Cosmic rays, gas, and dust in Local clouds

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Total gas tracers

- γ rays of interstellar origin

\[ p_{CR} + p_H \rightarrow \pi_0 \rightarrow 2\gamma \]

\[ I_\gamma \propto \int n_{CR} n_H \, dl \]

- Dust thermal emission from large dust grains mixed with gas

\[ I_\nu = \tau_\nu B_\nu(T) \]

Dust optical depth

\[ \tau_\nu = \kappa_0 \left( \frac{\nu}{\nu_0} \right)^\beta R_{DG} \mu H N_H \]

- Extinction caused by large dust grains mixed with gas

\[ A_\lambda = 1.086 \tau_\lambda^{ext} = 1.086 \int n_{dust} \sigma_\lambda^{ext} \, ds \]

Stellar reddening: \( E(B-V) = A_\nu / R_\nu \)
Objectives:

- **Modelling** diffuse \(\gamma\)-rays emission, dust optical depth, stellar reddening: linear combination of gas column density in different phases (HI, CO, DNM)
- **Test** reliability of the tracers
- **Constraints** on the gas phases and dust properties
Dust and γ-ray data jointly reveal significant amounts of gas in addition to that seen in HI and $^{12}$CO emissions.

Dark Neutral Medium (or dark gas)

DNM = dense HI + diffuse $H_2$
Anticenter region: 6 local clouds

6 Local clouds separated in position-velocity + Galactic background gas

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Tracing gas and dust in the local interstellar medium
γ-ray and dust models

Uniform Cosmic Rays density $n_{\text{CR}}$, dust-to-gas ratio, grain emissivity $\kappa_\nu$, extinction cross section $\sigma_\lambda^{\text{ext}}$ → $\gamma, \tau, E(B-V)$

$\sum_{\text{HI}} N_{\text{HI}}$ Cet, N$_{\text{HI}}$ TauS, N$_{\text{HI}}$ TauN, N$_{\text{HI}}$ TauM, N$_{\text{HI}}$ Cal, N$_{\text{HI}}$ Per, N$_{\text{HI}}$ Gal

$+ \sum_{\text{CO}} W_{\text{CO}}$ Cet, W$_{\text{CO}}$ TauS, W$_{\text{CO}}$ TauN, W$_{\text{CO}}$ TauM, W$_{\text{CO}}$ Cal, W$_{\text{CO}}$ Per, W$_{\text{CO}}$ Gal

$+ N_{\text{HII}}$ DNM, + COsat + non-ISM ancillary data

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Tracing gas and dust in the local interstellar medium
Final dust and γ-ray models residuals

- Data - model in sigma unit:
Emissivity spectra of local clouds consistent with the local interstellar spectrum (Casandjian 15)

Local dispersion ±9% : consistent with uncertainties in $N_{HI}$ column densities

Perseus value : no CR enhancement, cross-talk between HI and CO distributions

No energetic evolution relative to the local interstellar spectrum accross cloud phases

⇒ good CR penetration into the cloud ⇒ $\gamma$-rays OK to trace $N_H$
Evolution of grain emission properties

- Non-linear increase in $\tau_{353}$ with gas column density, $N_H$, likely due to grain evolution (coating, aggregation...)

- Better correlation of the stellar reddening caused by dust, $E(B-V)$, with gas column density, $N_H$
$X_{\text{CO}}$ estimates from $\tau_{353}$ systematically larger than $\gamma$-ray and $E(B-V)$ ones. Better to rely on $X_{\text{CO}}$ measurements from $\gamma$ rays.

Preliminary data points indicate:

- TauN
- TauS
- Cal
- TauM
- Per

$X_{\text{CO}}$ measurements with dust and $\gamma$ rays

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Dust emission/extinction and grains evolution
**X\textsubscript{CO} environnemental changes**

**γ-ray measurements:** \( X_{\text{CO}} = \frac{q'(\text{CO})}{2q'(\text{HI})} \)

Average \( X_{\text{CO}} \) of a cloud

**Simulation:** \( X_{\text{CO}} \) variations within a cloud

Larger \( X_{\text{CO}} \)

Bertram et al. 2015

**Simulation:**
\( X_{\text{CO}} \) decreases from cloud edge (photo-dissociated) to core (well shielded)

**γ-ray measurements:**
Average \( X_{\text{CO}} \) decrease from diffuse to bright and compact clouds

Consistent with \( X_{\text{CO}} \) decreases from edges to denser cores
Take away messages

- No energetic evolution relative to the local interstellar spectrum across cloud phases
  => good CR penetration into the cloud => γ-rays OK to trace $N_H$

- Dust optical depth $\tau_{353}$ do not linearly correlate with gas column density, $N_H$
  due to a chemical and/or structural change in the dust grains.

- γ-ray and dust data jointly reveal significant amounts of DNM gas in addition to that
  seen in HI, free-free, and $^{12}$CO emissions.

- Evidence for $X_{CO}$ variations in different environments
  => importance of clouds separation

See more:
Chamaeleon clouds: *Planck & Fermi-LAT Collaborations XXVIII* (2015), A&A ... 82A..31A
Nearby Anticenter clouds: Remy et al. (2017), A&A...601A..78R
Questions or bonus slides?
Gas emission lines

- Atomic gas: HI 21cm emission line (LAB, GASS, EBHIS, HI4PI, GALFA surveys)

\[
N_H = 1.83 \times 10^{18} \text{ cm}^{-2} \quad T_S \int \ln \left( \frac{T_S}{T_S - T_b} \right) \, dv
\]

Spin temperature $T_S$ unknown without absorption line measurement (uncertainty in dense HI)

- Molecular gas: CO (J 1-0) 2.6 mm emission line (CfA, Nanten surveys)

\[
W_{\text{CO}} = \int T_b \, dv
\]

CO to $H_2$ conversion factor:

\[
X_{\text{CO}} = \frac{N_{H_2}}{W_{\text{CO}}}
\]
Neutral gas phases

Anticentre region
Remy et al. (2017)

Chamaeleon region
Planck+Fermi XXVIII (2015)

Dark Neutral Medium: Opaque HI + diffuse H$_2$

Bright HI

CO-traced H$_2$

CO-saturated H$_2$
γ-ray detection of ionized gas

- γ-ray detection 10 σ, hadronic origin, not Inverse Compton
- Hα and free-free emissions model in NGC1499:
  - Mean electron density \( N_e = 5.0 \pm 1.1 \text{ cm}^{-3} \)
  - Electron temperature \( T_e = 7700 \pm 1700 \text{ K} \)
- γ-ray measurement for \( T_e = 8000 \text{ K} \):
  - \( N_e = 4.3 \pm 0.6 \text{ cm}^{-3} \)