Observing and modeling the extragalactic ISM

Vianney Lebouteiller (CNRS/AIM, CEA Saclay)
Outline

- **External galaxies**
  - Parameter space
  - The ISM within the galaxy evolution and star formation contexts

- **Some highlights**

- **Modeling strategies**
  - Accounting for the ISM complexity & structure

(Wide topic, focus on spectroscopy and gas tracers)
Physical scales & components

Physical processes generally act on / originate from a wide range of spatial scales (e.g., SF)

Fig.: HI-H2 conversion and SF process as a function of spatial scales (Saintonge+ 2022).

Main challenges for extragalactic observations

- Reach small enough scales to disentangle ISM components or recover them through indirect, integrated, signatures
- Understand/generalize physical mechanisms in conditions \( \neq \) from MW

Vianney Lebouteiller (CNRS/AIM, CEA Saclay)  Observing and modeling the extragalactic ISM 3 / 31
External galaxies

Physical scales & components

Physical processes generally act on / originate from a wide range of spatial scales (e.g., SF)

Fig.: HI-H2 conversion and SF process as a function of spatial scales (Saintonge+ 2022).

Main challenges for extragalactic observations

- Reach small enough scales to disentangle ISM components or recover them through indirect, integrated, signatures
- Understand/generalize physical mechanisms in conditions ≠ from MW
Physical scales & components

Physical processes generally act on / originate from a wide range of spatial scales (e.g., SF)

Main challenges for extragalactic observations

- Reach small enough scales to disentangle ISM components or recover them through indirect, integrated, signatures
- Understand/generalize physical mechanisms in conditions ≠ from MW

Fig.: HI-H2 conversion and SF process as a function of spatial scales (Saintonge+ 2022).
Physical scales & components

Digest & process wealth of spatial information

Combine detailed ISM models with state-of-the-art radiative transfer and chemistry + complex enough geometries

Fig.: NGC 4254, MUSE (blue/yellow) + ALMA (orange), PHANGS

Fig.: NGC 7496, HST+JWST, PHANGS
Expanding the parameter space and generalizing mechanisms

Detailed studies of nearby galaxies...

- ≠ environments at large
  - Z & ISM phases, young stellar clusters, X-ray binaries, AGNs, interactions...

- ≠ predominance of physical processes
  - Photoelectric effect, X-ray photoionization, CR ionization, shocks...

Main obstacles

- Knowledge of dust & energetic sources
- Mixing biases when dealing with poor/no spatial/spectral resolution

...to be adapted to the Early Universe

- Multiphase ISM also revealed at very high-z (e.g., (CII) 158 µm, (OIII) 88 µm (e.g., Harikane+ 2020)
- Spatial information increasingly available (e.g., Wong+ 2022, Dye+ 2022)

Fig.: CO(7-6), H$_2$, and (CI) lines in a z = 4.24 lensed galaxy with ALMA (Dye+ 2022)
Expanding the parameter space and generalizing mechanisms

Detailed studies of nearby galaxies...

- ≠ environments at large
  - Z & ISM phases, young stellar clusters, X-ray binaries, AGNs, interactions...

- ≠ predominance of physical processes
  - Photoelectric effect, X-ray photoionization, CR ionization, shocks...

Main obstacles

- Knowledge of dust & energetic sources
- Mixing biases when dealing with poor/no spatial/spectral resolution

...to be adapted to the Early Universe

- Multiphase ISM also revealed at very high-z (e.g., [CII] 158 μm, [OIII] 88 μm) (e.g., Harikane+ 2020)
- Spatial information increasingly available (e.g., Wong+ 2022, Dye+ 2022)

Fig.: CO(7-6), H$_2$, and [CI] lines in a $z = 4.24$ lensed galaxy with ALMA (Dye+ 2022)
External galaxies

Cosmic noon zoom

Fig.: IRAC1 blobs in SMACS0723 field are likely z=1-3 red spiral galaxies (NIRcam; Fudamoto+ 2022)

... but spectra of $z \gtrsim 3$ galaxies will remain spatially-unresolved with JWST for the most part
Exploring the metal-poor ISM

- Mass-metallicity relation (MZR): metal-enriched outflow rate, variable integrated IMF, infall (radial for low M* vs. cosmological for high M*) rate (e.g., Spitoni+ 2010)

Fig.: MZR in Local Group dIrr and dSph (Kirby+ 2013)

Fig.: MZR in the local Universe and SDSS z<0.2 galaxies (Duarte Puertas+ 2022)

Fig.: MZR vs. z in cosmological simulations (IllustrisTNG; Torrey+ 2019). Absolute calibration somewhat uncertain due to Z calibration with observations.

Vianney Lebouteiller (CNRS/AIM, CEA Saclay)
Exploring the metal-poor ISM

- Mass-metallicity relation (MZR): metal-enriched outflow rate, variable integrated IMF, infall (radial for low $M^*$ vs. cosmological for high $M^*$) rate (e.g., Spitoni+ 2010)

**Fig.** MZR in Local Group dIrr and dSph (Kirby+ 2013)

**Fig.** MZR in the local Universe and SDSS $z<0.2$ galaxies (Duarte Puertas+ 2022)

**Fig.** MZR vs. $z$ in cosmological simulations (IllustrisTNG; Torrey+ 2019). Absolute calibration somewhat uncertain due to $Z$ calibration with observations.
Exploring the metal-poor ISM

- Mass-metallicity relation (MZR): metal-enriched outflow rate, variable integrated IMF, infall (radial for low M* vs. cosmological for high M*) rate (e.g., Spitoni+ 2010)

Fig.: MZR in Local Group dIrr and dSph (Kirby+ 2013)

Fig.: MZR in the local Universe and SDSS z<0.2 galaxies (Duarte Puertas+ 2022)

Fig.: MZR vs. z in cosmological simulations (IllustrisTNG; Torrey+ 2019). Absolute calibration somewhat uncertain due to Z calibration with observations.
Observed diversity in the ISM composition/physical conditions

Fig.: D/G and mass fraction of small amorphous carbons (Galliano+ 2021)

Fig.: CO SLED (Cañameras+ 2018)

Fig.: Molecular line ratios in M51 (CLAWS; den Brok+ 2022)

Fig.: C/O gas phase abundance ratio (Nicholls+ 2017)
Observed diversity in the ISM composition/physical conditions

Fig.: D/G and mass fraction of small amorphous carbons (Galliano+ 2021)

Fig.: CO SLED (Cañameras+ 2018)

Fig.: Molecular line ratios in M51 (CLAWS; den Brok+ 2022)

Fig.: C/O gas phase abundance ratio (Nicholls+ 2017)
Observed diversity in the ISM composition/physical conditions

**Fig.** D/G and mass fraction of small amorphous carbons (Galliano+ 2021)

**Fig.** CO SLED (Cañameras+ 2018)

**Fig.** Molecular line ratios in M51 (CLAWS; den Brok+ 2022)

**Fig.** C/O gas phase abundance ratio (Nicholls+ 2017)
Observed diversity in the ISM composition/physical conditions

Fig.: D/G and mass fraction of small amorphous carbons (Galliano+ 2021)

Fig.: CO SLED (Cañameras+ 2018)

Fig.: Molecular line ratios in M51 (CLAWS; den Brok+ 2022)

Fig.: C/O gas phase abundance ratio (Nicholls+ 2017)
**Observed diversity in the radiation sources**

**Young massive clusters**
- Upper cut-off mass value debated \((\text{Mok}+2019)\) but maximum \(L\) & \(M\) reach \(\gtrsim 2\) dex above MW \((\text{Portegies Zwart 2010})\)

**High-mass X-ray binaries**
- Often dominate the high-\(E\) output from nearby actively SF galaxies \((\text{e.g., Grimm}+2003, \text{Mineo}+2012)\)
- Typically provide \(\sim 10^{39-41}\) erg/s \((\text{i.e., } \sim 1-10\% \text{ of total } L)\). Feedback may keep the (dust-poor) ISM warm without removing a significant gas fraction \((\text{Artale}+2015)\)
- Higher abundance & luminosity at low \(Z\) / high \(z\) \((\text{Gilbertson}+2022, \text{Lehmer}+2021)\)
- Mass of stellar accreting partner & SFR correlation hints at production site / presence in young massive clusters

**Fig.** Mass-size relationship in young star clusters and associations \((\text{Portegies Zwart 2010, Santoro}+2022)\)

**Fig.** Number of ULXs per unit SFR as a function of metallicity \((\text{Lehmer}+2021)\).
Observed diversity in the radiation sources

**Young massive clusters**

- Upper cut-off mass value debated (Mok+ 2019) but maximum L & M reach $\gtrsim 2$ dex above MW (Portegies Zwart 2010)

- Fig.: Mass-size relationship in young star clusters and associations (Portegies Zwart 2010, Santoro+ 2022)

**High-mass X-ray binaries**

- Often dominate the high-E output from nearby actively SF galaxies (e.g. Grimm+ 2003, Mineo+ 2012)
- Typically provide $\sim 10^{39-41}$ erg/s (i.e., $\sim$1-10% of total L!). Feedback may keep the (dust-poor) ISM warm without removing a significant gas fraction (Artale+ 2015)
- Higher abundance & luminosity at low Z / high z (Gilbertson+ 2022, Lehmer+ 2021)
- Mass of stellar accreting partner & SFR correlation hints at production site / presence in young massive clusters

- Fig.: Number of ULXs per unit SFR as a function of metallicity (Lehmer+ 2021).
Cold ISM within the galaxy evolution context

Star-formation main sequence (MS; SFR vs. $M_*$) set by gas content and efficiency gas $\rightarrow$ stars

- **MS normalization** with $z$ set by available gas supply from accretion
- At low $z$, **position along MS**, including flattening above $M_{knee}$, follows $M_{H2}$ vs. $M_*$ while scatter around MS follows molecular gas fraction
- Time-independent shape of MS $\Rightarrow$ long SF duty cycles ($\sim$ Gyr) as opposed to quick ↑↓ due to SFH) (e.g., Saintonge+ 2022)
- Strong function of $M_*$: low mass galaxies in particular have extended HI reservoirs largely decoupled from the star formation process.

- Equilibrium of gas accretion, star formation, and gas outflows: the "gas regulator models" (e.g., Bouché+10; Davé+12; Rathaus+16; Tacchella+20)

\[\text{Fig.}: \text{MS vs. } z \text{ with Herschel stacking (Schreiber+ 2014)}\]

\[\text{Fig.}: \text{Mass relationships (Saintonge+ 2022)}\]
Cold ISM within the SF context

- SF set by processes acting on different spatial scales
- CO does not trace well the dense molecular gas (e.g., Roman-Duval+ 2016)
- Accounting for dense gas fraction within galaxies still results in non-constant SFE (EMPIRE: Jimeñez-Donaire+ 2019; Beslic+ 2021)
- Dense gas threshold SF models (universal $\tau_{dep}$ above $n_t$) may remain valid even at small scales (<100pc) ⇒ use tracers with even higher critical densities?
- Turbulence-regulated SF models with feedback (e.g., Krumholz & Mc Kee 2005; Federrath & Klessen 2012)?
Cold ISM within the SF context

- SF set by processes acting on different spatial scales
- CO does not trace well the dense molecular gas \((e.g., \text{Roman-Duval}+2016)\)
- Accounting for dense gas fraction within galaxies still results in non-constant SFE \((\text{EMPIRE: Jimenez-Donaire}+2019, \text{Beslic}+2021)\)
- Dense gas threshold SF models (universal \(\tau_{\text{dep}}\) above \(n_t\)) may remain valid even at small scales \(<100\,\text{pc}\) \(\Rightarrow\) use tracers with even higher critical densities?
- Turbulence-regulated SF models with feedback \((e.g., \text{Krumholz} \& \text{Mc Kee} 2005, \text{Federrath} \& \text{Klessen} 2012)\)

Fig.: Top: SFE(dense) vs. P in EMPIRE \((\text{Jimenez-Donaire}+2019)\), bottom: vs. f(dense) in NGC3627 \((\text{Beslic}+2021)\)
Physical processes to explore in a comprehensive way

Gas & SF

- How do molecular clouds form, how long do they live? What sets the SFE?
- Conversion diffuse → dense, molecular gas vs. SF (CO-dark H$_2$, SK law)

- SF process itself ~ pc-scales: studies of protostars, SF filaments, and cloud-cloud collisions in Magellanic Clouds
  - Hot cores and complex organic molecules in the LMC (CH$_3$OCH$_3$, CH$_3$OCHO... with ALMA), chemical differences may suggest local mixing of gas with ≠ metallicity (Sewilo+ 2018, 2022)
  - Protostellar CO outflows in the SMC with ALMA (Tokuda+ 2022)
  - More to come with JWST, ELT...

Fig.: Bona fide hot core in the LMC (Sewilo+ 2022)
Physical processes to explore in a comprehensive way

Gas & SF

- How do molecular clouds form, how long do they live? What sets the SFE?
  - Conversion diffuse $\rightarrow$ dense, molecular gas vs. SF (CO-dark H$_2$, SK law)

- SF process itself $\sim$ pc-scales: studies of protostars, SF filaments, and cloud-cloud collisions in Magellanic Clouds
  - Hot cores and complex organic molecules in the LMC (CH$_3$OCH$_3$, CH$_3$OCHO... with ALMA), chemical differences may suggest local mixing of gas with $\neq$ metallicity (Sewilo+ 2018, 2022)
  - Protostellar CO outflows in the SMC with ALMA (Tokuda+ 2022)
  - More to come with JWST, ELT...

Fig.: Bona fide hot core in the LMC (Sewilo+ 2022)
Physical processes to explore in a comprehensive way (cont’d)

**Turbulence**
- CH\(^+\) out-of-equilibrium H\(_2\) / dissipation of mechanical energy in turbulence (Godard+ 2022)
- At high-z: shock waves powered by hot galactic winds & turbulent cool gas reservoirs (e.g., Vidal-Garcia+ 2021, Falgarone+ 2017, Muller+ 2017) ⇒ A. Vidal-Garcia’s talk

**Magnetic field**
- SALSA Legacy Program: SOFIA HAWK+ observations of 14 nearby galaxies (Lopez-Rodriguez+ 2022)

Fig.: SALSA NGC 1097 (Lopez-Rodriguez+ 2022)
Physical processes to explore in a comprehensive way (cont’d)

**Turbulence**
- CH$^+$ out-of-equilibrium H$_2$ / dissipation of mechanical energy in turbulence (Godard+ 2022)
- At high-z: shock waves powered by hot galactic winds & turbulent cool gas reservoirs (e.g., Vidal-Garcia+ 2021, Falgarone+ 2017, Muller+ 2017) ⇒ A. Vidal-Garcia’s talk

**Magnetic field**
- SALSA Legacy Program: SOFIA HAWK+ observations of 14 nearby galaxies (Lopez-Rodriguez+ 2022)

*Fig.*: SALSA NGC 1097 (Lopez-Rodriguez+ 2022)
Some highlights

**CO-dark molecular gas and (CII)**

=> S. Madden’s talk

**MW**

- Dark gas mass fraction not traced by CO or HI is 20 — 40% in MW, most likely (CO-dark) molecular gas (DMG) as opposed to optically-thick HI (Grenier+ 2005, Wolfire+ 2010, Hayashi+ 2019, Murray+ 2018)

**Local Group**

- \( f_{\text{DMG}} \approx 80-90\% \) in SMC/LMC SF regions (e.g., Piñeda+ 2017, Lebouteiller+ 2019)
- \( \alpha_{\text{CO}} > \text{MW} \)
- ...but fully accountable for by the CO filling factor (i.e., confirming that Z effect is to reduce the filling factor of molecular gas traced by CO due to low D/G) (Piñeda+ 2017)

(see also Mookerjea+ 2016 in M31)

Fig.: (Madden+ 2020)
**Some highlights**

**CO-dark molecular gas and ([CII])**

- *S. Madden’s talk*

**MW**
- Dark gas mass fraction not traced by CO or HI is 20 — 40% in MW, most likely (CO-dark) molecular gas (DMG) as opposed to optically-thick HI (Grenier+ 2005, Wolfire+ 2010, Hayashi+ 2019, Murray+ 2018)

**Local Group**
- $f_{\text{DMG}} \approx 80-90\%$ in SMC/LMC SF regions (e.g., Piñeda+ 2017, Lebouteiller+ 2019)
- $\alpha_{CO} > \text{MW}$
- …but fully accountable for by the CO filling factor (i.e., confirming that Z effect is to reduce the filling factor of molecular gas traced by CO due to low D/G) (Piñeda+ 2017) (see also Mookerjea+ 2016 in M33)

**Fig.**: (Madden+ 2020)
CO-dark molecular gas and [(CII)] (cont’d)

Extragalactic observations

- [(CII)] and other emission-lines readily available at high-z
- From models, [(CII)] and [(Cl)] become increasingly good tracers of the H$_2$ column density profile at low Z and for cosmic ray ionization rate $\zeta_H \gtrsim 10^{-14} \text{ s}^{-1}$ (Bisbas+ 2021)

- Dwarf Galaxy Survey (metal-poor SF galaxies) (Madden+ 2013)
  - Integrated [(CII)] emission
  - $f_{DMG} \approx 70-100\%$, $M_{H2}$ follows closely $L_{CII}$ in a single 1D model approach where A$_V$ traced by [(CII)]/CO is the main parameter (Madden+ 2020)
  - CO-to-H$_2$ conversion factor ($\alpha_{CO}$) not a simple function of Z but depends on the CO filling factor which can be partly recovered from the models (Ramambason+ in prep.)

---

Fig.: CO-to-H$_2$ value between MW value and extreme case of CO uniformly distributed (Ramambason+ in prep.) (⇒ L. Ramambason’s poster)
CO-dark molecular gas and ([CII]) (cont’d)

Extragalactic observations

- ([CII]) and other emission-lines readily available at high-z
- From models, ([CII]) and (CI) become increasingly good tracers of the H$_2$ column density profile at low Z and for cosmic ray ionization rate $\zeta_H \gtrsim 10^{-14}$ s$^{-1}$ (Bisbas+ 2021)

- Dwarf Galaxy Survey (metal-poor SF galaxies) (Madden+ 2013)
  - Integrated ([CII]) emission
  - $f_{\text{DMG}} \approx 70$-100$_{-0}^{+10}$, $M_{\text{H}_2}$ follows closely $L_{\text{CII}}$ in a single 1D model approach where $A_V$ traced by ([CII])/CO is the main parameter (Madden+ 2020)
  - CO-to-H$_2$ conversion factor ($\alpha_{\text{CO}}$) not a simple function of Z but depends on the CO filling factor which can be partly recovered from the models (Ramambason+ in prep.)

Fig.: CO-to-H$_2$ value between MW value and extreme case of CO uniformly distributed (Ramambason+ in prep.) (⇒ L. Ramambason’s poster)
Some highlights

**CO-dark molecular gas and \([\text{CII}]\) (cont’d)**

- **Extragalactic observations**
  - (CII) and other emission-lines readily available at high-z
  - From models, (CII) and (CI) become increasingly good tracers of the \(\text{H}_2\) column density profile at low Z and for cosmic ray ionization rate \(\zeta_H \gtrsim 10^{-14} \text{ s}^{-1}\) \((\text{Bisbas+ 2021})\)
  - **Dwarf Galaxy Survey** (metal-poor SF galaxies) \((\text{Madden+ 2013})\)
    - Integrated (CII) emission
    - \(f_{\text{DMG}} \approx 70-100\%\), \(M_{\text{H}_2}\) follows closely \(L_{\text{CII}}\) in a single 1D model approach where \(A_V\) traced by (CII)/CO is the main parameter \((\text{Madden+ 2020})\)
    - CO-to-\(\text{H}_2\) conversion factor \(\alpha_{\text{CO}}\) not a simple function of Z but depends on the CO filling factor which can be partly recovered from the models \((\text{Ramambason+ in prep.})\)

\[\text{Fig.}: \text{CO-to-}\text{H}_2\ \text{value between MW value and extreme case of CO uniformly distributed (Ramambason+ in prep.)} \Rightarrow \text{L. Ramambason’s poster}\]
Some highlights

CO-dark

Possible to recover distributions of dense clouds even for integrated galaxies
PDR heating

Some highlights

- Low D/G and PAH abundance (e.g., Galliano+ 2021) ⇒ low Z? Compensation by very small grains? By other heating mechanisms related to SF?

Vianney Lebouteiller (CNRS/AIM, CEA Saclay)
Observing and modeling the extragalactic ISM
Some highlights

**PDR heating**

**Limits of the PE heating**

- Low D/G and PAH abundance (e.g., Galliano+ 2021) ⇒ low Z? Compensation by very small grains? By other heating mechanisms related to SF?

---

**Fig.:** PE heating efficiency and observational proxy \( ([\text{CII}]+[\text{OI}] / \text{PAH}) \) (Berné+ 2022)

**Fig.:** \( ([\text{CII}]+[\text{OI}] / \text{PAH}) \) in Magellanic Clouds (Lambert-Huyghe+ unpublished)

**Fig.:** PAH heating efficiency vs. Z (de la Vieuville+ unpublished)

Vianney Lebouteiller (CNRS/AIM, CEA Saclay)  
Observing and modeling the extragalactic ISM

18 / 31
PDR heating

Limits of the PE heating

- Low D/G and PAH abundance (e.g., Galliano+ 2021) ⇒ low Z? Compensation by very small grains? By other heating mechanisms related to SF?

Fig.: PE heating efficiency and observational proxy
(CII)+(OI) / PAH (Berné+ 2022)

Fig.: (CII)+(OI) / PAH in Magellanic Clouds (Lambert-Huyghe+ 2022)

Fig.: PAH heating efficiency vs. Z (de la Vieuville+ unpublished)

Vianney Lebouteiller (CNRS/AIM, CEA Saclay)  Observing and modeling the extragalactic ISM
Some highlights

Pushing (CII) and PE to the limit

Model

- I Zw18, 18 Mpc, 1/35 Z⊙, D/G ~ 1000 lower than MW

Beyond the MW PE paradigm

- Single ULX dominates neutral gas heating with negligible contribution from PE
- (CII) traces an almost purely neutral atomic gas

Fig.: I Zw18 modeling strategy (Lebouteiller+ 2017)

Fig.: Cooling/heating contributions in the radiation-bounded (PDR) sector (Lebouteiller+ 2017)
Pushing (CII) and PE to the limit

Model

- I Zw18, 18 Mpc, 1/35 Z☉, D/G ~ 1000 lower than MW

Beyond the MW PE paradigm

- Single ULX dominates neutral gas heating with negligible contribution from PE
- (CII) traces an almost purely neutral atomic gas

Fig.: I Zw18 modeling strategy (Lebouteiller+ 2017)

Fig.: Cooling/heating contributions in the radiation-bounded (PDR) sector (Lebouteiller+ 2017)
Some highlights

Pushing (CII) and PE to the limit

Model
- I Zw18, 18 Mpc, 1/35 Z⊙, D/G ∼ 1000 lower than MW

![Fig.](IZw18 modeling strategy (Lebouteiller+ 2017))

Beyond the MW PE paradigm
- Single ULX dominates neutral gas heating with negligible contribution from PE
- (CII) traces an almost purely neutral atomic gas

![Fig.](Cooling/heating contributions in the radiation-bounded (PDR) sector (Lebouteiller+ 2017))
Some highlights

Cosmic rays

**CRIR**

- H$_3^+$ measurements: $\zeta_H \approx 3 \times 10^{-16} \text{ s}^{-1}$ MW disk (e.g., Indriolo+ 2009, 2012), ~ 10 – 1000 larger in GC (Oka+ 2019).
- Nearby SB galaxy disks (e.g., Van der Tak+ 2016), nuclei (e.g., ALCHEMI, Holdship+ 2022), and ULIRG nuclei (e.g., González-Alfonso+ 2018) with ionized molecules in dense gas (e.g., H$_2$O$^+$), even lensed galaxies beyond $z > 2$ (Indriolo+ 2018), all suggesting MW-like range of values 10$^{-16}$, −13 s$^{-1}$.
- $\zeta_H$ is larger in regions of more copious star formation: depends on proximity to cosmic-ray accelerators, particle propagation effects, and losses via interactions with the ISM (Indriolo+ 2018).

**CR impact on ISM**

- Ionization of molecules in dense gas $\Rightarrow$ chemical network.
- Along with gas density, CRIR impact ISM fractionation in external galaxies (isotopic ratios) (e.g., Viti+ 2019, 2020).
- Impacts the use of [CII] and [OI] through increased C, C$^+$ column densities wrt CO, impacts somewhat $X_{\text{CO}}$ factor as well (Bisbas+ 2021).
- Difficult distinction between CR and hard X-rays...

**Prospectives for the diffuse/large-scale ISM**

- Cosmic-ray-induced near-IR H$_2$ line emission with JWST (Bialy+ 2021, Gaches+ 2022).
- Also H$_3^+$ with JWST (Indriolo+ 2007).
Cosmic rays

CRIR

- $\zeta_3^+ \approx 3 \times 10^{-16} \text{ s}^{-1}$ MW disk (e.g., Indriolo et al. 2009, 2012), ~ 10 – 1000 larger in GC (Oka 2019).
- Nearby SB galaxy disks (e.g., Van der Tak et al. 2016), nuclei (e.g., ALCHEMI, Holdship et al. 2022), and ULIRG nuclei (e.g., González-Alfonso et al. 2018) with ionized molecules in dense gas (e.g., $\text{H}_2\text{O}^+$), even lensed galaxies beyond $z > 2$ (Indriolo et al. 2018), all suggesting MW-like range of values $10^{-16}, -13 \text{ s}^{-1}$.
- $\zeta_3^+$ is larger in regions of more copious star formation: depends on proximity to cosmic-ray accelerators, particle propagation effects, and losses via interactions with the ISM (Indriolo et al. 2018).

CR impact on ISM

- Ionization of molecules in dense gas $\Rightarrow$ chemical network.
- Along with gas density, CRIR impact ISM fractionation in external galaxies (isotopic ratios) (e.g., Viti et al. 2019, 2020).
- Impacts the use of [CII] and [OI] through increased C, C$^+$ column densities wrt CO, impacts somewhat $X_{\text{CO}}$ factor as well (Bisbas et al. 2021).
- Difficult distinction between CR and hard X-rays . . .

Prospectives for the diffuse/large-scale ISM

- Cosmic-ray-induced near-IR $\text{H}_2$ line emission with JWST (Bialy et al. 2021, Gaches et al. 2022).
- Also $\text{H}_3^+$ with JWST (Indriolo et al. 2007).
Cosmic rays

Some highlights

**CRIR**
- H$_3^+$ measurements: $\zeta_H \approx 3 \times 10^{-16}$ s$^{-1}$ MW disk (e.g., Indriolo+ 2009, 2012), ~ 10 – 1000 larger in GC (Oka+ 2019)
- Nearby SB galaxy disks (e.g., Van der Tak+ 2016), nuclei (e.g., ALCHEMI, Holdship+ 2022), and ULIRG nuclei (e.g., González-Alfonso+ 2018) with ionized molecules in dense gas (e.g., H$_2$O$^+$), even lensed galaxies beyond $z > 2$ (Indriolo+ 2018), all suggesting MW-like range of values $10^{-16}, -13$ s$^{-1}$.
- $\zeta_H$ is larger in regions of more copious star formation: depends on proximity to cosmic-ray accelerators, particle propagation effects, and losses via interactions with the ISM (Indriolo+ 2018)

**CR impact on ISM**
- Ionization of molecules in dense gas $\Rightarrow$ chemical network
- Along with gas density, CRIR impact ISM fractionation in external galaxies (isotopic ratios) (e.g. Viti+ 2019, 2020)
- Impacts the use of [CII] and [OI] through increased C, C$^+$ column densities wrt CO, impacts somewhat $X_{\text{CO}}$ factor as well (Blsbas+ 2021)
- Difficult distinction between CR and hard X-rays...

**Prospectives for the diffuse/large-scale ISM**
- Cosmic-ray-induced near-IR H$_2$ line emission with JWST (Bialy+ 2021, Gaches+ 2022)
- Also H$_3^+$ with JWST (Indriolo+ 2007)
Some highlights

Formation/destruction timescales of molecular clouds

- PHANGS-* (ALMA, Hα, MUSE, VLA, ...): timescales for GMC formation, cluster formation, HII region formation and front expansion, decorrelation cloud/cluster.

*Fig.*: Gas-to-SFR ratio, see, e.g., (Kruijssen+ 2019, Chevance+ 2022a)
Formation/destruction timescales of molecular clouds (cont’d)

Short-lived molecular clouds and rapid feedback $\Rightarrow$ inefficient SF

**LMC**
- LMC: GMC lifetime $\approx 11$ Myr likely set by internal processes rather than galactic dynamics, contrary to HI clouds (Ward+ 2022)

**MS galaxies**
- Molecular cloud lifetime ("inert" phase) $\sim 16$ Myr (Kim+ 2022)
- Efficiently dispersed by stellar feedback within 1-5 Myr once the star-forming region becomes partially exposed. Early feedback mechanisms (photoionisation and stellar winds) efficiently disperse molecular clouds, prior to SNe explosions (see also Chevance+ 2022b) $\Rightarrow$ A. Zakardjian’s talk
- (integrated cloud-scale star formation efficiency $\approx 1$-8%)
- $1/2$ CO and H$\alpha$ is diffuse
- CO-visible cloud lifetimes become shorter with decreasing galaxy mass, attributed to CO-dark H$_2$ mass at low Z

*Fig.: Timescales for the various phases (Kim+ 2022).*
Last word on observations

Period is ripe for synergistic dataset analyses

- Resolved, IFUs: (Blue)MUSE, JWST, ALMA/NOEMA then SKA
- Sweet spot @ $z \lesssim 2$ (UV $\rightarrow$ opt., opt. $\rightarrow$ NIRspec, near-IR $\rightarrow$ MIRI, CO ladder with ALMA)
- Sweet spot @ $z \sim 7$ (UV $\rightarrow$ NIRspec, far-IR $\rightarrow$ ALMA, CO $\rightarrow$ SKA)

Few considerations

- UV emission lines N IV], C IV, He II, O III], Si III], C III]... (~1400-1900Å): accurate diagnostics for E(B-V), n_e, T_e, O/H, U... (Mingozzi+ 2022)
- Mid-IR diagnostics will remain unavailable at $z \sim 2$ − 10 until PRIMA (http://agora.lam.fr)
Some highlights

Period is ripe for synergistic dataset analyses

- Resolved, IFUs: (Blue)MUSE, JWST, ALMA/NOEMA then SKA
- Sweet spot $z \lesssim 2$ (UV $\rightarrow$ opt., opt. $\rightarrow$ NIRspec, near-IR $\rightarrow$ MIRI, CO ladder with ALMA)
- Sweet spot $z \sim 7$ (UV $\rightarrow$ NIRspec, far-IR $\rightarrow$ ALMA, CO $\rightarrow$ SKA)

Few considerations

- UV emission lines N IV, C IV, He II, O III, Si III, C III)\ldots ($\sim$1400-1900Å): accurate diagnostics for E(B-V), $n_e$, $T_e$, O/H, U\ldots (Mingozzi+ 2022)
- Mid-IR diagnostics will remain unavailable at $z \sim 2 - 10$ until PRIMA (http://agora.lam.fr)
Some highlights

Period is ripe for synergistic dataset analyses

- Resolved, IFUs: (Blue)MUSE, JWST, ALMA/NOEMA then SKA
- Sweet spot $z \lesssim 2$ (UV $\rightarrow$ opt., opt. $\rightarrow$ NIRspec, near-IR $\rightarrow$ MIRI, CO ladder with ALMA)
- Sweet spot $z \sim 7$ (UV $\rightarrow$ NIRspec, far-IR $\rightarrow$ ALMA, CO $\rightarrow$ SKA)

Few considerations

- UV emission lines $\text{N IV, C IV, He II, O III, Si III, C III} \ldots$ ($\sim 1400$-$1900\text{Å}$): accurate diagnostics for $E(B-V), n_e, T_e, O/H, U \ldots$ (Mingozzi+ 2022)
- Mid-IR diagnostics will remain unavailable at $z \sim 2 - 10$ until PRIMA (http://agora.lam.fr)

Vianney Lebouteiller (CNRS/AlM, CEA Saclay)  Observing and modeling the extragalactic ISM
Modeling strategies

Scale & adapt

Challenges

- Integrate adapted prescriptions in models (e.g., low metallicity chemistry, dust properties etc...) and in the input energetic sources
- Distinguish physical processes for galaxies (e.g., photoionization, shocks, turbulence, B, CRs...) from spatially/spectrally unresolved tracers
- Account for ISM complexity (e.g., phases, distribution of matter...) 
- Account for geometry gas+sources (distribution, optical depth, projection effects...), only partly alleviated by spatial/spectral decomposition and/or IFUs
- High level of degeneracy ⇒ manage multiple solutions in large grids
### Modeling strategies

#### Many potential approaches

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Difficulties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulations</td>
<td>Dynamical effects, large volume 3D RT post-processing tools exist, e.g., with MOCASSIN</td>
<td>Comparison with specific observations (statistics), light chemistry network</td>
</tr>
<tr>
<td>1D</td>
<td>State-of-the-art RT &amp; chemistry</td>
<td>Scale to complex geometries</td>
</tr>
<tr>
<td>Pure 3D</td>
<td>3D RT, diffuse light...</td>
<td>Geometry (gas+sources) not free parameter</td>
</tr>
<tr>
<td>MC 3D</td>
<td>Good 3D approximation</td>
<td>Geometry not free parameter</td>
</tr>
<tr>
<td>Pseudo-3D from 1D</td>
<td>State-of-the-art RT &amp; chemistry</td>
<td>Not 3D!</td>
</tr>
<tr>
<td>Topological 3D from 1D</td>
<td>Central ionizing source (AGN, PN, HII region)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inferred geometry</td>
<td></td>
</tr>
</tbody>
</table>

---

Fig.: SPHINX (Rosdhal+ 2018)
Fig.: MOCASSIN (Hubber+ 2016)
Fig.: M3-MAPPINGS V (Jin+ 2022)
Fig.: M3-MAPPINGS V (Jin+ 2022)
Fig.: PyCloudy, PyCROSS (Fitzgerald+ 2020; Morisset+ 2013)
Fig.: MULTIGRIS+Cloudy (Lebouteiller Ramambason 2022)
### Modeling strategies

#### Many potential approaches

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Difficulties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulations</td>
<td>Dynamical effects, large volume</td>
<td>Comparison with specific observations (statistics), light chemistry network</td>
</tr>
<tr>
<td>1D</td>
<td>3D RT post-processing tools exist, e.g., with MOCASSIN</td>
<td>Scale to complex geometries</td>
</tr>
<tr>
<td>Pure 3D</td>
<td>State-of-the-art RT &amp; chemistry</td>
<td>Geometry (gas+sources) not free parameter</td>
</tr>
<tr>
<td>MC 3D</td>
<td>3D RT, diffuse light...</td>
<td>Geometry not free parameter</td>
</tr>
<tr>
<td>Pseudo-3D from 1D</td>
<td>State-of-the-art RT &amp; chemistry</td>
<td>Not 3D!</td>
</tr>
<tr>
<td>Topological 3D from 1D</td>
<td>Central ionizing source (AGN, PN, HII region)</td>
<td>Not 3D!</td>
</tr>
<tr>
<td></td>
<td>Inferred geometry</td>
<td></td>
</tr>
</tbody>
</table>

*Fig.:* SPHINX (Rosdhal+ 2018)  
*Fig.:* MOCASSIN (Hubber+ 2016)  
*Fig.:* M3-MAPPINGS V (Jin+ 2022)  
*Fig.:* M3-MAPPINGS V (Jin+ 2022)  
*Fig.:* PyCloudy, PyCROSS (Fitzgerald+ 2020; Morisset+ 2013)  
*Fig.:* MULTIGRIS+Cloudy (Lebouteiller Ramambason 2022)
### Modeling strategies

Many potential approaches

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Difficulties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulations</td>
<td>Dynamical effects, large volume</td>
<td>Comparison with specific observations (statistics), light chemistry network</td>
</tr>
<tr>
<td>1D</td>
<td>State-of-the-art RT &amp; chemistry</td>
<td>Scale to complex geometries</td>
</tr>
<tr>
<td>Pure 3D</td>
<td>3D RT, diffuse light...</td>
<td>Geometry (gas+sources) not free parameter</td>
</tr>
<tr>
<td>MC 3D</td>
<td>Good 3D approximation</td>
<td>Geometry not free parameter</td>
</tr>
<tr>
<td>Pseudo-3D from 1D</td>
<td>State-of-the-art RT &amp; chemistry</td>
<td>Not 3D!</td>
</tr>
<tr>
<td>Topological 3D from 1D</td>
<td>Inferred geometry</td>
<td>Not 3D!</td>
</tr>
</tbody>
</table>

Central ionizing source (AGN, PN, HII region)

**Fig.**: SPHINX (Rosdhal+ 2018)  
**Fig.**: MOCASSIN (Hubber+ 2016)  
**Fig.**: M3-MAPPINGS V (Jin+ 2022)  
**Fig.**: PyCloudy, PyCROSS (Fitzgerald+ 2020; Morisset+ 2013)  
**Fig.**: MULTIGRIS+Cloudy (Lebouteiller Ramambason 2022)
## Many potential approaches

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Difficulties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulations</td>
<td>Dynamical effects, large volume</td>
<td>Comparison with specific observations (statistics), light chemistry network</td>
</tr>
<tr>
<td>1D</td>
<td>State-of-the-art RT &amp; chemistry</td>
<td>Scale to complex geometries</td>
</tr>
<tr>
<td>Pure 3D</td>
<td>3D RT, diffuse light...</td>
<td>Geometry (gas+sources) not free parameter</td>
</tr>
<tr>
<td>MC 3D</td>
<td>Good 3D approximation</td>
<td>Geometry not free parameter</td>
</tr>
<tr>
<td>Pseudo-3D from 1D</td>
<td>State-of-the-art RT &amp; chemistry</td>
<td>Not 3D!</td>
</tr>
<tr>
<td>Topological 3D from 1D</td>
<td>Inferred geometry</td>
<td></td>
</tr>
</tbody>
</table>

Fig.: SPHINX (Rosdhal+ 2018)

Fig.: MOCASSIN (Hubber+ 2016)

Fig.: M3-MAPPINGS V (Jin+ 2022)

Fig.: M3-MAPPINGS V (Jin+ 2022)

Fig.: PyCloudy, PyCROSS (Fitzgerald+ 2020; Morisset+ 2013)

Fig.: MULTIGRIS+Cloudy (Lebouteiller Ramambason 2022)

Vianney Lebouteiller (CNRS/AIM, CEA Saclay)
## Many potential approaches

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Difficulties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulations</td>
<td>Dynamical effects, large volume, 3D RT post-processing tools exist, e.g., with MOCASSIN</td>
<td>Comparison with specific observations (statistics), light chemistry network</td>
</tr>
<tr>
<td>1D</td>
<td>State-of-the-art RT &amp; chemistry</td>
<td>Scale to complex geometries</td>
</tr>
<tr>
<td>Pure 3D</td>
<td>3D RT, diffuse light...</td>
<td>Geometry (gas+sources) not free parameter</td>
</tr>
<tr>
<td>MC 3D</td>
<td>Good 3D approximation</td>
<td>Geometry not free parameter</td>
</tr>
<tr>
<td>Pseudo-3D from 1D</td>
<td>State-of-the-art RT &amp; chemistry</td>
<td>Not 3D!</td>
</tr>
<tr>
<td>Topological 3D from 1D</td>
<td>Central ionizing source (AGN, PN, HII region)</td>
<td></td>
</tr>
</tbody>
</table>

Vianney Lebouteiller (CNRS/AIM, CEA Saclay)  
Observing and modeling the extragalactic ISM  

**Fig.:** SPHINX (Rosdhal+ 2018)  
**Fig.:** MOCASSIN (Hubber+ 2016)  
**Fig.:** M3-MAPPINGS V (Jin+ 2022)  
**Fig.:** M3-MAPPINGS V (Jin+ 2022)  
**Fig.:** PyCloudy, PyCROSS (Fitzgerald+ 2020; Morisset+ 2013)  
**Fig.:** MULTIGRIS+Cloudy (Lebouteiller Ramambason 2022)
## Modeling strategies

Many potential approaches

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Difficulties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulations</td>
<td>Dynamical effects, large volume 3D RT post-processing tools exist, e.g., with MOCASSIN</td>
<td>Comparison with specific observations (statistics), light chemistry network</td>
</tr>
<tr>
<td>1D</td>
<td>State-of-the-art RT &amp; chemistry</td>
<td>Scale to complex geometries</td>
</tr>
<tr>
<td>Pure 3D</td>
<td>3D RT, diffuse light...</td>
<td>Geometry (gas+sources) not free parameter</td>
</tr>
<tr>
<td>MC 3D</td>
<td>Good 3D approximation</td>
<td>Geometry not free parameter</td>
</tr>
<tr>
<td>Pseudo-3D from 1D</td>
<td>State-of-the-art RT &amp; chemistry</td>
<td>Not 3D! Geometry not free parameter</td>
</tr>
<tr>
<td>Topological 3D from 1D</td>
<td>Inferred geometry</td>
<td>Not 3D!</td>
</tr>
</tbody>
</table>

Fig.: SPHINX (Rosdhal+ 2018)  
Fig.: MOCASSIN (Hubber+ 2016)  
Fig.: M3-MAPPINGS V (Jin+ 2022)  
Fig.: PyCloudy, PyCROSS (Fitzgerald+ 2020; Morisset+ 2013)  
Fig.: MULTIGRIS+Cloudy (Lebouteiller Ramambason 2022)
Observed emission is the sum of N components distributed in several stellar clusters surrounded with several sectors described by 1D models (Péquignot 2008, Cormier+ 2012, Cormier+ 2019, Lebouteiller+ 2017, Polles+ 2019, Lebouteiller Ramambason 2022, Ramambason+ 2022)

Explanations

- Combine 1D models that propagate radiation through HII region+PDR(+molecular cloud) ⇒ 1D (depth) structure constrained, need to constrain the spherical geometry (diffuse/reflected light and geometry simplification but still better than 1D though...)
Topological models: locally optimally emitting clouds (LOC)

- Observed emission is the result of strong selection effects due to the fact that some lines emit preferentially under some physical conditions (Ferguson+ 1997, Richardson+ 2014, 2016).

\[ L_{\text{line}} = \int \cdots \int L(p_1, \ldots, p_n)\psi(p_1, \ldots, p_n) dp_i \cdots dp_n \]
\[ \psi = U^{\alpha} N^{\alpha_n} \ldots \]

Applications
- Machine Learning application (Morisset+ in prep.)
- Depth/\text{A}_V: Application to statistical distribution of clouds with log-normal \text{A}_V in PDRs (Bisbas+ 2019)
  - + power-law tail due to self-gravity (possibly leading to star formation) reminiscent of result obtained in Ramambason+ (2022) for which only power-law distributions of depth can reproduce CO emission.
Global SED approach adapted to galaxy evolution parameters (\(z, \text{SFH}, \text{IMF} \ldots\))

Galaxy-wide parameters & gas properties

- **CIGALE & x-CIGALE: global energy balance** *(Boquien+ 2019)*
  - Full SED models from far-UV to far-IR
  - Using geometry templates for dust attenuation

- **BEAGLE** *(Chevallard Charlot 2016)*
  - Dust attenuation prescription related to inclination, global geometry (e.g., disk, bulge)
  - RT through ISM & IGM

- **General**
  - Nebular emission is accounted for (PDRs and CO in progress)
  - So far simple grids with tabulated U and Z, constant \(n \sim 100 \text{ cm}^{-3}\)
Complex models for single spectra

Still a relevant problem for single-dish/long-wavelength observations or for distant Universe

Objective: use the tracers to recover model parameters, including potentially geometry
Physical processes to explore in a comprehensive way (cont’d)

- **Energy input and gas heating mechanisms**
  - **Neutral atomic gas:** PE heating, soft X-rays, CRs...
  - **Molecular gas:** hard X-rays, shocks, cosmic ray ionization...
  - **Main challenge:** knowledge on dust content, X-ray sources, CR propagation and SFR dependency

- **All phases/scales:** shocks expected from various sources acting on various scales (from mergers, AGNs, starbursts... to protostellar outflows and stellar winds)
- **Main challenge:** lack of spatial decomposition/resolution – mixing biases
Dense gas fractions and SFE

Dense gas fraction in extragalactic ISM

- HCN, HCO⁺ more and more observations but still few studies apart from very nearby galaxies (e.g., Magellanic Clouds; Galametz+ 2020) and starbursts/AGNs
- Consistent results in that SFE ↘ when dense gas fraction (or stellar surface density, interstellar P... ) ↗, at kpc-scales (EMPIRE; Jimeñez-Donaire+ 2019) down to <100pc-scales (Beslic+ 2021, PAWS Schinnerer in prep.)
- SFE traced by IR/HCN or Hα/HCN

Fig.: NGC3627 with NOEMA and PHANGS-MUSE (Beslic+ 2021)

Fig.: SFE(dense) vs. f(dense) in NGC3627 (Beslic+ 2021)

All in all favoring turbulence-regulated SF models (e.g., Burkhart & Mocz 2018)
Shocks

- Near/mid-IR H$_2$ as well as optical lines for tracing relatively diffuse shocks (e.g., Hong+ 2013, Medling+ 2015) but difficult interpretation without spatial resolution. JWST important for nearby galaxies.

Dust and mineralogy with JWST

- PAHs, fullerenes, CO$_2$ ice...
- Spitzer: crystalline silicates are a common component of the ISM (Spoon+ 2022).
- Strength of crystalline silicate bands toward nuclei correlate with strength of amorphous silicate strength.
- Transition from emission to absorption at high obscuration consistent with an origin for the amorphous/crystalline silicate features in a centrally heated dust geometry (edge-on disk or cocoon).
- Crystalline silicate bands able to classify the obscuration level of AGNs, even in the presence of strong circumnuclear star formation.

Fig.: Simulated MIR spectra of centrally heated dust shells with increasing dust mass (Spoon+ 2022) – amorphous silicates.

Fig.: Observed spectra showing the transition emission/absorption for crystalline silicates (Spoon+ 2022).
& much more...

**Shocks**
- Near/mid-IR H$_2$ as well as optical lines for tracing relatively diffuse shocks (e.g., Hong+ 2013, Medling+ 2015) but difficult interpretation without spatial resolution. JWST important for nearby galaxies.

**Dust and mineralogy with JWST**
- PAHs, fullerenes, CO$_2$ ice...
- Spitzer: crystalline silicates are a common component of the ISM (Spoon+ 2022).
- Strength of crystalline silicate bands toward nuclei correlate with strength of amorphous silicate strength.
- Transition from emission to absorption at high obscuration consistent with an origin for the amorphous/crystalline silicate features in a centrally heated dust geometry (edge-on disk or cocoon).
- Crystalline silicate bands able to classify the obscuration level of AGNs, even in the presence of strong circumnuclear star formation.

**Fig.:** Simulated MIR spectra of centrally heated dust shells with increasing dust mass (Spoon+ 2022) – amorphous silicates.

**Fig.:** Observed spectra showing the transition emission/absorption for crystalline silicates (Spoon+ 2022).
& much more. . .

**Shocks**
- Near/mid-IR H$_2$ as well as optical lines for tracing relatively diffuse shocks (e.g., Hong+ 2013, Medling+ 2015) but difficult interpretation without spatial resolution. JWST important for nearby galaxies.

**Dust and mineralogy with JWST**
- PAHs, fullerenes, CO$_2$ ice. . .
- Spitzer: crystalline silicates are a common component of the ISM (Spoon+ 2022).
- Strength of crystalline silicate bands toward nuclei correlate with strength of amorphous silicate strength.
- Transition from emission to absorption at high obscuration consistent with an origin for the amorphous/crystalline silicate features in a centrally heated dust geometry (edge-on disk or cocoon).
- Crystalline silicate bands able to classify the obscuration level of AGNs, even in the presence of strong circumnuclear star formation.

---

**Fig.**: Simulated MIR spectra of centrally heated dust shells with increasing dust mass (Spoon+ 2022) – amorphous silicates.

**Fig.**: Observed spectra showing the transition emission/absorption for crystalline silicates (Spoon+ 2022).