Observational and Theoretical Review of the Multiphase ISM

So, it works in Practice…but does it work in Theory?

So, it works in Theory….so What?

1) Galactic Diffuse Phases

2) Dark CO Gas

3) Decomposition of Phases

4) Miscellaneous Phases

Motte et al. 2010
Rosette
PDR: Gas phase in which FUV radiation plays a role in the heating and/or chemistry

- **FUV**: 6 eV – 13.6 eV
- **$G_0 = 1$** Interstellar field
- **$G_0$**: Habing $\chi$; Draine $\sim 1.7 G_0$
- **U**: Mathis $\sim 1.1 G_0$
- **$G_0 = 10^5$** Orion trapezium

**Warm H**
- $T = 8000$ K
- $n = 0.3$ cm$^{-3}$
- $r \sim 100s$ pc

**Cold H**
- $T = 80$ K
- $n = 30$ cm$^{-3}$
- $r \sim$ few pc

**Cold H$_2$**
- $T = 10$ K
- $A_v = 8$
- $n_e = 30$–$100$ cm$^{-3}$
- $r \sim 10s$ pc

**Classic PDR**

- **C$^+$/HI**
- **FUV**
- **H$^+$**
- **OR star**

**C$^+$/H$_2$** "Dark" CO

**WNM**
- **C$^+$/HI**
- **FUV**
- **H$^+$**
- **OR star**

**CNM**
- **C$^+$/H$_2$** "Dark" CO
- **FUV**
- **H$^+$**
- **OR star**
Warm $H$  
$T = 8000 \text{ K}$  
$n = 0.3 \text{ cm}^{-3}$

Cold $H$  
$T = 80 \text{ K}$  
$n = 30 \text{ cm}^{-3}$

Warm $H^+$  
$T = 8000 \text{ K}$  
$n_e = 5 \text{ cm}^{-3}$

Cold $H$  
$T = 80 \text{ K}$  
$n = 30-100 \text{ cm}^{-3}$

Classic PDR

C$^+$/HI

WIM

WNM

EUV

C$^+$/H$_2$  “Dark” CO

OR star

Short lived/Transient regions  
(shocks, shears, turbulence)
Ionization: FUV, X-ray, C.R.
Heating: P.E., C.R., X-ray/EUV
Cooling: [CII], [OI], Lyα,
e\textsuperscript{-} recombination

\[ n \Gamma = n^2 \Lambda \]
\[ \downarrow \]

\[ T \]

\[ T = 7860 \quad n = 0.35 \text{ cm}^{-3} \]
WNM

\[ T = 85 \quad n = 33 \text{ cm}^{-3} \]
CNM

Diffuse Gas Heating/Cooling

Wolfire et al. (2003)
C II Cooling/H (CNM) > 10 C II Cooling/H (WNM)

** Note **
CNM in Thermal Balance: [CII] measures the total energy dumped into the gas.

Heating Rate = const
n \downarrow
Z \downarrow
T \uparrow
[CII] = const

Wolfire et al. (2003)
C.R. ionization
Indriolo et al. 2012

Thermal Pressure
Jenkins et al. 2011

C II Cooling/H (CNM) > 10 C II Cooling/H (WNM)

** Note **

CNM in Thermal Balance: [CII] measures the total energy dumped into the gas.

Heating Rate = const
n \downarrow
Z \downarrow
T \uparrow
[CII] = const

Wolfire et al. (2013)
50% of gas mass in unstable $T_s$ 

Locally: 60% WNM, 40% CNM (also Pineda et al. 2013)

In plane 25% of WNM in unstable $T_s$ or 15% of total mass.

Out of plane dominated by dynamical processes.

In plane uncertainties large, and statistics poor: 8 in 79 out

Begum et al. 2010
Multiphase Galactic Disks

\[ P_{\text{max}} - P_{\text{min}} \]

Thermal Pressure in CNM

\[ P_{\text{two-phase}} = \sqrt{P_{\text{min}} P_{\text{max}}} \]

Jenkins & Tripp 2011

Kim, Kim, & Ostriker 2011
Regulation of Thermal Pressure

\[ P_{\text{tot}} \propto \sum_{(\text{WNM})}^2 \text{gas} \]

\[ P_{\text{th}} = \alpha P_{\text{tot}} \]

\[ \alpha \approx 10\% - 20\% \]

CNM / WNM are PDRs (heated by FUV)

More CNM leads to more star formation (FUV)

Ostriker, McKee, & Leroy 2010
Molecular Hydrogen

Dark Molecular Gas
C\(^+\)/H\(_2\) but no CO

N\(_{\text{tot}}\) - N\(_{\text{HI}}\) - N\(_{\text{CO}}\) = N\(_{\text{Dark Gas}}\)

IRAS 100 \(\mu\)m \(30\%\) DG
Planck IR \(50\%\) DG
EGRET \(\gamma\) rays \(30\%\) DG
Fermi \(\gamma\) rays \(50\%\) DG
Extinction (2MASS) 43-71\% DG
Herschel Got C\(^+\) \(30\%\) DG

Grenier et al. 2005, Science, 307, 1292
Wolfire, Hollenbach, & McKee 2010

Pineda et al. 2013

Grenier et al. 2005

Dark Gas Fraction

Tielens & Hollenbach 1985
van Dishoeck & Black 1988
Madden et al. 1997

(IC 10  80% PDR with C\(^+\)/H\(_2\))

\[ f_{\text{DG}} = 1 - \exp \left( \frac{-4.0 \Delta A_V}{\bar{A}_V} \right) \]

\[ \bar{A}_V = 5.26 Z' \tilde{N}_{22} \]

\[ f_{\alpha} = \frac{[M(R_{\text{co}}) - M(R_{\text{co}})]}{M(R_{\text{co}})} \]

Dark Gas Fraction

\[ M(R_{\text{co}}) = 1 \times 10^6 M_\odot \quad \tilde{N}_{22} = 0.75 \]

\[ Z' = 0.5 \]

\[ Z' = 1.0 \]

\[ Z' = 1.9 \]

\[ M(R_{\text{co}}) = 3 \times 10^6 M_\odot \]

\[ M(R_{\text{co}}) = 1 \times 10^6 M_\odot \]

\[ M(R_{\text{co}}) = 3 \times 10^5 M_\odot \]

\[ M(R_{\text{co}}) = 1 \times 10^5 M_\odot \]
Dark Molecular Gas?  
C⁺/H₂ but no CO

N_{tot} - N_{HI} - N_{CO} = N_{Dark Gas}

IRAS 100 µm  30%  DG
Planck IR      50%  DG
EGRET γ rays  30%  DG
Fermi γ rays  50%  DG

Extinction (2MASS) 43-71% DG

Herschel Got C⁺  30%  DG

Hydro Models:
FUV penetration:
Glover & Mac Low 2011
Distribution of densities:
Glover & Mac Low 2007
Time dependence: Clark et al 2012
Decomposition of Phases

**Warm H**
- $T = 8000 \text{ K}$
- $n = 0.3 \text{ cm}^{-3}$
- $r \sim 100 \text{ s pc}$

**Cold H**
- $T = 10 \text{ K}$
- $A_v = 8$
- $r \sim 10 \text{ s pc}$

**Warm H$^+$**
- $T = 8000 \text{ K}$
- $n_e = 5 \text{ cm}^{-3}$
- $r \sim 100 \text{ s pc}$

**Cold H$^+$**
- $T = 80 \text{ K}$
- $n = 30 \text{ cm}^{-3}$
- $r \sim \text{ few pc}$

**C$^+$/H$^+$**
- OR star

**C$^+/H_2$ “Dark” CO**
- $[\text{CII}], [\text{OI}], [\text{CI}], \text{H}_2$
PDR Emission

- Orion PDR
- Classic PDRs
- $G_0/n = \text{const}$

Diffuse Gas

Kaufman et al. 1999

Heating Efficiency

Kaufman et al. 1999
PDR Emission

[Image of a diagram showing [OI]/[CII] ratio versus electron density (n) with Orion PDR and Classic PDRs highlighted.]

- Orion PDR
- Classic PDRs

Heating Efficiency

[Image of a diagram showing FUV heating efficiency (G_0/n) versus electron density (n).]

- G_0/n = const

Kaufman et al. 1999

Diffuse Gas
Croxall et al. 2012
What $n_e$ to use?

Get $n_e$ from [SIII] 18.7/33.5 for $n_e > 10^2$

or

Pick $n_e = 10$
NGC 1097
NGC 4559

\[ \text{[NII]} 122 \]
\[ + \text{[SIII]} 18.7/33.5 \]

Ionized Gas

or

\[ \text{[NII]} 122 \]
\[ + n_e = 10 \]

Diffuse neutral emission

Constraints from dust emission

Croxall et al. 2012
Averge U from dust emission

\[ dM_{\text{dust}} \propto (1 - \gamma) U_{\text{min}} + \gamma U^{-2} \]

\[ L_{\text{PDR}} \propto L(U > 100) \]

Draine & Li 2007

NGC 6946 PACS 160 resolution

~ 165 pc

Aniano et al. 2012
Low average $U \sim 5$, low $f_{\text{PDR}} < 20\%$

Diffuse gas + low $U$ on GMCs

Also Cubick et al. 2008, Pineda et al. (2010, 2013) find $U < 100$

Wolfire, Hollenbach in prep: average $U$ on GMCs $\sim 10-30$
$\text{[NII]}$ 122 + $\text{[SIII]}$ 18.7/33.5

**Ionized Gas**

or

$\text{[NII]}$ 122 + $n_e = 10$

**Diffuse Gas**

30% of $\text{[CII]}$

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Croxall et al. 2012

**NGC 1097**

**NGC 4559**

$10^2$

$10^3$

$10^4$

$10^3$

$G_0$

$10^2$

$10^3$

$10^3$

$10^4$

$10^3$

$10^4$

$10^3$

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$10^3$
Mookerjea et al. 2011 HerM33es
20-30% [CII] ionised gas
80-70% [CII] neutral PDR

Lebouteiller et al. 2012 SHINING
5-15% [CII] diffuse ionised
85-95% [CII] neutral PDR

Cormier et al. 2012
90% [CII] diffuse
10% [CII] neutral PDR
Kennicutt et al. 2011

Herschel PACS

KINGFISH

FWHM 250 pc

ΔE/k ~ 229 K

H2 S(0) ΔE/k ~ 510 K

NGC 3521

Spitzer IRS

SINGS

Brunner et al. 2009

Meijerink et al. 2007

Δ

ΔE/k ~ 510 K

Roussel et al. 2007

Meijerink et al. 2007

Meijerink et al. 2011

Appleton et al. 2006

Shocks ?

Turbulent Dissipation ?

Large scale mechanical energy dissipation ?

Godard et al. 2009

X-rays ?

Cosmic Rays ?

Turbulent Dissipation ?
Phase Distribution Constraints from OVI

$n_0 = 1.3 \times 10^{-8} \text{ cm}^{-3}$

N(OVI) from FUV absorption line of OVI

Conductive interfaces
Turbulent mixing layers

d de Avillez & Breitschwerdt 2005
Phase Distribution Constraints from OVI

N(OVI) from FUV absorption line of OVI

n(OVI) only few $10^{-8}$ cm$^{-3}$
D. Cox numerous

MO too much OVI
Slavin & Cox clouds in WNM reduces OVI

Reality!
Phase Distribution Constraints from OVI

N(OVI) from FUV absorption line of OVI

$n_0 = 1.3 \times 10^{-8} \text{ cm}^{-3}$

Bowen et al. 2008

de Avillez & Breitschwerdt 2005

N(OVI) from FUV absorption line of OVI

Bowen et al. 2008

de Avillez & Breitschwerdt 2005
Conclusions

1.) CNM pressure distribution width set by turbulence but median set by two-phase pressure.

2.) Tentatively: the mass fraction of in-plane thermally unstable gas is not very high. I am waiting for better statistics.

3.) The mass fraction of out-of-plane thermally unstable gas IS high

4.) Self-regulating cycle (pressure, star formation, phase transitions) maintains the two-phase pressure in the midplane

5.) Dark gas. How do models compare with observations (at low Z). Could it be substantially HI and not $\text{H}_2$? Do hydro models produce more DG?

6.) Ample evidence for small scale mechanical heating/turbulent dissipation. Can this dominate at large scale in diffuse gas?
Conclusions

7.) [CII] mainly comes from moderate n and moderate to low $G_0$
    PDRs plus some neutral diffuse gas (mainly in outer galaxy).

8.) WIM/HII contribution to [CII] is uncertain $\sim 30\%$

9.) OVI constraints. Must not overproduce OVI. Likely
    comes from turbulent mixing regions between HIM/CNM/WNM