[CII] Emission as a Star Formation Rate Tracer

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Star Formation in the Milky Way and Nearby Galaxies

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Regarding the use of [CII] 158 μm as a SFR tracer...

The availability of a rich new set of [CII] observations from Herschel, combined with the detection of redshifted [CII] emission in submillimeter galaxies (SMGs) from ground-based instruments, has sparked a resurgence of interest in this application.

NGC5457

Advantages
1. Very bright line in star forming galaxies (~0.1 - 1% L_{FIR})
2. Major coolant for the diffuse, neutral ISM
3. ALMA will detect [CII] in normal star forming galaxies at z ≳ 2

Caveats
1. [CII] could be produced in regions of the galaxy that are not necessarily associated to star formation
2. [CII] “deficit”
ALMA can detect the Milky Way in [CII] at any $z$
The Goal

Use resolved regions from a sample of 50 KINGFISH galaxies

Study how [CII] 158 μm emission correlates with other star formation tracers

Derive a SFR calibration based on [CII] 158 μm
[CII] versus 24 μm associated to SF

24 μm

“Cirrus” Contribution
e.g. dust heated by old stars

To remove the cirrus contribution we use the procedure described in Leroy+12

Fraction of 24 μm associated to cirrus:

\[ \text{avg. } f_{24\mu m, \text{cirrus}} \sim 20\% \]
\[ (~19\% \text{ Leroy+12, 7\% Law+11}) \]

AGN Contribution

X-ray Dominated Regions contribute to 24 μm

contribute to [CII] emission

Stacey+10: \sim 10\% (47\% PKS 0215)
We find good $\Sigma_{\text{[CII]}} - \Sigma_{24\mu m}$ correlation. Most of the [CII] upper limits are consistent with the correlation.
The [CII] - 24μm Correlation

NGC 1377: Nascent Starburst or buried AGN? (Roussel+06; Imanishi+09)

50 galaxies

$\log_{10} \Sigma_{24,\mu m}$ [erg s$^{-1}$ kpc$^{-2}$]

$\log_{10} \Sigma_{[CII]}$ [erg s$^{-1}$ kpc$^{-2}$]

[CII] S/N < 3
NGC 1377
AGN Contribution: mask the central \( \sim 0.5 \) kpc region

About half of the AGN regions show a moderate 24\( \mu \)m excess compared to [CII]

Regions from 28 Galaxies classified as AGNs (Moustakas+10; Grier+11)
AGN Contribution: mask the central ~0.5 kpc region.

About half of the AGN regions show a moderate $24 \mu m$ excess compared to $[^{12}\text{CO}]$. Remove NGC 1377, AGN points and $[^{12}\text{CO}]$ upper limits.

Regions from 28 Galaxies classified as AGNs (Moustakas+10; Grier+11)

We find good $\Sigma[^{12}\text{CO}] - \Sigma_{24\mu m}$ correlation with a $\sim 0.24$ dex scatter.

Slope = 1.2

$1\sigma$ Scatter = 0.24
We find tight, nearly linear correlation between $\Sigma_{\text{[CII]}}$ and $\Sigma_{\text{SFR}}$ with a $\sim 0.23$ dex $1\sigma$ scatter.
$L_{\text{FUV}} = f(SFR, \text{time})$

$L_{\text{FUV}} \longrightarrow L_{\text{CII}}$

PE Heating Efficiency

$\varepsilon_{\text{ph}} \sim 0.1 - \text{few \%}$

$L_{\text{CII}} = \varepsilon_{\text{ph}} \times L_{\text{FUV}}$

$L_{\text{CII}} = \varepsilon_{\text{ph}} \times f(SFR, \text{time})$
Comparison to SB99 model

- Time = 2 Myr, $\varepsilon_{ph} = 0.1, 1 \& 3\%$
- Time = 20-100 Myr, $\varepsilon_{ph} = 0.1, 1 \& 3\%$

At a given $\Sigma_{SFR}$, increasing $\varepsilon_{ph}$ implies higher $\Sigma_{[CII]}$
Comparison to SB99 model

Bulk of the data explained by a continuous star formation episode with duration $>20$ Myr, and $\epsilon_{\text{ph}} \sim 1\%-3\%$
1. FIR color/Dust Temperature

2. Fraction of the dust luminosity radiated from regions with intense radiation fields (U > 100)

3. Dust-weighted mean starlight intensity

4. Percentage of the total grain mass contributed by PAHs

2, 3 & 4: Parameters from Draine & Li Model 2007
Aniano +12
Positive means [CII] is underluminous wrt SFR

Positively charged dust grains

A higher charge implies a higher Coulomb barrier to overcome, thus decreasing the energy per ejected electron (Tielens & Hollenbach+95; Malhotra+97; Luhman+03; Croxall+12; Beirao+12)

Low PAH abundance
Implement an IR color correction for

\[ \nu_{70}F_{70}/\nu_{160}F_{160} \gtrsim 1.25 \]

\[
\log_{10} \Sigma_{[CII]} \rightarrow \log_{10} \Sigma_{[CII]} + \log_{10} (\nu_{70}F_{70}/\nu_{160}F_{160}) - 0.1
\]
The $[\text{CII}]$ - SFR Correlation

Before IR Color Correction

After IR Color Correction

Before IR Color Correction

After IR Color Correction

$\nu_{70} F_{70}/\nu_{160} F_{160} \gtrsim 1.25$

$\Sigma_{\text{CII}}$ SFR Correlation

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

$log_{10} \Sigma_{\text{CII}} [\text{ erg s}^{-1} \text{ kpc}^{-2}]$

$log_{10} \Sigma_{\text{CII}} + log_{10}(\nu_{70} F_{70}/\nu_{160} F_{160}) - 0.1$
Residual in each galaxy for the KINGFISH sample

- IR color correction does not apply
- Before IR color correction
- After IR color correction
The $[\text{CII}]$ - SFR Correlation
Comparison to previous studies

Before IR color correction

After IR color correction

$\log(\text{SFR}) = 1.01 \log(L_{\text{[CII]}}) - 41.2$
log_{10} SFR [M yr^{-1}] vs \log_{10} L_{\text{[CII]}} [\text{erg s}^{-1}]

Before IR color correction

After IR color correction

KINGFISH galaxies

Boselli et al. 02, SFR(24 \mu m+H\alpha)

de Looze et al. 11, SFR(24 \mu m+FUV)

Sargsyan et al. 12, SFR(FIR)

Boselli + 02

Sargsyan + 12

de Looze + 11

KINGFISH
Summary

We find a tight, nearly linear correlation between $\Sigma_{\text{[CII]}}$ and $\Sigma_{\text{SFR}}$ with a $\sim 0.2$ dex $1 \sigma$ scatter

$$\log_{10}(\Sigma_{\text{SFR}}) = 1.04 \log_{10}(\Sigma_{\text{[CII]}}) - 43.0$$

This includes the “color correction”, applied to points with $\nu 70 F_{70}/\nu 160 F_{160} \gtrsim 1.25$

Even without this correction, there is a remarkably good correlation between SFR and [CII]. We need more work to see how it may apply in the $L_{\text{FIR}} > 10^{11} L_\odot$ regime