Velocity-Resolved Fine Structure Line Observations and Star Formation:

Some New Results

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SOFIA Galactic Ecosystems Workshop
March 1, 2022
The Interstellar Medium is Complex but plays a critical role in the evolution of galaxies
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.
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 $\sim 5$ 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

[CII] 1900 GHz

[CI] 809 GHz

[CI] 492 GHz

Average of reference positions (expanded scale) (continuum shifted)
PDR emission and diffuse cloud absorption are clearly distinguished in velocity-resolved spectra.

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

\begin{align*}
[OI] & \quad 63 \text{ μm} \quad E_u = 228 \text{ K} \quad E_I = 0 \text{ K} \\
[OI] & \quad 146 \text{ μm} \quad E_u = 327 \text{ K} \quad E_I = 228 \text{ K} \\
[CII] & \quad 158 \text{ μm} \quad E_u = 92 \text{ K} \quad E_I = 0 \text{ K}
\end{align*}
Excitation and Emission

Rapid decay of $^3P_1$ line and collisions from $^3P_2$ to $^3P_0$ lead to population inversion of upper 145 $\mu$m transition.
Does \([\text{CII}]\) Emission Trace Star Formation?

GOT C+ Survey
Sampled 500 los in Milky Way using Herschel HIFI instrument
Velocity-resolved \([\text{CII}]\) spectra

De Looze fit to galaxies
Slope = 0.98

Entire Milky Way
Slope = 0.89

Global fit to all data from GOT C+ Survey
Slope = 0.89

Pineda+(2014)
[OI] 63 μm as Tracer of Star Formation Rate

- Generally does a reasonably good job for “normal” galaxies but a “deficit” appears for more luminous galaxies with warmer dust
- Higher $T_{\text{dust}}$ if reflected in higher $T_{\text{gas}}$ would enhance [OI] 63 μm
- Oxygen can remain largely atomic to substantial $A_v$ when irradiated by large flux from HII region/hot PDR
- Is the greater density of star-forming clouds for ULIRGS somehow responsible?
- Is it related to the infamous “[CII] deficit”?

[Graphs from deLooze + (2017) and Diaz-Santos+ (2017)]
Hints of Problem with the [OI] 63 μm Line

**Galactic Star-forming Region**
G5.89-0.39
D = 1.28 kpc
Powered by single O-star
Massive outflows

**Galaxy NGC 7552 – Rosenberg+ (2015)**

Strong suggestion of significant self-absorption!

Leurini+ (2015)
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 $\mu$m 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 = 4x10^5 M_{sun}
L = 5x10^5 L_{sun}
Dust temperature (color) and H₂ column density (contours)
W3 IRS5 is center of stellar activity

Goldsmith+ (2021)
[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 the 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

• $T \approx 220$ 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
- \(N(\text{low-excitation O}^0)\) 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 $A_v$) 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
[CII] Self-Absorption is More Widespread than Generally Appreciated

W3 IRS5
Two observing modes: OTF and DBS
Gerin+ (2015) – self-absorption present in many sources
-40 km/s velocity agrees with center of [OI] 63 μm absorption

[CII] in M17SW from Guevara+ (2020)
Producing [CII] Absorption

- $C^+$ has significant abundance ONLY at boundaries; very hot part heated by HII region and boundary heated by ISRF
- $N(C^+)$ very low in dense PDR material in which oxygen remains atomic
- Need low density, material to produce [CII] absorption
- Enhanced CR ionization rate can moderately enhance $X(C^+)$
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. Self-absorption is more significant than generally appreciated with modest optical depths affecting line emission
  • In [OI], there is evidence for extensive regions of low-excitation atomic oxygen, that absorbs the emission from hot gas adjacent to HII region and dramatically reduces emitted flux, significantly affecting use of [OI] as tracer of star formation

• Understanding these issues will require velocity-resolved fine structure line images, which will be produced by SOFIA and GUSTO & ASTHROS balloon missions, and hopefully by FIR Probe mission
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 $\mu$m and 122 $\mu$m[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 $\mu$m 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 $\mu$m 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
ASTHROS Telescope

Cart for testing and transport

Sunshield support