The Role of SOFIA in Extragalactic Science

A Roadmap exercise

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Points I want to make in this presentation

• [CII] is the workhorse of SOFIA for local universe galaxies
  • [CII] is one of the brightest coolants of the neutral ISM of galaxies
  • [CII] => SFR in local and high-z galaxies
  • [CII] => tracer of CO-dark gas (especially in low Z galaxies where CO is faint or not detected)
  • SOFIA FIFI-LS has already mapped galaxies completely in [CII]

• [CII] mapping is a starting point: need to tackle the complex multiphase ISM
  • Structure of the ISM? Ionized phase: Low n & high n? Molecular/PDR?
  • Low metallicity ISM is a particular niche: [OIII] is brighter than [CII]. SOFIA can do the 52 mu [OIII] line that Herschel/PACS could not do.
  • SOFIA can do some OI 63, OIII 88 & 52 in galaxies, but needs improved spectral resolution (especially in the blue channel of FIFI-LS)

• Big Science Goal: What is the structure of the ISM and how does it evolve in terms of porosity, phases, metal enrichment, star-formation, feedback?

• The local universe is the laboratory to help interpret high-z observations and develop diagnostic tools – SOFIA’s role!
Conclusion:
How can SOFIA grow the exgal community?

• FIFI-LS is a mapping machine for galaxies, but needs improved *spectral resolution* by factor of 2 (at least the blue channel is very low R) & needs more spaxels (to map faster)

• Map other ISM phases with SOFIA. SOFIA should expand to shorter wavelengths – bright nebular lines covering wide range of critical densities & ionisation energies. Ideally ~ to fill the gap where EXES ends and FIFI-LS+ (with higher FoV & spectral resolution) begins.

• HIRMES would be a perfect solution: higher R in MIR/FIR, faster mapping, wavelength coverage and improved sensitivity

• SOFIA’s *BIGGEST* extragalactic niche: Magellanic Clouds => more NZ flights

• *upGREAT* => an *[OIII]* channel (88 or 52 mu) ?

• SOFIA: the only MIR-FIR we have to prepare for *SPICA & Origins*
Tracing star formation with [CII] – Local galaxies

*de Looze +. 2014*

log $L([\text{CII}]) [L_{\odot}]$

log SFR (FUV+24) $[M_{\odot}/yr]$

*KINGFISH galaxies*

Herrera-Camus + 2015

$\log_{10} \Sigma_{\text{SFR}} [M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}]$

$\log_{10} \Sigma_{[\text{CII}] [\text{erg s}^{-1} \text{ kpc}^{-2}]$
Tracing star formation with [CII] – high redshift

![Graph showing the relationship between log(L_{[CII]}/L_\odot) and log(SFR/M_\odot yr^{-1}).]
Tracing star formation with [CII] – high redshift

Carniani + 2018
High $[\text{OIII}]/[\text{CII}]$ Z=6-9 galaxies

Harikane + 2020

also: Inoue+2014, 2016, Hashimoto+2018; Tamura+2019; Laporte+2019…
[CII] and CO in Galaxies: metal-rich vs. metal-poor

Global studies

Madden + 2000, 2020
[CII] and CO in Galaxies: metal-rich vs. metal-poor

Global studies

Madden + 2000, 2020
Full-Disk CII Mapping of NGC6946 & M51 with SOFIA

[Images and plots displaying galaxy mapping and data analysis]

Pineda+ 2018

Bigiel+ 2020
Full-Disk CII Mapping of NGC6946 & M51 with SOFIA

**Spatially resolved L[CII] – SFR**

**NGC6946: Bigiel+ 2020**

[Graph showing CII integrated flux distribution]

**M51: Pineda + 2018**

[Graph showing CII integrated flux distribution]

Separate galactic components: what contributes to the [CII] emission on global scales? integrated flux ~75% arm, 15% center, 10% interarm

Some other galaxies with SOFIA FIR spectroscopy: FIFI-LS full maps of M82 (Fischer; Latzko) & NGC253 (Beck), IC10 (Polles)..... upGREAT pointings in M51 (Pineda); M101 (Tarantino), NGC4214 (Fahrion + 2014)
The Complexity of the Multi-Phase ISM

- Cold Neutral Medium
- Warm Ionised Medium
- Warm Neutral Medium
- Dense Molecular Cloud
- HII region

The diagram illustrates various components of the interstellar medium (ISM) and their interactions. The graph below shows the monochromatic luminosity $\nu L_\nu$ in $[L_\odot]$ as a function of wavelength in micrometers ($\mu$m). The labels indicate different ionized species and features, such as STARS and DUST.
ISM structure at low Z: VERY porous, clumpy. Small covering factor of PDRs. High filling factor of diffuse gas where UV photons escape from HII regions.
Resolve ISM phases in Local Group galaxies

Low metallicity star-forming galaxies

**LMC 30 Dor**
- $Z = 1/2 \, Z_\odot$
- $D = 50 \, \text{kpc}$

**IC10**
- $Z = 1/3 \, Z_\odot$
- $D = 700 \, \text{kpc}$

**NGC1569**
- $Z = 1/4 \, Z_\odot$
- $D = 3.36 \, \text{Mpc}$
Resolve ISM phases in Local Group galaxies: LMC

160μm HERITAGE Meixner+ 2010
Hα MCELS Smith+

Zoom into 30 Doradus PDR
Resolve ISM phases in Local Group galaxies: LMC

6’ x 5’ SOFIA/FIFI-LS: 80pc x 70pc tracing ionized + neutral gas

Chevance + 2020 maps by Christian Fischer
PDR modelling => little CO-bright H$_2$ but 75% CO-dark gas
Resolve ISM phases in Local Group galaxies: LMC

Indebetouw + 2013: ALMA CO(2-1) resolves subpc clumps/filaments.

Chevance+2020: PDR modelling => little CO-bright $H_2$ but 75% CO-dark gas
Resolve ISM phases in Local Group galaxies: LMC

Indebetouw + 2013: ALMA CO(2-1) resolves subpc clumps/filaments.

Chevance+2020: PDR modelling => little CO-bright $H_2$ but 75% CO-dark gas

ALMA + SOFIA => excellent science synergy!
 Resolve ISM phases in Local Group galaxies: LMC & IC10 & NGC1569

Electron density in the ionised gas

- 30Dor: electron density in the ionised gas < 1000 cm$^{-3}$
- IC10: density ranges between 100 and 400 cm$^{-3}$
- NGC1569: electron density < 500 cm$^{-3}$
Summary

- SOFIA/FIFI-LS is a mapping machine for complete wide-field maps of [CII] in nearby galaxies.

- NGC6946 and M51 case studies show significant and systematic variation of key line ratios CII/SFR, CII/CO across the disk. Should have maps in more galaxies – statistical studies. Link the local conditions to the global.

- Nearby Low metallicity galaxies show different ISM structure than disk SF galaxies: [OIII] is the brightest FIR line, not [CII]. [OIII] can be exploited by SOFIA in low metallicity galaxies.

- Low metallicity star-forming galaxies: little CO detected, but vigorous SF:
  **most of the H$_2$ is not traced by CO.**
  [CII] tracing total H2 gas mass in low Z galaxies – other environments?

- Local Group Galaxies, especially the Magellanic Clouds, are SOFIA’s extragalactic strong points: diverse environments, including low metallicity laboratories and close enough to be well resolved.
- Bridging cloud-scale conditions to the larger scale environment:
  - LMC & SMC - SOFIA and ALMA synergy

- SOFIA needs to map galaxies in more diagnostic lines.
Conclusion: How can SOFIA grow the exgal community?

• FIFI-LS is a mapping machine for galaxies, but needs improved spectral resolution by factor of 2 (at least the blue channel is very low R) & larger FoV (mismatch of blue vs red FoV)

• SOFIA should expand to shorter wavelengths – bright nebular lines covering wide range of critical densities & ionisation energies. Ideally ~ to fill the gap where EXES ends and FIFI-LS (with higher spectral resolution and FoV) begins.

• upGREAT => an [OIII] channel (88 or 52 mu) ?

• HIRMES would be a perfect solution: higher R in MIR/FIR, faster mapping, wavelength coverage and improved sensitivity
  • faster mapping of many more galaxies: PHANGS, SAMI, CALIFA...statistically significant properties within galaxies
  • To map full galaxies also in OI, OIII, NII
  • The versatility of HIRMES would definitely bring the exgal community on board

• SOFIA’s BIG niche: Magellanic Clouds => more NZ flights !!!

• SOFIA : the only MIR-FIR we have to prepare for SPICA & Origins

SOFIA to exploit the nearby universe to calibrate distant, high-z universe