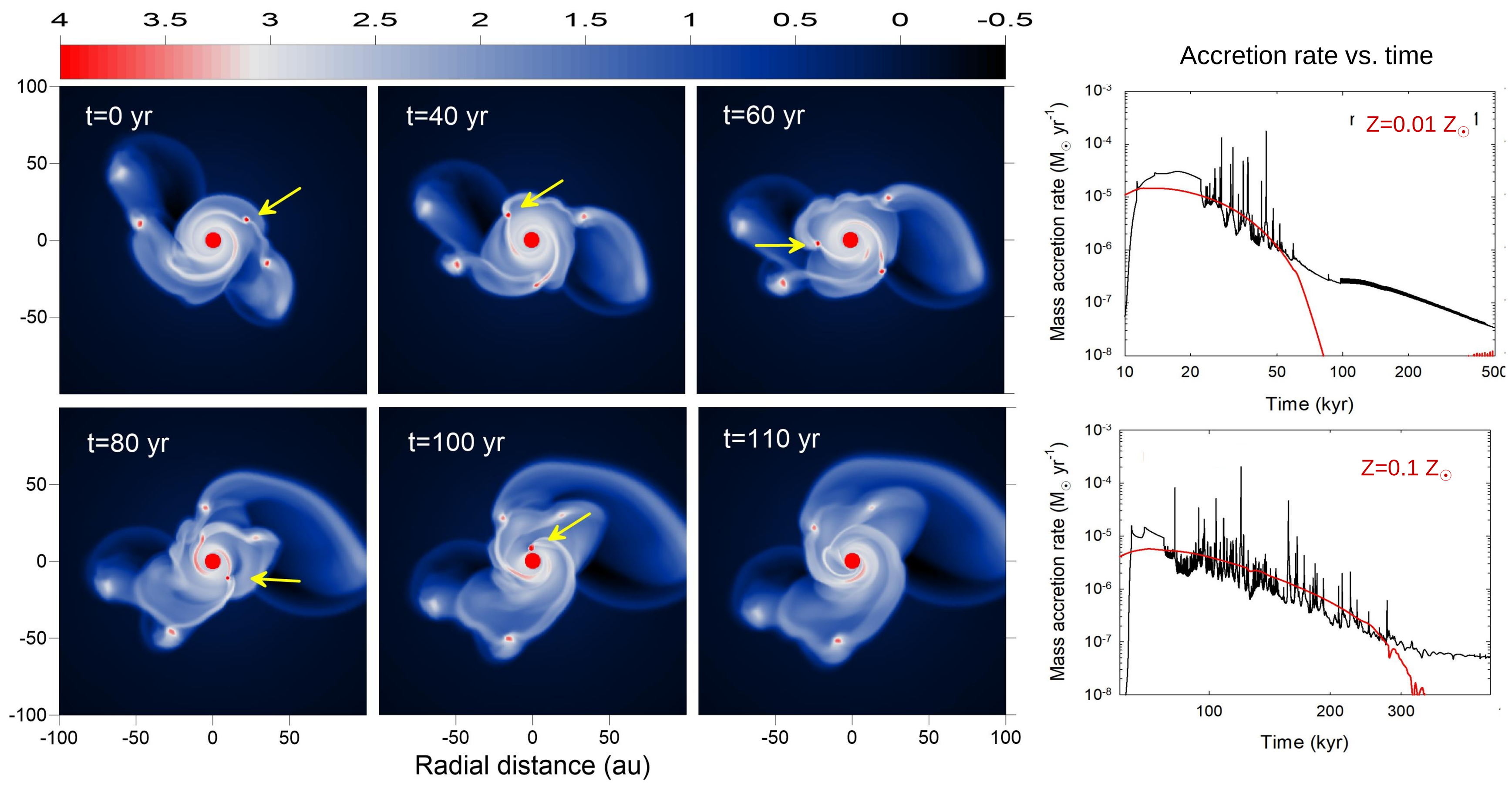
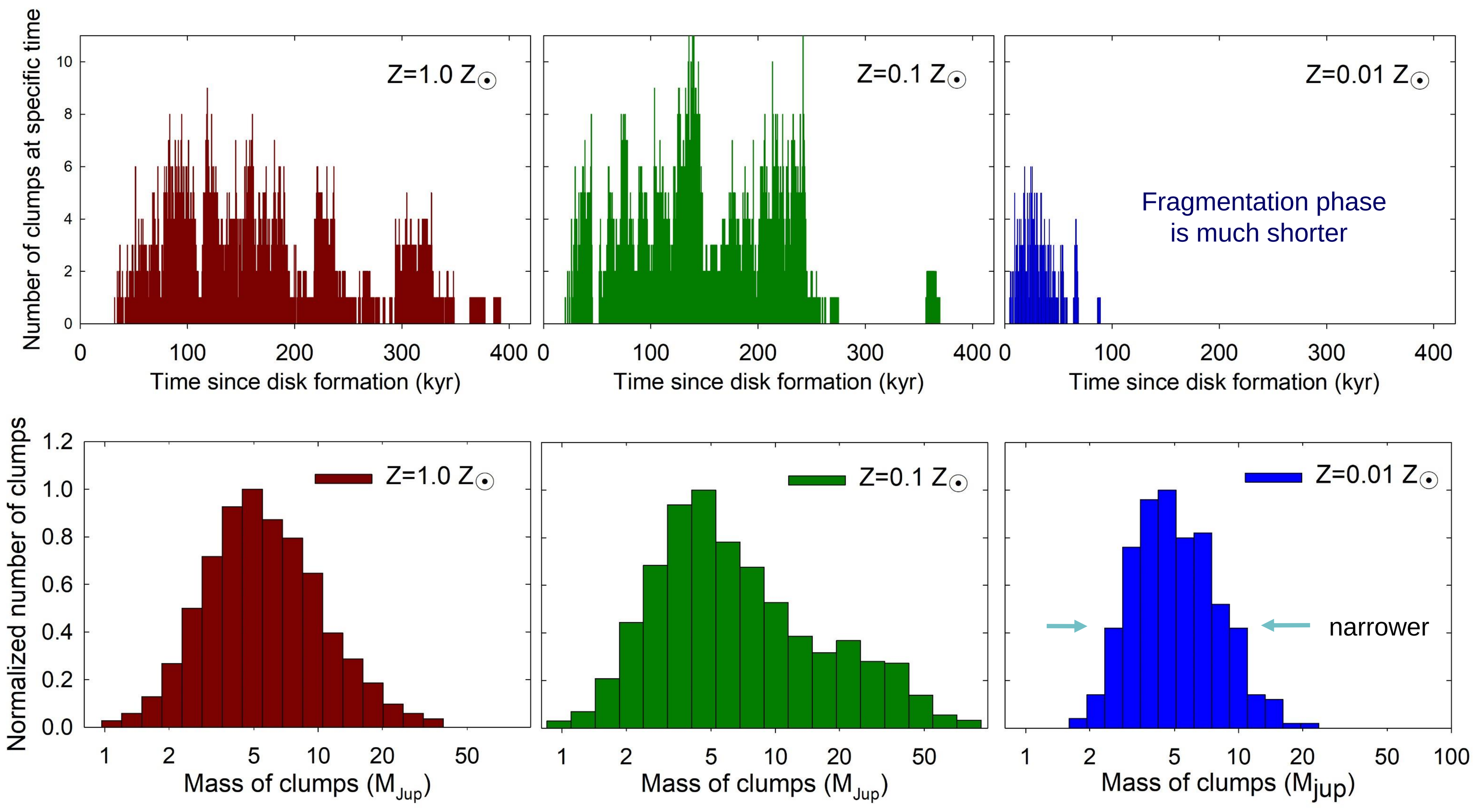
Relatively little is known about the formation and evolution of circumstellar disks at metallicities corresponding to the Magellanic Clouds and other moderately metal-deficient environments. We present our recent numerical hydrodynamics and thermo-chemical studies of the dynamical and chemical evolution of circumstellar disks around solar-mass stars at sub-solar metallicities (Z=0.1-0.01 Zsun). Gravitational fragmentation is present in these disks, but the outcome differs from that of the solar-metallicity disks as the metallicity drops below 0.1 Zsun. The chemical evolution of subsolar metallicity disks also differs from that of the solar-metallicity counterparts. We find that the abundances of basic molecules in lower metallicity disks cannot be understood or reproduced by scaling down the respective species abundances of the reference solar-metallicity model. This is because the chemical reactions responsible for the destruction and formation of the studied molecules change as the metallicity of the disk is reduced. We found a strong overabundance (relative to scaled-down values) in the models with lower metallicity for gaseous species (CN, CO, HCO^+, $N2H^+$), which are particularly useful in observations.

Disk dynamical evolution at $Z = 0.1\ Z_\odot$ and $0.01\ Z_\odot$

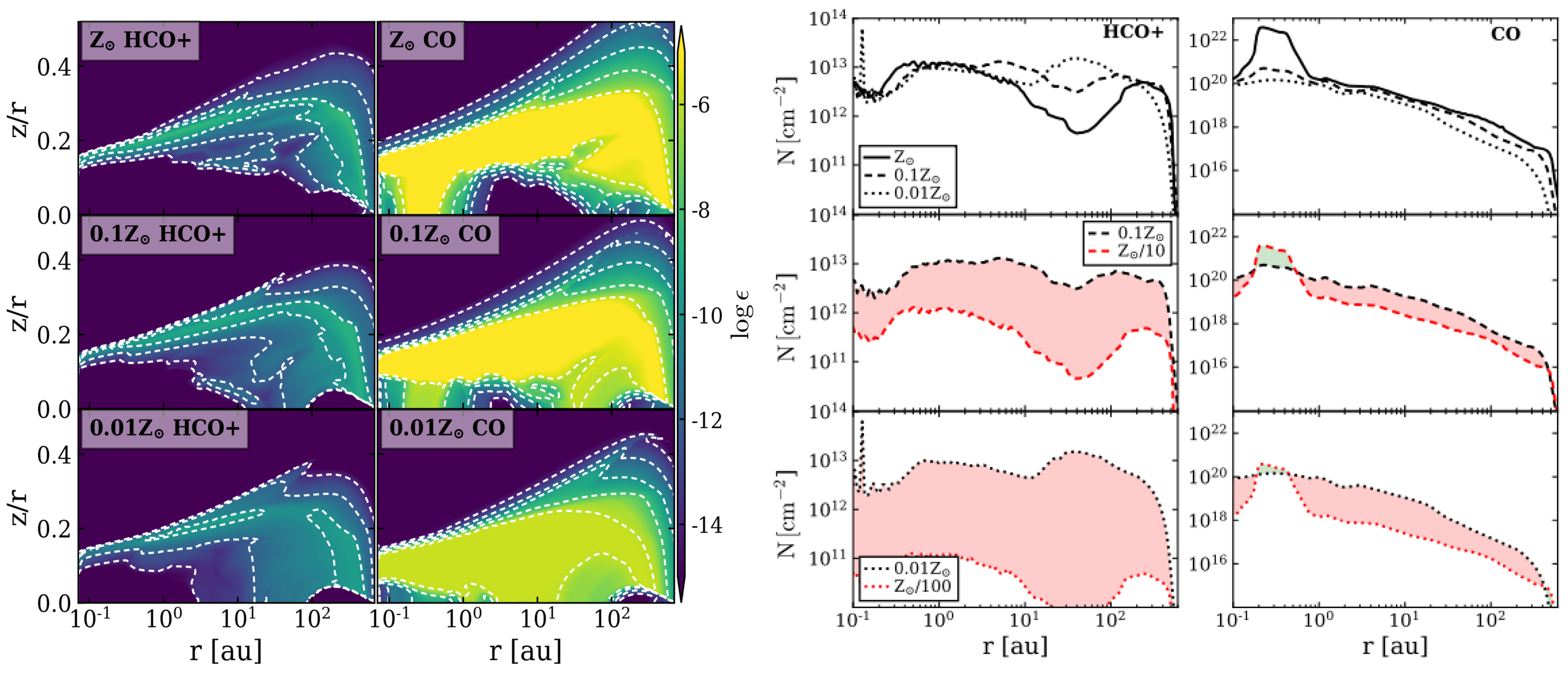


The top figure shows the process of migration and tidal destruction of a clump formed via gravitational fragmentation in a circumstellar disk with metallicity $0.01\ Z_\odot$. The clump with mass $\approx 10\ M_{Jup}$ is identified by the yellow arrow. The mass of the central star is $0.8\ M_\odot$. Clump destruction leads to an accretion burst and recurrent episodes of clump formation-migration-destruction manifest themselves as spikes in the accretion rate shown on the r.h.s. Note that accretion bursts cease when the mass infall on the disk (the red lines) from the collapsing gaseous envelope diminishes. The burst phase lasts shorter in lower-metallicity disks around stars of similar mass.

The bottom figure shows the number of clumps vs. time and the normalized distribution of the clump masses in gravitationally unstable circumstellar disks with Z=1.0, 0.1, and $0.01\ Z_\odot$. In all cases, the stellar mass is $\approx 0.8\ M_\odot$. The number of clumps and their masses are similar in the Z=1.0 and $0.1\ Z_\odot$ models, but the $Z=0.01\ Z_\odot$ model is distinct. The number of clumps and the fragmentation stage are notably shorter, and the lack of massive clumps is also evident. These differences can be explained by a shorter lifetime of the contracting $Z=0.01\ Z_\odot$ cloud thanks to a higher gas temperature and mass infall rate in this model (see the red line in the top figure).

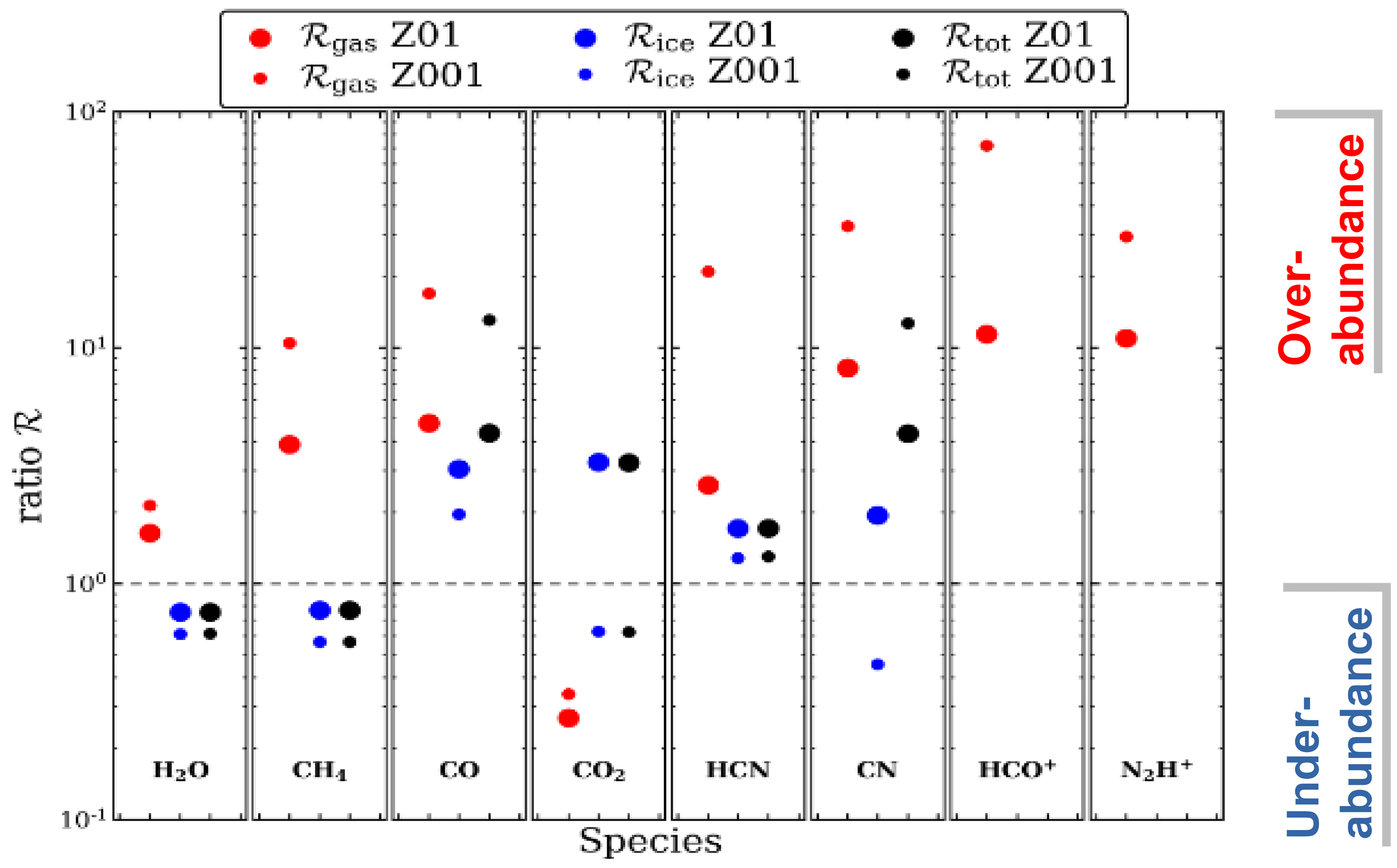


Disk chemical evolution at $Z = 0.1\ Z_\odot$ and $0.01\ Z_\odot$



The top figure on the l.h.s. shows the contour plots of the gas abundances of HCO+ and the total (gas + ice) abundances for CO. The top row corresponds to the model with solar metallicity. The middle and bottom rows correspond to the models with metallicity $0.1\ Z_\odot$ and $0.01\ Z_\odot$, respectively. With decreasing metallicity the formation reactions of CO are enhanced. This is more notorious around the midplane of the disk. On the r.h.s. we show the corresponding total vertical column density of HCO+ and CO. The top row shows models with $1\ Z_\odot$, $0.1\ Z_\odot$, $0.01\ Z_\odot$ metallicity (solid, dashed, and dotted lines, respectively). The middle and bottom rows show the difference between the model with metallicity $0.1\ Z_\odot$ and $0.01\ Z_\odot$ (black dashed line and dotted line, respectively) and the scaled down values of the solar metallicity model by a factor of 10 and 100 (red dashed line and red dotted line). The red region shows the radii where the vertical column density of the sub-solar metallicity models is higher than the simple scaled-down values. The green region corresponds to lower values than the scaled down values.

The bottom figure shows the ratio, $\mathcal{R}$ of the total molecular amount of the scaled-down and the sub-solar metallicity models with $0.1\ Z_\odot$, and $0.01\ Z_\odot$. The red, blue, and black circles correspond to the ratios of the gaseous, ice, and total (gas + ice) species, respectively. The dashed horizontal line shows the value for the ratio equal to 1.



Summary. We have conducted numerical hydrodynamics and chemothermal simulations of circumstellar disks around solar-mass stars with metallicities ranging from $1.0\ Z_\odot$ to $0.01\ Z_\odot$. The FEOSAD code that features distinct gas and dust temperatures [1] and the ProDiMo [2] code were used for this purpose. We demonstrated that gravitational fragmentation of circumstellar disks and associated accretion bursts are present down to $Z=0.01\ Z_\odot$, but the strength of the process declines at $Z<0.1\ Z_\odot$ for objects of similar stellar mass [3]. The chemical evolution of subsolar metallicity disks shows that the chemical destruction and formation reactions of the molecules change in their reaction rates and in reaction type with metallicity. Moreover, the impact of metallicity on the chemical abundances is clearly non-linear. The particular case of CO and H_2O suggests the CO/H_2O ratio in disks increase with decreasing metallicity.

[1] Vorobyov et al. 2020, A&A, 638, 102; [2] Woitke et al. 2009, 501, 383; [3] Vorobyov et al. 2020, A&A, 641, 72; [4] Guadarrama et al. 2022, A&A, 667, 28.
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