Radiation-hydrodynamical simulations of photoevaporating protoplanetary disks with various metallicities

Riouhei Nakatani¹, Takashi Hosokawa², Naoki Yoshida¹,², Hideko Nomura, and Rolf Kuiper³

1. The University of Tokyo, 2. Kyoto University, 3. Kavli IPMU, 4. Tokyo Institute of Technology, 5. University of Tübingen

Email: r.nakatani@utap.phys.s.u-tokyo.ac.jp

(Nakatani et al. in prep.)

Abstract: Recent studies show that a protoplanetary disk lifetime is shorter in the low metallicity environments than the solar neighborhood. Photoevaporation is suggested as an important mechanism to explain it. We perform radiation-hydrodynamical simulations of photoevaporation of a protoplanetary disk. We simultaneously solve hydrodynamics, self-consistent EUV/FUV radiative transfer, and non-equilibrium chemistry. Grain temperatures are also calculated by solving the radiative transfer of the stellar irradiation and grain (re)radiative mechanism to the gas. We perform simulations in the low metallicity environment, the range of 10^{-2} Z_{S} ≤ Z ≤ 10 Z_{S}. We develop a semi-analytic model. It can well explains the metallicity dependence of the photoevaporation rates and the radial distribution of them. Our results are consistent with the observed lifetimes.

I. Motivation

• A protoplanetary disk has the lifetime estimated to be 3 - 6 Myr [1] (see the black line of Fig.1).

• Extreme outer Galaxy clusters suggest a short disk lifetime estimated to be ≲ 1 Myr [2].

A lifetime is shorter in lower metallicity environments. (see the red line of Fig.1)

References: [1] (see the black line of Fig.1).

II. Numerical Simulation & Methods

Consistent radiation-hydrodynamics with non-equilibrium chemistry

Simulation setup

• 2D spherical polar coord.
• Symmetry
• Axis (θ = 0)
• mid-plane (θ = π / 2)
• Computational domain
• r = [1, 100] AU
• θ = [0, π/2] rad

Stellar parameters (a low-mass PMS star)

\[ \Psi_{\text{EUV}} = 6 \times 10^{12} \text{ s}^{-1} \]
\[ \Psi_{\text{FUV}} = 4 \times 10^{12} \text{ erg s}^{-1} \]
\[ \Psi_{\text{ions}} = 2 R_{\odot} M_{\odot} = 0.5 M_{\odot} \] (e.g., Draine, B. A., and Li, W.)

Chemical Reactions

• Photoionization,
• H$_{2}$ photodissociation
• CO photodissociation
• Collisional reactions

Heating/Cooling Processes

• Photo-heating
• EUV (photoionization)
• FUV (photoelectric effect)
• Other cooling
• Recombination
• Dust-gas heat transfer

Dust Temperatures

• Radiation transfer (hybrid-scheme) for direct & diffusion component
• \( T_{\text{dust}} = [\text{free-emission}] = \text{[direct & diffusion components absorption]} \)

III. Results: Solar Metallicity: Disk

Density Near FUV & EUV molecular flow

Neutral flow density increases with decreasing metallicity. With very low metallicity, the neutral flow is not even excited.

IV. Results: Various Metallicity Disks

• Neutral flow density increases with decreasing metallicity.

In (neutral) base regions (\( n_{\text{H}} \approx Z^{-1} \)), dust-gas cooling \( \propto n_{\text{H}} n_{\text{H}_{2}} \approx Z^{-1} \)

FUV heating \( \propto n_{\text{H}} \rightarrow Z \times Z^{-1} = 1 \)

Cooling is effective with lower \( Z \) Temperature becomes lower Neutral flow is not excited

V. Results: Metallicity Dependence

FUV heating is less effective than cooling. It becomes hard to excite neutral flow.

High density flow with lower Z

FUV heating is less effective than cooling. It becomes hard to excite neutral flow.

Only ionized flow is excited. It is caused by EUV, so metallicity-independent

References:

[1] (see the black line of Fig.1).

[2] (see the red line of Fig.1).