Diffuse Emission from Local Clouds

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Collaboration

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Outline

• What a gamma-ray astronomer should know about the interstellar medium
  – ‘Dark Gas’ - how and why
• Modeling the diffuse gamma-ray emission
  – Gamma-ray observations of interstellar clouds
• LAT results on local clouds – summary
• Advances coming up – Planck
• Conclusions
LAT Sky Map

>1 GeV for three years
• Interstellar clouds are not literally clouds but appear as dark nebulae or ‘clouds’ against the Milky Way
Why are the clouds dark?

- What we see (in absorption) is the interstellar dust
• Grains of ‘metals’ – carbon-ish and silicon-ish – with a size spectrum ranging from very small to small and
  – About 1% by mass of the interstellar medium

Dust

• Dust is fantastically important to the interstellar medium – reprocesses star light (incidentally absorbs UV to shield clouds), and catalyzes the formation of molecular hydrogen
  – Otherwise, even if they wanted to, two H atoms would have no phase space for combining to form H$_2$

• Realization of the catalytic aspect of dust (Hollenbach & Salpeter 1971) was a great advance and (I imagine) spurred the search for tracers of molecular hydrogen
The neutral interstellar medium is gas mixed with dust; associations of gas, especially dense ones, are referred to as clouds – which doesn’t meaningfully help for understanding them.

The gas is very, very cold (few K to 10s of Kelvin) and very, very tenuous ($10^3$ cm$^{-3}$ is a high density)
- $10^3$ H$_2$ molecules cm$^{-3}$ at 5 K corresponds to a pressure of $10^{-13}$ torr, much lower than can be achieved in the laboratory.

They are quite unlike atmospheric clouds in other ways
- To the extent that they are stable, they are (sort of) self gravitating, with important magnetic support
- They are huge and massive – largest ~100 pc and ~$10^6$ Msun.

Overall, most of the mass of the interstellar medium is atomic hydrogen*
- The densest component of the neutral medium is primarily H$_2$
- This is where stars (OB assoc., SNR, pulsars, XRB, …) form

* He makes up 21% by mass of the ISM and is assumed to be in proportion to the H
Atomic hydrogen

- Directly detected via the 21-cm hyperfine (spin flip) transition
- H I is pervasive in the Milky Way – you cannot find a direction in the sky with less than $6 \times 10^{19}$ cm$^{-2}$ column density (Lockman Hole)
- It is also generally optically thick (and self absorbing – ask Gulli)
- The optical depth correction is important and cannot be done precisely – historically in studies of diffuse gamma-ray emission this was not always appreciated (by, e.g., me)
  - The standard approach had been to assume a spin temperature of $T_S = 125$ K

$$N_{HI}(v, T_S) = -\log \left( 1 - \frac{T_B}{T_S - T_{bg}} \right) T_S C \Delta v$$

Brightness of the CMB at 1.4 GHz: $1.83 \times 10^{18}$ cm$^{-2}$ km$^{-1}$ s
• It is hard to see
  – $\text{H}_2$ has no dipole moment, and so no rotational spectrum.
  – The lowest vibrational bands are a few 1000 K above ground. It can be detected directly when shock heated or in absorption in the UV, but is not directly detectable under ordinary interstellar conditions

• CO is the 2nd most abundant molecule, down by a factor of $\sim 10^5$ from $\text{H}_2$, but it does have a permanent dipole moment (0.1 Debye or so) and the lowest excited rotational level ($J = 1$) is only a $\sim 5$ K above ground
Interstellar CO (which also forms on grains) is collisionally excited by H$_2$, and then emits a microwave (115.271 GHz) photon from the $J = 1-0$ transition.

This transition is forbidden; the spontaneous rate is about 1 yr$^{-1}$, but conditions in molecular clouds are such that collisional de-excitation is not a serious problem even for such a long-lived state.

Note that this is a spectral line and that millimeter wave spectroscopy can be extremely high resolution – one part in $10^6$ is absolutely no problem.

- This is one reason that CO observations are extremely useful for studies of Galactic structure, which I will not say anything about.
For various reasons, CO ought to be at least an ok tracer of molecular hydrogen

- Conditions for their formation and destruction are similar, and as mentioned collisional excitation is well matched to conditions of molecular clouds

However, CO is abundant enough that it is certainly optically thick (bad news for a mass tracer; in principle you measure its temperature rather than its column density)
• However\(^2\), molecular clouds are extremely clumpy, and the semi-quantitative reasoning is that clumps exist down to the scale where CO is just optically thick, and observations of the CO line are in effect counting ‘clumps’, and the integrated intensity of the CO line is an ok surrogate tracer of molecular mass.

Wolfire, Hollenbach, & Tielens (1993)
The relationship between $W$(CO) and $N$(H$_2$) obviously needs to be calibrated indirectly.

Many approaches have been taken:
- Some related to dust, like obscuration optically or (better) in the near infrared.
- Also ‘virial equilibrium’ arguments.

High energy gamma rays were recognized early (like in the COS-B era) as potentially a very good calibrator:
- The availability of large-area CO surveys was fortuitously coincident with COS-B’s analysis needs.
- More later.

The ‘standard’ value of $N$(H$_2$)/$W$(CO) is $\sim 2 \times 10^{20}$ cm$^{-2}$ s$^{-1}$ (K km s$^{-1}$)$^{-1}$, and of course it is not a physical constant of Nature.
Dark Gas

• CO is not a perfect tracer of H\textsubscript{2} and we do not really know N(H I) perfectly
  – The challenge is in what to do about it: No universal column density tracer
• Schlegel, Finkbeiner, & Davis (1998) used IRAS and COBE/DIRBE data to infer dust column densities
  – ‘Color correcting’ to a uniform dust temperature scale
  – Results were expressed in terms of E(B-V) [excess reddening] equivalent
  – If you can believe in constant gas-to-dust ratio and uniform grain size distributions then E(B-V) is a tracer of total column density
• Grenier et al. (2005) pointed out in an analysis of EGRET data that E(B-V) is not a linear combination of W(CO) and N(H I)
  – So… ‘dark gas’
• The (long-standing) provisional solution has been deriving the ‘dark gas’ component as a residual from correlations with dust column density map
Illustration for Orion: Complications

- Schlegel et al. flag 4 regions in Orion as difficult to process (bright IR sources and 42’ beam of DIRBE)
- Independently we smooth across bright IR sources
- Result is deep holes in ‘dark gas’ map where suspicious 2FGL* sources collect – these are flagged in the 2FGL catalog

Red points are unassociated 2FGL sources (blue point is a 2FGL source associated with a blazar)

*2FGL = Second Fermi gamma-ray source catalog (1108.1435)
Planck Collaboration has made a dark gas analysis this year, deriving ‘dark gas column densities’ using HFI 857 GHz and IRAS long-wavelength bands.

- HFI beam is 5’ vs. 42’ for DIRBE (Good)
- N.B.: Their analysis avoided the tough regions, and Planck data are not going to be released soon

Fig. 8. Map of the excess column density derived from the 857 GHz data. The map is shown in Galactic coordinates with the Galactic centre at the centre of the image. The grey regions correspond to those where no IRAS data are available, regions with intense CO emission (W_{CO} > 1 Kkms^{-1}) and the Galactic plane (|b| < 5°). Planck Collaboration (2011)
Modeling the Diffuse Emission

- The diffuse gamma-ray emission is modeled as a linear combination of templates of gas tracers and other diffuse components.

\[
N_{pred}(l, b) = \int \int d\Omega k \left( \sum_{i=rings} [q_{HI,i} N_{HI}(r_i, l_k, b_k) + q_{CO,i} W_{CO}(r_i, l_k, b_k)] + q_{EBV} E(B - V)_{res}(l_k, b_k) + q_{IC} I_{IC}(l_k, b_k) + I_{iso}(l_k, b_k) \right) \epsilon(l_k, b_k) PSF(l, b, l_k, b_k) + \sum_{j=sources} F_j \epsilon(l_j, b_j) PSF(l_j, b_j, l, b)
\]

- Ionized ISM is not included as a ‘template’ and Helium and heavier elements are included by assuming that they are proportional to H.

- As long as the maps are not linearly dependent, a likelihood analysis can tell you the contribution from each one.

- Note important assumption: CR densities & spectra are uniform across the region being studied.

- Interpretations are emissivity (effective rate of gamma-ray emission per H atom), N(H2)/W(CO).
Local interstellar clouds and gamma rays

Schematic top-down view

- **COS-B**: Rho Oph (point source*), Orion
  * Mostly PKS 1622-253
- **EGRET**: Rho Oph (diffuse source), Orion, Monoceros, Cepheus
- **Fermi era LAT team publications**:
  “Fermi Large Area Telescope measurements of the diffuse gamma-ray emission at intermediate Galactic latitudes” ([0912.0973](https://arxiv.org/abs/0912.0973); CA: G. Johannesson, A. W. Strong, T. A. Porter)
  “Fermi observations of Cassiopeia and Cepheus: diffuse gamma-ray emission in the outer Galaxy” ([0912.3618](https://arxiv.org/abs/0912.3618); CA: L. Tibaldo & I. A. Grenier)

+ Preliminary results on Chamaeleon, R CrA, Orion A&B

Dame et al. (1987)
Gamma-ray observations of interstellar clouds

- History of the observations
  - Orion A&B as an example
  - Exposures are much more uniform with the LAT as well
  - Radio and mm surveys of the gas have improved markedly as well
• Emissivity spectra are essentially consistent with what would be expected from local interstellar spectrum, i.e., what GALPROP would predict
• Deviations are within systematic uncertainties
• X-ratios are not much changed since the pre-dark gas era, although the interpretation is not the same
• In a sense X-ratio is not as central as it had been in terms of describing the ISM
Diffuse gamma-ray emission from local molecular clouds is a testing ground for understanding gamma-ray production in the interstellar medium as well as for our understanding of the interstellar medium.

The huge observations advances provided by the LAT are needing to be met with advances in understanding the neutral ISM.

- **Modeling also becomes more involved because of background gamma-ray sources.**

Dark gas is an important component and challenging at the same time.

From LAT observations of local clouds we can say that the gamma-ray production processes are understood.
Fermi and the LAT

- Large Area Telescope was launched in June 2008 on the NASA mission now called Fermi

- Major contributions from France, Italy, Japan, Sweden, & U.S.
- LAT collaboration has ~400 members
Fermi and the LAT

• LAT energy range is 20 MeV - >300 GeV (>4 orders of magnitude)
• Peak collecting area is about 8000 cm\(^2\) (moderate)
• Field of view is 2.4 sr (huge)

• High-energy gamma-ray astronomy is a relatively young field, partly because at GeV energies it must be done from space

• LAT is by far the most sensitive instrument ever in this energy range
  – Celestial gamma-ray rate is \(~2\) Hz for the LAT
  – Within the first few weeks of the mission, LAT had collected as many gamma rays than had been detected by all previous missions combined, and measured them with better precision
  – Huge ‘discovery potential’
EGRET results on local clouds

Cepheus (local)
Orion
Ophiuchus
Monoceros (local)

Monoceros local
Interarm
Perseus arm

Digel et al. (1996 & 2001)
More on interstellar CO

- Interstellar CO was detected in 1970 (Wilson, Jefferts, & Penzias)
- Surveys of CO in the Milky Way were published by the mid 1970s, and small survey telescopes were operational in the early 1980s, built by the Columbia Univ./GISS group led by P. Thaddeus