Evaporation Timescales of HI Clouds

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1. Introduction
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Discovery of Tiny HI clouds

sub-pc (~0.01pc) clouds
“tiny” HI clouds recently discovered!

Braun & Kanekar (2005)
Stanimirovic & Heiles (2005)

\[ N \sim 10^{18} / cm^2 \]

simple interpretation:
CNM cloud surrounded by WNM

Growth rate?
... Most fundamental quantity
Formation of Tiny HI Clouds

thermal instability and turbulence behind shock fronts:
many clumps form

... one of natural mechanisms of HI clouds formation

Once the clouds formed, how they evolve?

Koyama & Inutuka (2002)
Physical State of Diffuse ISM Clouds

Myers (1978)

Log\[n/cc\]

Log\[T/K\]

diffuse clouds
WNM/CNM
under pressure equilibrium

constant pressure
\(P/k \sim 10^3\)

Fig. 1.—Interstellar gas temperature, density, and pressure, based on seven galactic spectral line surveys. Circles, representative points for coronal gas observed in 1032 Å O vi line, based on filling factor \(f_\text{c} = 0.1, 0.2, \text{ and } 0.4,\) and on \(n(T)\) power-law exponent \(\eta = 0.0, 0.5, \text{ and } 1.0;\) semicircles pointing down, intercloud gas observed in 21 cm H i line; semicircles pointing up and triangles pointing down, diffuse clouds observed in 21 cm H i line; triangles pointing up, dark clouds observed in 21 cm H i line; triangles pointing left, dark clouds observed in 2.6 mm CO lines; diamonds, Bok globules observed in 2.6 mm CO lines; squares, molecular clouds associated with nebulosity, observed in 2.6 mm CO lines; semicircles pointing left, H ii regions observed in 6 cm H109\(\alpha\) line and 6 cm continuum.

Myers (1978)
Physical State of Diffuse Clouds

Diffuse (n<10^2 cc) gas in the ISM:

- Co-existence with two phases
  Warm Neutral Medium (WNM)
  \[ T \sim 10^4 \text{ K}, \ n \sim 10^{-1} / \text{cm}^3 \]
  Cold Neutral Medium (CNM)
  \[ T \sim 10^2 \text{ K}, \ n \sim 10^1 / \text{cm}^3 \]

- pressure balance with heat-conductive interface

- negligible self-gravity

\[ \tau \sim \frac{1}{\sqrt{G \rho}} \sim 1.2 \times 10^8 \left( \frac{n}{\text{cm}^{-3}} \right)^{-1/2} \text{ yr} \sim \text{Galactic rotation} \]

\[ l \sim 2 \times 10^3 \left( \frac{T}{10^2 \text{ K}} \right)^{1/2} \left( \frac{n}{\text{cm}^{-3}} \right)^{-1/2} \text{ pc} \sim \text{Galaxy size} \]
Heating/Cooling rates

Koyama & Inutsuka (2000)

Our results do **NOT** depend on the details of the heating/cooling processes
Thermal instability

sequence of heating \((\Gamma)\) = cooling \((\Lambda)\)

\(\Gamma < \Lambda\) unstable eq.

\(\Gamma > \Lambda\) stable eq.

Frontal motion between WNM and CNM corresponds to CNM domain (cloud) growth at “saturation pressure” \(p_{\text{sat}}\), \(\Gamma = \Lambda\) over the whole system.

Koyama & Inutsuka's cooling function used

\(\nabla P/k\)
Evaporation & Condensation

Pressure determines whether evaporation or condensation

\[ p > p_{\text{sat}} \quad \text{whole system cooling : condensation} \]

\[ p < p_{\text{sat}} \quad \text{whole system heating : evaporation} \]

Describing evaporation and condensation of clouds
Basic equations

**continuity**
\[ \frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{v} = 0 \]

**EOM**
\[ \frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} = -\frac{1}{\rho} \nabla p \]

**energy eq.**
\[ \frac{\partial \rho e}{\partial t} + \nabla \cdot (\rho e \mathbf{v}) + p \nabla \cdot \mathbf{v} = -(n^2 \Lambda - n \Gamma) + \nabla \cdot \kappa \nabla T \]

\[ \rho e = pl(y-1) \quad \text{heat-loss function } \mathcal{L} \]

\[ p = nk_B T \quad \text{conductivity for neutral gas } \kappa \propto T^{1/2} \]

\[ \mathcal{L} \]

0 \quad T \quad like a cubic function
Characteristic scales

cooling time
\[ \tau_{cool} \approx \frac{kT}{n \Lambda} \approx 10^4 - 10^6 \text{ yr} \approx 3 \times 10^{11-13} \text{ s} \]

sound velocity
\[ c_S \approx 10^5 \left( \frac{T}{10^2 K} \right)^{1/2} \text{ cm/s} \]

Field length:
cooling = thermal conduction providing the thickness of front (transition layer)
\[ l_F = \sqrt{\frac{kT}{n^2 \Lambda}} \approx 3 \times 10^{15} - 10^{18} \text{ cm} \]

\[ v < l_F / \tau_{cool} \approx 10^4 \text{ cm/s} \ll c_S \]

ISM is quickly separated into two phases then the domain grows slowly
Numerical Simulation

Numerical simulation for spherically symmetric clouds

1D (radial), Lagrangean mesh (2000), 2nd-order Godunov boundary condition: a constant outside pressure (p_WNM)

example \( p = p_{\text{sat}} = 2823 \text{kB}; \) saturation pressure

Radius of clouds is defined at which the density is half the CNM density

snapshots of a cloud evaporating
Evaporation rate $dM/dt$

- Numerical simulation is consistent with quasi-steady state ev.
- McKee-Cowie's $dM/dt$ overestimates by a factor of 4-5

$$\frac{dM}{dt}(r) = 4\pi r^2 \rho(r) v(r)$$

Case of $p=p_{\text{sat}}$

- McKee&Cowie's $dM/dt$
- $dM/dt$ at surface
- $dM/dt(r)$
- Quasi-steady state (QSS) numerical solution
- Full Numerical Simulation
Evaporation Timescale

R~0.01pc clouds evaporate in ~Myr

If tiny HI clouds exist ubiquitously, some mechanisms are needed to create the clouds continuously.

expectation from the analytic formula
Critical Size for Condensation

- When \( p > p_{\text{sat}} \), static clouds can exist.
- Static clouds are always unstable.
- 0.01pc clouds must evaporate in the standard case of \( \Gamma \).
Analytic Approximation Formula

1. **Isobaric approximation**
   because of much slower motion than sound velocity

   \[
   T_{ds} = dU + pdV \\
   = d(U + pV) - Vdp \\
   = dH - Vdp \\
   \rightarrow T_{ds} = dH
   \]

\[
\frac{\gamma}{\gamma - 1} \frac{k_B}{\mu} \rho \frac{dT}{dt} + \frac{dp}{dt} = -\rho \mathbf{\mathcal{L}} + \nabla \cdot \kappa \nabla T
\]

2. Assuming **quasi-steady state (QSS)**

\[
\frac{\partial}{\partial t} \rightarrow -\dot{R} \frac{\partial}{\partial r} \equiv -\dot{R} \partial_r
\]

\[
\dot{R} : \text{speed of a front}
\]

\[
\dot{R} < 0 \quad \text{v>0} \\
\text{(in case of evaporation)}
\]
Analytic Approximation Formula

in case of d-dim. spherically symmetric, energy eq. becomes

\[ \frac{\gamma}{\gamma - 1} \frac{k_B}{\mu} \rho u_d \partial_r T = -\rho \mathcal{L} + \partial_r \kappa \partial_r T + \frac{d - 1}{r} \kappa \partial_r T \]

replace with LHS for d=1

or,

\[ \frac{\gamma}{\gamma - 1} \frac{k_B}{\mu} \rho u_1 \partial_r T = -\rho \mathcal{L} + \partial_r \kappa \partial_r T \]

assuming the same

or,

\[ u_d \partial_r T = u_1 \partial_r T + \frac{\gamma - 1}{\gamma} \frac{\mu}{k_B} \frac{d - 1}{r} \kappa \partial_r T \]
Analytic Approximation Formula

\[ u_d \frac{\partial}{\partial r} T = u_1 \frac{\partial}{\partial r} T + \frac{y-1}{\gamma} \frac{\mu}{k_B} \frac{d-1}{r} \frac{\kappa}{\rho} \frac{\partial}{\partial r} T \]

non-zero only at \( r=R \) (cloud surface)

A non-trivial solution is obtained at \( r=R \), so

\[ u_d(R) = u_1(R) + \frac{y-1}{\gamma} \frac{\mu}{k_B} \frac{d-1}{R} \frac{\kappa(R)}{\rho(R)} \]

mean curvature

(fluid velocity) = (fluid velocity for \( d=1 \)) + (curvature term)

- non-zero \( dT/dr \) only at front
- substitution LHS in \( d=1 \) for 1st and 2nd terms in RHS
Analytic Approximation Formula

By further transformation, \((u \rightarrow \dot{R})\)

\[
\dot{R} = V(p) - \frac{\gamma - 1}{\gamma} \frac{\mu}{k_B} \frac{d - 1}{R} \frac{\kappa(R)}{\rho_{\text{CNM}}} \equiv V(p) \left(1 - \frac{R_{\text{crit}}}{R}\right)
\]

Evaporation rate:

\[
\dot{M} = -4\pi \rho_{\text{CNM}} R^2 \dot{R} \propto R^2 \propto M^{2/3} \quad \text{for} \quad R \gg R_{\text{crit}}
\]

\[
\propto R \propto M^{1/3} \quad \text{for} \quad R \ll R_{\text{crit}}
\]

Curvature term is very similar to McKee & Cowie (1977)'s evaporation rate within a factor of 4-5

\[
\dot{m} = \frac{16\pi \mu \kappa R}{5k_B} = 1.3 \times 10^{15} T_f^{1/2} R_{pc} \quad \text{g s}^{-1}
\]

\[
\dot{M} = \frac{16\pi \mu \kappa(R) R}{5k_B}
\]

substantially different from MC77 for

- large \(p_{\text{WNM}}\)
- large clouds
Evaporation Timescale

R~0.01pc clouds evaporate in ~Myr

expectation from the analytic formula
Summary

- **Clouds of 0.01 pc evaporate in 1Myr**
- \( \tau_{\text{evap}} \) for >0.1 pc depends strongly on \( P_{\text{WNM}} \)
  -> large clouds can grow

- Tiny clouds must be formed continuously,
or, ambient pressure would be much higher than standard value, \( P/k_B \approx 10^{3.5} \)
  probably because of higher heating rate.

- Study of statistical properties such as mass function is important for future analysis