Radiation Hydrodynamics Simulations of Photoevaporating Protoplanetary Disks: Implications to Metallicity Dependence of Disk Lifetimes

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Papers: Nakatani et al. (2018a,b)
Standard Scenario of Low-Mass Stellar-system Formation

(a) GMC, Dark Cloud

(b) Clump
- Gravitational contraction
- Core

(c) PMS star + Disk
- Jet
- Accretion
- Protoplanetary disk
- Protostar + Disk + Envelope

Our interest

Debris disk/Planetary system

~10⁴-⁵ yr
~10⁶ yr
~10⁷ yr
~10⁶ yr
~10³ au
Protoplanetary Disk (PPD)

- Geometrically thin Keplerian disk around a young star
- Main components: Gas/Dust
- Birthplace of planets
  → disk dispersal time characterizes planet formation timescale.
The lifetimes have been estimated with IR observations.

**Typical PPD SED**

- **Observed SED**
- **Stellar component**

- **Circumstellar dust**
- **IR-excess**

- **Stellar component**

**Protoplanetary disk fractions**

- HG 2024
- Trapezium
- Taurus
- Chameleon
- NGC 2264
- NGC 2362

**Typical lifetime**

\[ \sim 3\text{-}6 \text{ Myr} \]

*** Disk Fraction = \( \frac{\text{disk-bearing members in a cluster}}{\text{total number of members}} \)
Subaru NIR observations have revealed metallicity dependence in disk lifetimes.

Low Z environments may faster disk dispersal for some reason.
Significances of the metallicity dependence.

<< Lifetime – planet formation >>
- Time limit to gaseous \textit{planet formation}
- Set \textit{initial configuration}
- Influence on \textit{chemical states}

<< The metallicity dependence – planet formation >>
- Suggest \textit{planet-formable environments}
- Disk evolution/planet \textit{formation in general metallicity environments}
Photoevaporation - a disk-dispersing mechanism -

e.g., Bally & Scoville (1982); Shu et al. (1993), Hollenbach et al. (1994)

Unbound, hot photoevaporative flow

Surface gas heating

FUV: \((6 \text{ eV} \lesssim h\nu \lesssim 13.6 \text{ eV})\)
EUV: \((13.6 \text{ eV} \lesssim h\nu \lesssim 0.1 \text{ keV})\)
X-rays: \((0.1 \text{ keV} \lesssim h\nu \lesssim 10 \text{ keV})\)

\[
\frac{\text{gravitational energy}}{\text{thermal energy}} = \frac{GM_\ast}{r c_s^2} \lesssim 1
\]

\[\iff r \gtrsim \frac{GM_\ast}{c_s^2} \sim 10 \text{ AU} \left(\frac{M_\ast}{M_\odot}\right) \left(\frac{T}{10^4 \text{ K}}\right)^{-1}\]

Typical mass loss rate (photoevaporation rate): \(10^{-10} - 10^{-8} M_\odot \text{ yr}^{-1}\)
Metallicity affects the disk opacity to FUV and X-ray.

<table>
<thead>
<tr>
<th></th>
<th>FUV</th>
<th>EUV</th>
<th>X-rays</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Photon energy</strong></td>
<td>$6 \text{ eV} \leq h\nu \leq 13.6 \text{ eV}$</td>
<td>$13.6 \text{ eV} \leq h\nu \leq 100 \text{ eV}$</td>
<td>$0.1 \text{ keV} \leq h\nu \leq 10 \text{ keV}$</td>
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<tr>
<td><strong>Main absorber</strong></td>
<td>Dust</td>
<td>Atomic hydrogen</td>
<td><strong>Metal elements</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$(\geq 0.3 \text{ keV})$</td>
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<tr>
<td><strong>Penetrability</strong></td>
<td>High</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td><strong>Metallicity</strong></td>
<td>Dependent</td>
<td>Independent</td>
<td>Dependent</td>
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<tr>
<td><strong>dependence</strong></td>
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Our Aims:
- Understand metallicity dependence of mass-loss rates
- Give implications to the observational lifetimes

**Diagram:**
- **FUV (6 eV ≤ h\nu ≤ 13.6 eV)**
- **EUV (13.6 eV ≤ h\nu ≤ 100 eV)**
- **X-rays (0.1 keV ≤ h\nu ≤ 10 keV)**
- **Metal elements (≥ 0.3 keV)**

**Thermalization:**
- FUV dust to dust
- EUV H to p
- X-ray + primary electron to secondary electron
We performed the first self-consistent rad.-hydro. simulations

<table>
<thead>
<tr>
<th></th>
<th>Hollenbach+94</th>
<th>Gorti+09</th>
<th>Owen+10</th>
<th>Ercolano+10</th>
<th>Wang+17</th>
<th>Nakatani+18a</th>
<th>Nakatani+18b</th>
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<tr>
<td>(Detailed) Chemistry</td>
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</table>
Photoevaporating Disk = Cold disk + Hot wind

(Nakatani +18a)

DB: Rz.vtr

Length unit: 100au

(Our simulations are in 2D spherical polar coordinates.)

UV- & X-ray-heated region = Wind region
Optically thick region = Steady disk region

Photoevaporating disk
Cold disk ( ~10 - 100 K) + Hot winds (> 10³ K)
EUV (H$^+$ EUV$\rightarrow$ H$^+$ + e$^-$)  
FUV (dust + FUV$\rightarrow$ dust + e$^-$)  

Ionized flow  
Neutral flow  
OI cooling  
Adiabatic cooling  
H$_2$ cooling  

Dominant cooling  
Dominant heating  

Chemical structure  
Density distribution  

Dashed lines ($\tau_{\text{FUV}}$)  
Magenta: 0.5  
Yellow: 1  
Black: 2  

Solid lines ($n_H/\text{cm}^{-3}$)  
Cyan: $10^5$  
Blue: $10^6$  
Black: $10^7$  
Red: $10^8$  

EUV-driven ionized flow  
launch at $\tau_{\text{FUV}} \sim 1$ (base)  
(yellow dashed line)  
$v_p \sim 5 - 30$ km/s  

Photoevaporative flows  
launch at $\tau_{\text{FUV}} \sim 1$ (base)  
(yellow dashed line)  
$v_p \sim 0.5 - 5$ km/s  

Dust-gas collisional cooling (blue region) is dominant at the base  
$v_p \sim 0.5 - 5$ km/s  

$k(T_{\text{gas}} - T_{\text{dust}})$ is lost from gas per collision  

Color Scales
We do find metallicity dependence

\[ Z = 10^{-3} Z_\odot \]

\[ Z = 10^{-0.5} Z_\odot \]

\[ Z = 10^{0.5} Z_\odot \]

Time: 0

Disk

Only ionized flow

Dust cooling > FUV heating
Heating time > Dynamical time

Ionized flow (EUV-driven) + neutral flow (FUV-driven)

high \( n_H \propto Z^{-1} \)

FUV penetrates deeper;
Photoevaporation rate is the highest at subsolar metallicities.
Photoevaporation can yield the short lifetimes

Our model predicts long lifetimes here

Consistent between the model and obs.
Summary


2. Methods: Hydrodynamical simulations with radiative transfer and non-equilibrium chemistry to examine the metallicity dependence of photoevaporation.

3. Results: Photoevaporation rates has a peak at $Z \sim 10^{-1} Z_\odot$. X-rays strengthen the FUV heating in the extremely low-metallicity range.

4. Conclusion: Our model gives consistent lifetimes with the observed lifetimes. Our model predicts disks would have even longer lifetimes in the much lower metallicity environments $Z \leq 10^{-2} Z_\odot$. 