Velocity-Resolved Fine Structure Line Observations and Star Formation:

New Results and New Capabilities

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The Interstellar Medium is Complex but plays a critical role in the evolution of galaxies.
The Baryonic Lifecycle of the Interstellar Medium

- Describes the cycling of material between different ISM phases and incorporation into new stars
- Star formation takes place in relatively quiescent, dense, cold molecular clouds
- Massive young stars disrupt star-forming regions, heating & ionizing them and increasing turbulence

**Tracers of different Phases**
What Controls the Rate of Star Formation?

- Reservoir of material – gravitationally bound molecular gas
- Impediments to cloud collapse and star formation – turbulence, magnetic fields
- Limitation of star formation by effects of young stars

We would like to understand the relationship between ISM and young stars to quantify roles of above processes
This requires tracing the different phases of the ISM
The challenge is the huge variation in physical conditions, particularly n and T, as well as chemical composition
Picking an Arbitrary Starting Point – Molecular Clouds

• Development of receiver technology at mm wavelengths along with construction of increasingly capable telescopes has allowed construction of fairly well-defined picture of molecular clouds

• Primary tracer is lower rotational transitions of carbon monoxide and its isotopologues $^{13}$CO and $^{18}$O

• Level spacing of $T^* = hf/k \sim 5.5J \text{ K}$ for transition $J\rightarrow J-1$ is ideal for measurement of clouds at temperatures of 8 – 20 K. Low dipole moment and slow radiative decay rates make transitions in LTE for $n>1000 \text{ cm}^{-3}$

• Molecules with higher dipole moments and faster decay rates(HCN, HCO+) delineate higher density regions in cloud corers ($n \geq 10^4 \text{ cm}^{-3}$)
Molecular Cloud Structure

- $^{13}$CO is effectively optically thin, so integrated intensity traces column density, and with reasonable assumptions we get $N(H_2)$ & total mass of the region
- $N(H_2) < 10^{22}$ cm$^{-2}$; $M = 2.1 \times 10^4$ M$_{\text{sun}}$
- Taurus has only low-mass star formation (no B-stars) and while there are some outflows from young embedded stars the bulk of the structure seen must result from the PROCESS OF CLOUD FORMATION
- Young stars form in regions with $A_v > 6$ mag., possibly from instabilities in the ubiquitous filamentary structure
Molecular Clouds and CO-dark Gas

• The temperatures of “dark clouds” – those lacking massive star formation – are 8 K to 12 K

• Chemical models indicate that for $A_v \gtrsim 1.5$ mag., most of the carbon is in the form of CO, as is oxygen not tied up in dust grains.

• In BOUNDARY LAYER, carbon is $C^+$, but hydrogen is $H_2$ due to efficient self-shielding. This is the CO-dark molecular gas.

• HI and CO do **not** trace this ISM phase

• The temperature of CO-dark $H_2$ is $\sim 50$ K due to photoelectric heating by ISRF and $\geq 100$ K if you are in neighborhood of young star or stars.

$$E_u = \frac{hf}{k} = 92.1 \text{ K for } [\text{CII}]$$

making it well-suited for tracing regions with $T > 50$ K
Disentangling the Sources of [CII] Emission

• Observations of the Milky Way have suggested that about 30% of the [CII] luminosity arises from photon–dominated regions (PDRs), 25% from atomic clouds, 25% from CO–dark H₂, and 20% from the diffuse warm ionized medium (Pineda, Langer, Goldsmith 2014).

• [CII] emission is very widespread and locally easily dominated by a PDR.

• There has not yet been a “definitive” image of the CO-dark gas around a molecular cloud, though there are hints such as L1599 cloud observed in [CII] using SOFIA.
Complexity of Cloud Boundaries

Taurus is very low ISRF region $\chi \sim 0.5$

Nonetheless, strong H$_2$ S(1) emission is seen

$\lambda = 17 \, \mu m$

$\text{Eu/k} = 845 \, \text{K}$

Peaks 0.5 pc outside $^{13}$CO edge

Turbulent dissipation could be additional heating source

Formation cascade also possible

Tauru cloud boundary: sharp in $^{13}$CO

Goldsmith+ (2010)
[CII] From Regions of Massive Star Formation
Orion: $X \geq 10^4$

Complex Kinematics Indicated!

Goicoechea+ (2015)
Dust Continuum

Blue = warm dust
Red = cool dust

Herschel PACS & SPIRE

[Image of dust continuum with color coding]

40 hours with SOFIA upGREAT
7-element receiver
Fully-sampled image
2.5 million spectra

Previous Herschel map of [CII]
Expanding spherical half shell with constant expansion velocity $v = 13$ km s$^{-1}$

- Mass of shell $\sim 2600 \, M_\odot$
- Age $\sim 2 \times 10^5$ yr
- Kinetic energy in shell $= 4 \times 10^{48}$ ergs
- [CII] luminosity of shell is $0.3 \times$ luminosity of $\theta^1$ C Ori

Pabst+ (2019)
The Structure of the Expanding Orion Bubble

The Trapezium and PDR are on "our" side of the Orion Molecular Cloud.

The expansion is largely into the low density material towards the Earth.

The feedback in terms of stimulated star formation is limited.

The PDR has relatively little foreground material.

Pabst + (2019)
W49N

Extremely Massive & Luminous Star-Forming Region

\[ M = 10^6 \, M_{\text{sun}} \quad L = 10^7 \, L_{\text{sun}} \]

Smith+ (2009)

*Herschel* HIFI observations

Gerin+ (2014)

**SIGNIFICANT FEATURES**

- Emission at \( \sim 5 \, \text{km/s} \) is hugely self-absorbed
- There is strong absorption at higher velocities unrelated to the source
- This is low-excitation C+ in diffuse clouds along the line of sight
- Consistent with 11.4 kpc distance to W49

\[
\begin{align*}
\text{[CII]} & \quad 1900 \, \text{GHz} \\
\text{[CI]} & \quad 809 \, \text{GHz} \\
\text{[CI]} & \quad 492 \, \text{GHz}
\end{align*}
\]
In unresolved data, line/continuum ratio drops dramatically as continuum strengthens. A consequence of equal area of diffuse cloud absorption and true W49 emission.

Distant galaxies typically observed with low-resolution spectrometers. What will happen in Starburst or ULIRG with multiple regions with C\(^{+}\) in beam?
Atomic Oxygen ($O^0$)

- $\{O\}/\{H\} = 5 \times 10^{-4}$
- High IP 13.62 eV
- Traces neutral ISM
- No FS lines from $O^+$; $O^{++}$ requires 35.1 eV – [OIII] 88 μm important tracer of gas ionized by very hot stars
- Two $O^0$ fine structure transitions:
  - [OI] 63 μm and [OI] 146 μm
- [OI] 63 μm widely used as tracer of star formation by ISO & Herschel
- Both lines are observable only from above Earth’s atmosphere
[OI] Excitation and Emission

Rapid decay of $^3P_1$ line and collisions from $^3P_2$ to $^3P_0$ lead to population inversion of upper 145 μm transition.
Does [CII] Emission Trace Star Formation?

GOT C+ Survey
Sampled 500 los in Milky Way using Herschel HIFI instrument
Velocity-resolved [CII] spectra

Pineda+(2014)
[OI] 63 μm as Tracer of Star formation rate

- Generally does a reasonably good job for “normal” galaxies; possibly better than [CII]
- This is in a sense surprising as [OI] comes from much more limited fraction of ISM than [CII]
- Some entire galaxies appear “offset” in [OI]
- [CII] tends to diverge at high $\Sigma$ end of individual galaxies
Hints of Problems with [OI] 63 μm Line

Galactic Star-forming Region G5.89-0.39
D = 1.28 kpc
Powered by single O-star
Massive outflows
Leurini+ (2015)

Galaxy NGC 7552 – Rosenberg+ (2015)

Strong suggestion of significant self-absorption!
Conclusions About [CII] (& Other Fine Structure Lines) as Star Formation Tracers

[CII] works well for local galaxies
Concern has been raised for ULIRGs and other “exotic” galaxies
Of interest not only for understanding individual galaxies but also for modeling results of “Intensity Mapping” studies of high-redshift galaxies in which individual galaxies are NOT resolved, but collective emission is measured

But there are concerns:
The greatest is optical depth and how it may effect observed intensities
Survey of Massive Star-Forming Regions with SOFIA/upGREAT

- [OI] 63μm observed in 12 regions
- Good detections – very variable line strengths
- CO J=5-4, J=8-7, and also [NII] 205μm observed simultaneously
- CO 8-7 traces warm molecular gas heated by UV from young star(s) and HII region
- [OI] shows clear self-absorption in half of sources observed
- Also see possible velocity shifts of [OI] relative to molecular gas
Structure of Photon Dominated Region

Moving away from enhanced UV source:

- Temperature drops rapidly $H$ converts to $H_2$
- Oxygen remains atomic to $A_v = 8$ mag but too cold to emit for $A_v > 2.5$ mag
- A few % of oxygen is $O^0$ throughout entire region
- Total $N(cold \ O^0) \sim 10^{18}$ cm$^{-2}$
- $\Rightarrow$ 63 μm could be thick
SOFIA Observations of [OI] 63 μm in W3

W3 is region of massive star formation at \( D = 2 \) kpc

Radio continuum; FIR; CO

\( M = 4 \times 10^5 \, M_{\odot} \)

\( L = 5 \times 10^5 \, L_{\odot} \)

Dust temperature (color) and \( \text{H}_2 \) column density (contours)

W3 IRS5 is center of stellar activity
[OI] and CO in W3

- 8 positions along NW-SE cut
- [OI] and CO 8-7, CO 5-4 shown
- In ALL but extreme NW positions, [OI] is drastically self-absorbed as indicated by line profiles and comparison with CO
- CO 5-4 also self-absorbed in central region
[OI] - Near W3 E

• Line wings well-fit by Gaussians

• This should represent “PDR Emission” that would be observed if there were no foreground low-excitation gas

• $T \sim 220 \text{ K}$ at central position! As strong as Orion (geometry)
Modeling Absorption

- PDR models suggest gas at ~30K which has effectively no emission
- A second Gaussian representing pure absorption fits observed line profile well
- Peak absorption optical depth = 7.8
- Velocity shift = -2 km/s
- \( N(\text{low-excitation } \text{O}^0) \) consistent with PDR models
Foreground [OI] Absorption in W3

- Peak optical depths $\tau > 2$ derived for entire central region with relatively strong observed emission
- Total emission at different positions reduced by factors 2 – 4 compared to values expected from fitted background Gaussians
- Implication is that we may be underestimating the [OI] luminosity by a significant factor
- Observational occurrence depends on geometry – not seen when PDR on Earth-facing side of cloud (Orion) ⇒ should appear in ~50% of randomly selected sources as observed
- Effect will be greatest in regions with most massive (large $A_\nu$) clouds
- Will impact [OI] 63 μm line in starburst galaxies with massive GMCs and high star formation rates – “OI deficit”
- One way to confirm/correct is to observe the 146 μm line
Observational Capabilities

- Currently upGREAT instrument on SOFIA has good capability for [NII] 205 μm, [CII] 158 μm, and [OI] 63 μm. No capability for [NII] 122 μm and limited capability for [NII] 205 μm and [OI] 146 μm
- Fine structure line capability will be enhanced if HIRMES instrument is selected to be completed for SOFIA
- A large-format (e.g. 128 pixel) Fine structure mapping line instrument has also been proposed for SOFIA ([CII] and [OI] 146 μm)
- Origins Flagship mission will certainly have enormous sensitivity, but high velocity resolution only if HERO instrument upscope is included
- Two balloon missions focusing on fine structure line emissions are currently under development
Galactic/Extragalactic Ultra/LDB Spectroscopic/Stratospheric Terahertz Observatory **GUSTO** (C. Walker, Univ. of Arizona, PI)

- 90 cm dia. Telescope (~40” resolution)
- 8 pixel HEB arrays for [NII] 205 μm, [CII] 158 μm, and [OI 63 μm
- **Long Duration Balloon** offers ~ 70 day lifetime, but payload recovery is not certain

**Level 1 Requirements: Data Products**

**GPS:** Galactic Plane Survey: $-25^\circ < l < 25^\circ$; $-1^\circ < b < 1^\circ$

**LMCS:** Large Magellanic Cloud Survey: $4^\circ \times 6^\circ$ map of entire LMC

**TDS:** Targeted Deep Surveys: ~1 deg$^2$ of regions in Galaxy/LMC

NASA Explorer Mission of Opportunity (MoO) balloon mission – Launch Dec. 2022
90 cm “optical” telescope

LHe dewar
Refrigerator-cooled radiation shield
~100 day hold time
**ASTHROS** Astrophysics Stratospheric Telescope for High-Resolution Observations at Submillimeter-waves (J. Pineda, PI)

- Antarctic NASA APRA balloon mission
- 205 μm and 122 μm[NII] fine structure lines
- High angular resolution (20” and 12”’) of ionized gas regions in the Milky Way and M83
- Study the extended, dense WIM (D-WIM) and determine electron densities from line ratio
- Observe 112 μm HD line in a protoplanetary disk
- 21-day flight Dec. 2023
ASTHROS Instrument

2.5m dia. Al honeycomb/CFRP antenna (Media Lario, Italy)
Low blockage symmetric Cassegrain
<8 μm rms aggregate surface accuracy
2 4-pixel HEB science receiver arrays
80-100 GHz receiver for system tests and pointing observations
8 ASIC digital spectrometers
4 K closed cycle Lockheed Martin pulse tube cryocooler

ASTHROS Telescope is a BIG Step Compared to GUSTO

Panel Mold
ASTHROS Telescope

Sunshield support

Cart for testing and transport
Conclusions

• Fine structure lines are powerful tracers of ISM, especially regions mechanically and radiatively affected by massive star formation

• [CII] and [OI] generally trace star formation both in Galactic sources and external galaxies but there are important caveats emerging from detailed studies of velocity-resolved spectra
  • In [CII], absorption by diffuse ISM can corrupt results for emission regions when observed with inadequate velocity resolution
  • In [OI], there is evidence for extensive regions of low-excitation atomic oxygen, that absorbs the emission from hot gas adjacent to HII region

• Understanding these issues will require velocity-resolved fine structure line images, which will be produced by SOFIA and upcoming balloon missions