Équilibre thermique du réservoir de gaz neutre à très faible métallicité.

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Motivations / objectifs

- Importance du gaz moléculaire (sombre en CO ou non) *(e.g., Madden+ 1997; Wolfire+ 2010)* et du gaz atomique *(e.g., Glover & Clark 2012; Krumholz 2012)* dans la formation stellaire
- Régulation de la formation stellaire: retro-action des supernovæ, chauffage par effet photoélectrique *(e.g., Forbes+ 2016)*, autres mécanismes?
- [C II] 157 μm, refroidisseur omniprésent du gaz neutre, détecté à très grand z ⇒ Quels diagnostics, en particulier dans les galaxies pauvres en métaux?

Modélisation d'I Zw 18 (18 Mpc, 1/35 $Z_\odot$, G/D$\sim$ 1000 MW, aucune détection de molécules)

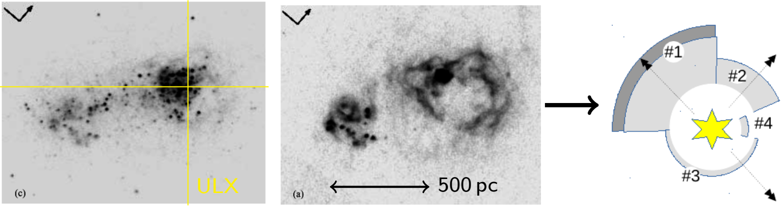
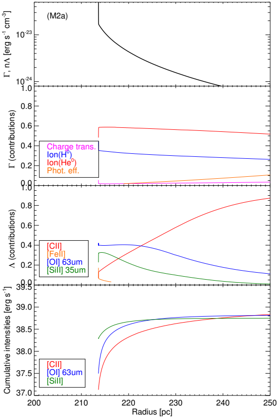


Fig.: *I Zw 18 en bande R et Hα (Cannon+ 2002) – stratégie de modélisation (Lebouteiller+ soumis)*

Résultats

- Chauffage du MIS dominé par photoionisation dû à une source X binaire $(10^{40}\,\mathrm{erg\,s^{-1}})$. Effet photoélectrique et rayons cosmiques négligeables.



Implications

- Corrélation L_X–SFR *(e.g., Grimm+ 2003)* ⇒ [C II] trace encore la formation stellaire
- [C II] (et [O I] 63 μm) ne tracent que le gaz atomique, même dans l'hypothèse de fragments froids et denses. Fragments $\ll 1$ pc, pouvant représenter $\sim$ 50% de la masse totale de gaz
- Transition entre mécanismes de chauffage: $Z \searrow \Rightarrow \Gamma_{\mathrm{PE}} \searrow$, mais plus grande abondance et luminosité de binaires X à faible Z *(e.g., Kaaret+ 2011)* $\Rightarrow \Gamma_X \nearrow$
- Effet potentiellement important dans galaxies lointaines si confirmation de l'évolution super-linéaire de G/D vs. métallicité *(e.g., Rémy-Ruyer+ 2014)*

Extra slides

I Zw 18: characteristics and relevant questions

- $Z \approx 1/35\,Z_\odot$ *(Garnett at al. 1997)*, $D \approx 18\,\mathrm{Mpc}$ *(Aloisi+ 2007)*
- Physical H I diameter $\sim$ LMC
- $M_{\mathrm{HI}} \approx 10^8\,\mathrm{M}_\odot$ in main body *(Lelli+ 2012)*
- SFR $\approx 0.1\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ *(Cannon+ 2005)* $\Rightarrow$ SFR/$\mathrm{M}_{\mathrm{gas}} \sim 1$ Gyr

- No cold gas & molecule detections
- Diffuse N(H_2) $\lesssim 5 \times 10^{14}\,\mathrm{cm}^{-2}$ toward star clusters *(Vidal-Madjar+ 2000)* $\Rightarrow f_{\mathrm{H}_2} \lesssim 5 \times 10^{-7}$
  - Larger critical surface density to form H_2 *(Sternberg+ 2014)*
- $\mathrm{CO}_{1-0} < 8 \times 10^{-22}\,\mathrm{W\,m^{-2}}$ (≈ 380 pc beam) *(Leroy+ 2007)*
  - Low H_2 abundance & H_2 more efficiently converted into stars?
  - CO not tracing well H_2?

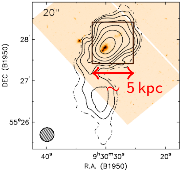


Fig.: *I Zw 18 H I 21 cm* *(Lelli+ 2012)*

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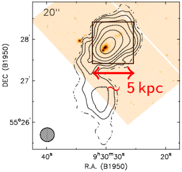
Herschel Dwarf Galaxy Survey **(Madden+ 2013)**

- $M_{\mathrm{dust}} \approx 560\,\mathrm{M}_\odot$ *(Rémy-Ruyer+ 2015)*
  - D/G ≈ 1/1000 MW – more if CO-dark gas
- Recent detections of [C II] 157 μm and [O I] 63 μm *(Cormier+ 2014)*
- What are the heating mechanisms? What consequences for the molecular gas?



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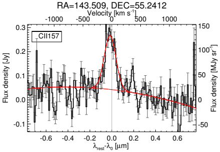


Fig.: *[C II] detection* *(Cormier+ 2015)*

Photoelectric effect (PE) expectations

- PE explains [C II] & [O I] in MW neutral atomic phase *(e.g., Weingartner & Draine 2001)*
- PE heating efficiency: heating rate / power absorbed by dust grains or PAHs
  - Observational proxies: $\epsilon_{\rm TIR} = \frac{\rm [CII]+[OI]\ (+[SiII]...)}{\rm TIR}$, $\epsilon_{\rm PAH} = \frac{\rm [CII]+[OI]\ (+[SiII]...)}{\rm PAH}$
- $\epsilon_{\rm TIR} \sim 0.1 - 1\%$ in normal galaxies
- $\epsilon_{\rm PAH} \sim 5 - 15\%$ in LMC & KINGFISH sources *(e.g., Croxall+ 2012; Lebouteiller+ 2012; Okada+ 2014)*, ≈ theory *(e.g., Tielens 2005)*

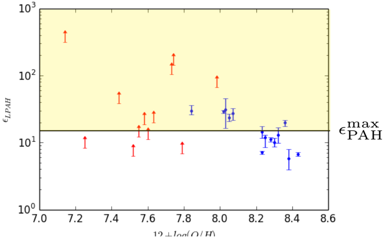


Fig.: $\epsilon_{\rm PAH}$ *(in %) in the DGS (de la Vieuville+ in prep.)*

In I Zw 18, ϵ must be regarded with caution

- D/G ≈ 0.1% MW, $f_{\rm PAH} < 3\%$ MW
- $\epsilon_{PAH} \gtrsim 50\%$ ⇒ unrealistically large (even if all energy of UV photon goes to photo-e^-) ⇒ PAHs do not contribute to PE
- $\epsilon_{\rm TIR} \approx 1\%$ ⇒ Is PE still dominant with compensation by small grains?

Photoionization & photodissociation model with Cloudy

Known heating sources & “favorable” geometry

- OB cluster ($M_* \sim 0.3 - 1 \times 10^6\ \mathrm{M}_\odot$; *(Schneider+ 2016)*)
- XR point source detected with Chandra and XMM-Newton *(Thuan+ 2004; Kaaret & Feng 2013)*
  - ULX with $L_\mathrm{X} \approx 10^{40}\ \mathrm{erg\,s^{-1}}$, likely a HMXB (not that uncommon in low-Z galaxies...)

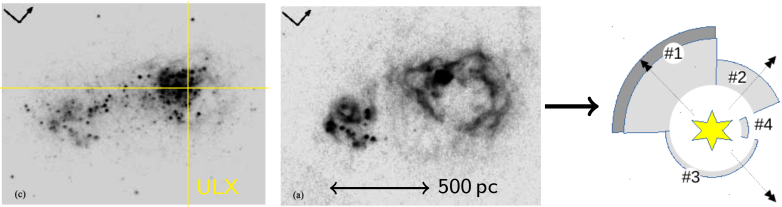


Fig.: *I Zw 18 in R band and Hα (Cannon+ 2002) – Modeling strategy (Lebouteiller+ in prep.)*

Multi-sector model, building on H II region study by Péquignot (2008)

- Radiation-bounded & matter-bounded sectors. Topology (covering factors, distance) and physical conditions well constrained in H II region by optical lines
- New constraints: dust SED, H I region lines [C II] and [O I]

Photoelectric effect revisited

- PE alone not enough to heat observed H I mass and to explain [C II] and [O I], even if D/G scaled with Z (heating contribution $\lesssim 10\%$)
- Addition of XRs ⇒ more efficient heating / PE contributes to $\sim 5\%$ of total heating

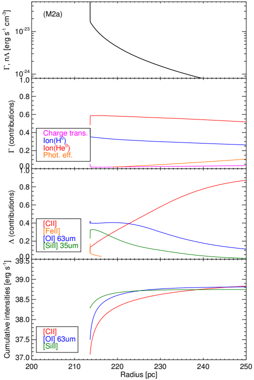


Fig.: *Heating/cooling vs. cloud depth in radiation-bounded sector.*

Cosmic rays

- Small contribution to heating even if Galactic background rate ($\lesssim 13\%$)
- Scaling with SFR for final model

Final model

- Reproduces: optical lines, Spitzer lines, [C II], [O I], dust SED, M(H I)

XR absorption in the H I region

Effect of XRs

- Partial ionization of H I region ($\approx 0.05 - 0.5\%$)
- Dominates heating of H I region
  - Warm H I layer (few 10s-100s K)

The joys of XR studies

- Many caveats
  - Degeneracy to recover intrinsic soft-XR emission
  - Emission modeled along our sightline probably $\neq$ emission seen by most of the gas
  - State transition, collimated emission, etc...
- Properties of radiation-bounded sector can accomodate somewhat $\neq$ XR models
  - XR ionization not only a natural explanation for H I region cooling lines but models provide reasonable parameters (depth, n, T, ...)

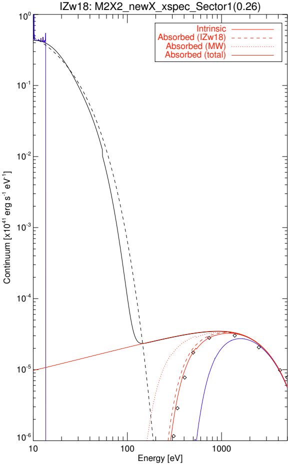


Fig.: *UV & XR input radiation field.*

Why is $\epsilon_{\rm TIR}$ "normal" in I Zw 18...

...despite negligible PE heating?

- H I region cooling line emission dominated by XR heated gas
- TIR = $\rm TIR_{dust}$ + $\rm TIR_{ff}$ ($\approx 75-25\%$)
- Worst case scenario $\Rightarrow \epsilon_{\rm TIR} \sim \frac{\rm [CII]+[OI]}{\rm TIR_{ff}} \approx 3\%$
- Correlation SFR–$L_{\rm X}$ *(e.g., Grimm+ 2003)* + correlation SFR–TIR $\Rightarrow \epsilon_{\rm TIR}$ pretty stable

Transition of heating mechanisms at low-metallicity

- Low D/G $\Rightarrow \Gamma_{\rm PE} \searrow$
- Enhanced abundance of HMXBs *(e.g., Kaaret+ 2011; Brorby+ 2015)* $\Rightarrow \Gamma_{\rm X} \nearrow$
- Important effect for high-z normal galaxies?

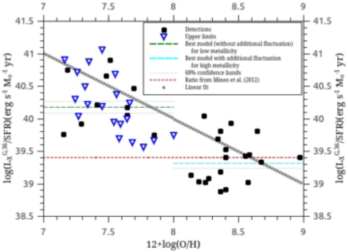
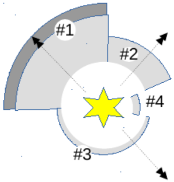


Fig.: *$L_{\rm X}$/SFR vs. metallicity; (Douna+ 2015)*

Molecular gas – diffuse ISM

Case 1) Radiation-bounded sector with uniform properties

- Density reaches $\sim 300\,\mathrm{cm}^{-3}$, constrained in part by [O I]/[C II]
  - $N(\mathrm{H_2}) \sim 10^{14}\,\mathrm{cm}^{-2} \Rightarrow$ same properties as FUV sightlines observed with FUSE *(Aloisi+ 2003)*
  - $\mathrm{M(H_2)} \sim 1\,\mathrm{M}_\odot$
  - In this case [C II] and [O I] trace an almost purely atomic medium



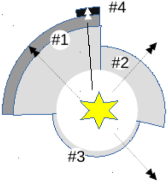
XR-induced $\mathrm{H_2}$ formation through H^- process?

- In the models, $\sim 1/2$ of $\mathrm{H_2}$ formed through H^- route
- Low D/G $\Rightarrow$ low formation rate on dust
- Large n_e/n_H provided by XR ionization
- Large $L_\mathrm{X}/L_\mathrm{UV} \Rightarrow$ ionization of dense cloud interiors $>$ photodissociation in the LW bands

Molecular gas – on the possible existence of clumps

Case 2) Exploration of clump properties from models

- Constraints on covering factor and cloud depth: 160 μm upper limit, CO_{1-0} upper limit
    - Constant P model reaching $10^6\,\mathrm{cm}^{-3}$ $\Rightarrow$ Gas becomes molecular even when no dust
    - Covering factor $< 0.05\%$ $\Rightarrow$ 10 linear parsecs (distributed in all clumps)
    - Similar to $1.5 - 6\,\mathrm{pc}$ "isolated" clumps in WLM? *(Rubio+ 2015)*
- Clumps responsible for $\lesssim 1/2$ of [C II] and [O I] , **but**
    - [C II] & [O I] traces their atomic layers – only 2% of [C II] can be associated to H_2



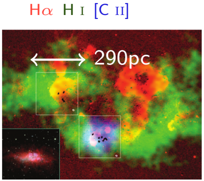


Fig.: *WLM ($\approx 1/8\,Z_\odot$) with ALMA; (Rubio+ 2015)*

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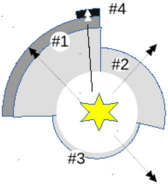
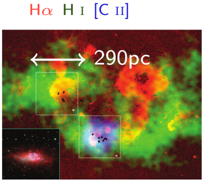
  - [C II] & [O I] traces their atomic layers – only 2% of [C II] can be associated to H_2
- $M(H_2) \lesssim 10^7\,M_\odot$, compatible with X_{CO} 100× lower than MW





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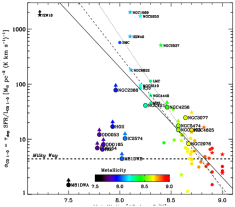

Fig.: *CO/H_2 (Schruba+ 2012)*