[CII] 158 um self-absorption and optical depth effects: M17SW

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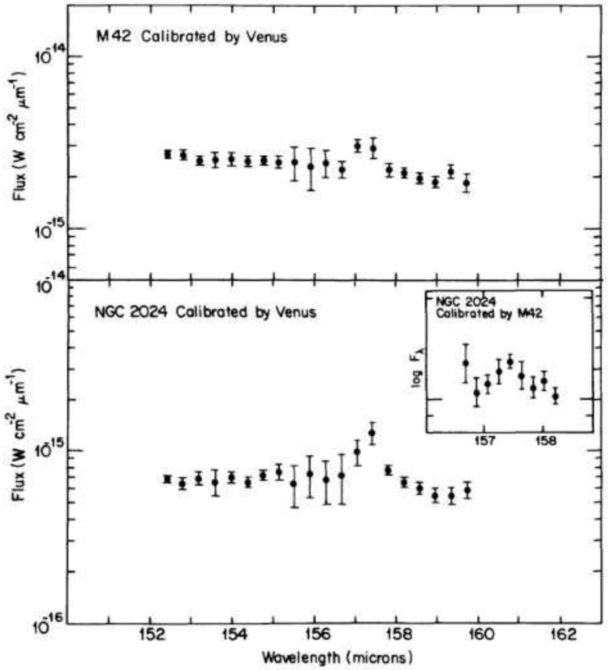
Motivation

- **First detection of the [CII] fine-structure emission line (Russell et. al. 1980): "*Optical depth effects in the 157 µm line may be significant but have not been taken into account in our calculation because our data base is still too restricted* ".**



M42 [CII] 1980

NGC 2024 [CII] 1980

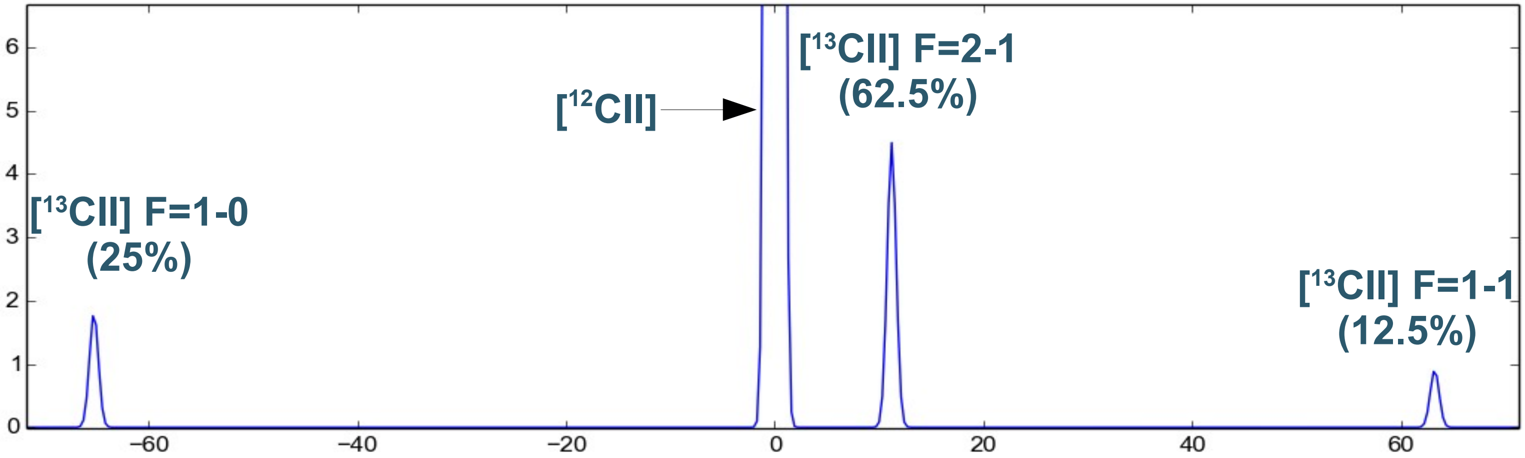
- **Now, with the upGREAT/SOFIA 14 pixel array we are able to detect, much faster than before, the optically thin [^{13}CII] hfs satellites at high spectral resolution and S/N,**
  calculate the optical depth directly and study its impact in the interpretation of the [CII] line

[CII] and [^{13}CII] hfs satellites

- **[CII] transition frequency is 1900.537 GHz or 157.74 µm. [CII] is one of the dominant cooling lines of the ISM, together with [OI] 63 µm.**

- **The hyperfine structure of the ^{13}C^{+} isotope results in three hfs-components. (Cooksy, A.L. et. al. 1986, Ossenkopf et. al. 2013)**

- **The strongest line, F = 2-1, is located close to the [^{12}CII] line. The other two lines are located farther away to both sides of the [^{12}CII] line and have lower intensity. The separation is small enough so all the lines can be observed simultaneously.**

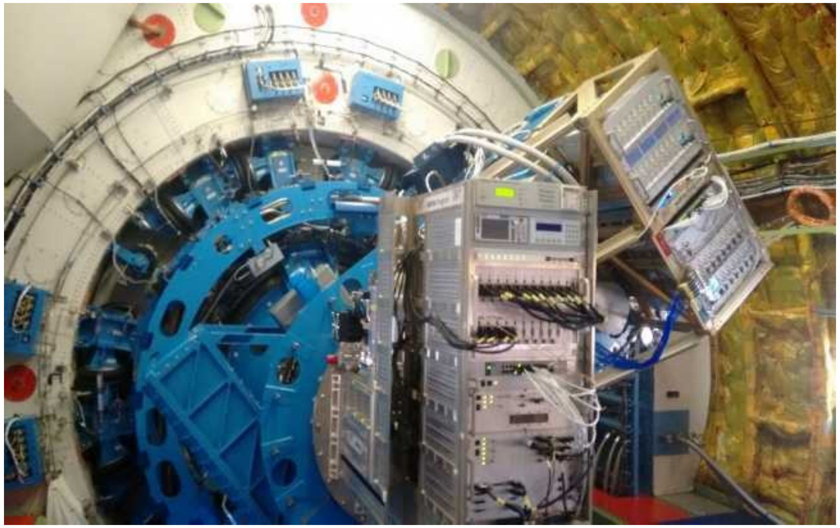


Observational Program

- We have a running observational program using the SOFIA/upGREAT 14 pixel array for observing 6 sources located in the Galaxy in [^{12}CII] and [^{13}CII]

- The targets are PDRs covering a wide range of physical conditions, going from simple (M43, one central star) to more complex (M17, clumpy, many UV sources).

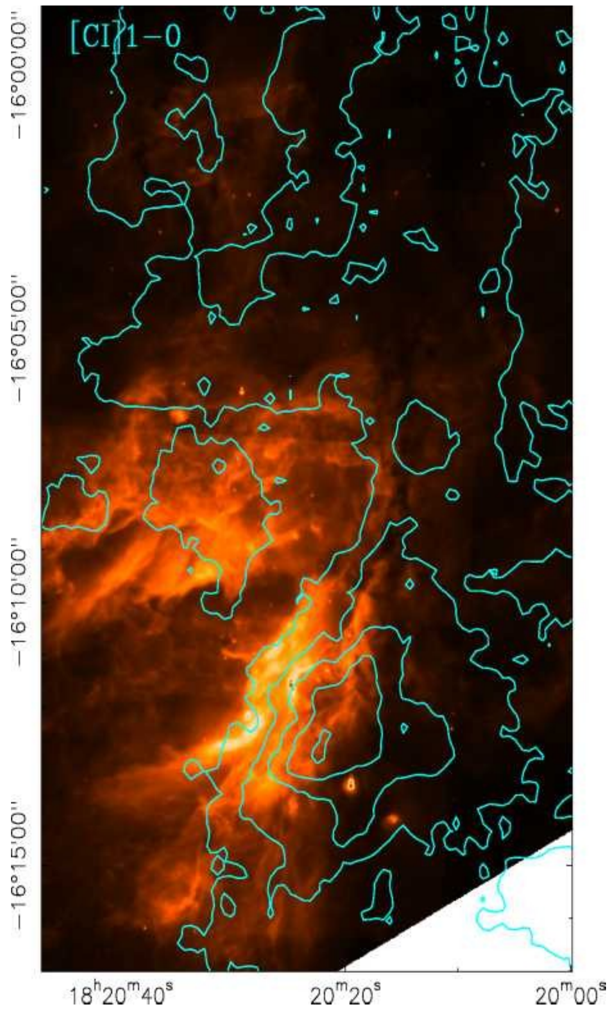
- The targets already observed are M43 in December 2015 and M17 in June 2016, partially observed S106 in May 2016.
  Still pending: Horsehead, Mon R2 and DR21



Credit: NASA/Jim Ross

M17

- It is considered one of the brightest and most massive star forming regions in the Galaxy
- GMC located at a distance of 1.98 kpc.
- The cloud is illuminated by a cluster (>100) of OB stars
- Edge-on geometry, very well suited for studying PDR structure from the exciting sources to the ionization front and into the molecular cloud

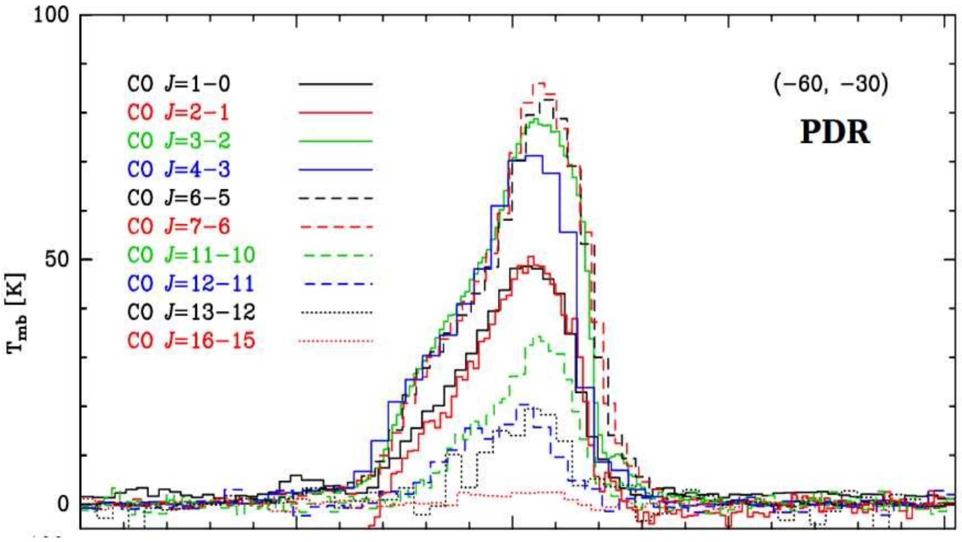


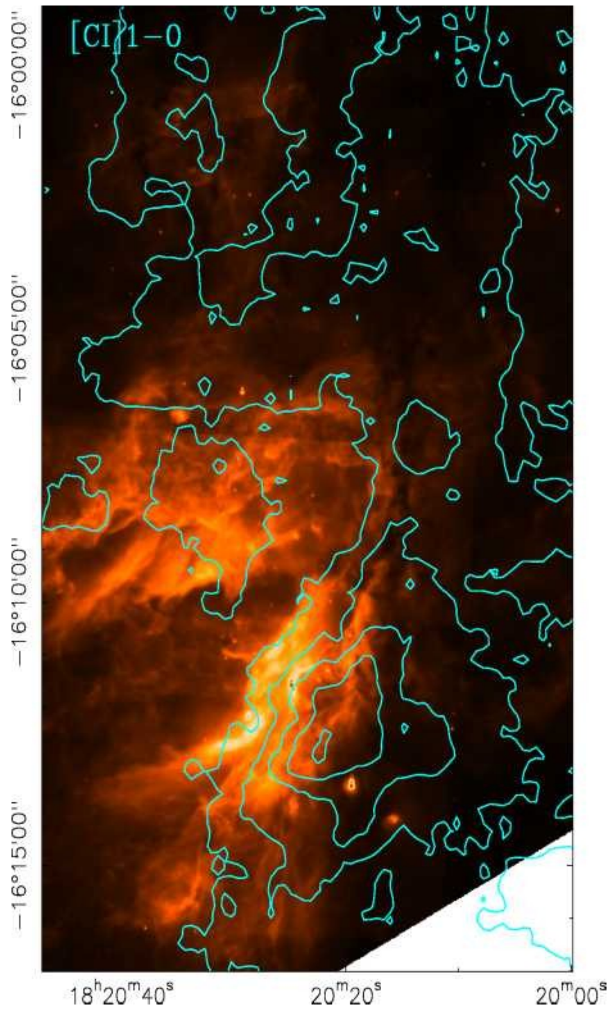
Spitzer 8 µm image and NANTEN2 [CI] $^3P_1$-$^3P_0$ in contours

M17

- **M17SW has a highly clumpy structure from several studies of ionized, atomic and molecular emission** (Stutzki & Güsten 1990, Meixner et. al. 1992, Perez-Beaupuits et. al. 2012, 2015).

- **From mid and high J CO we expect a T_{ex} ~ 200 K**



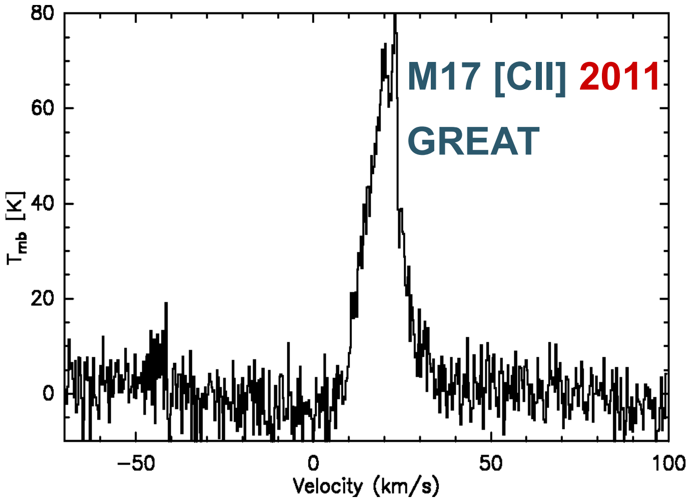


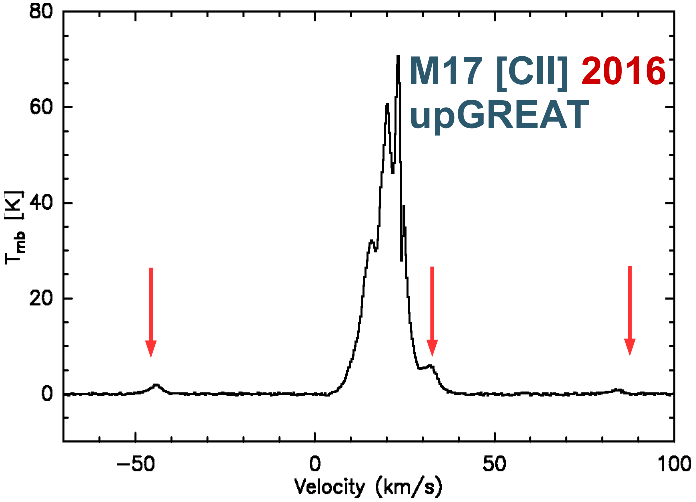
From Perez-Beaupuits et. al. 2015 M17SW low, mid and high CO spectra

Observational Data

- **Deep integration (t_{ON}=15 min/point) using the 14 pixel array of SOFIA/upGREAT**

- **The objective is to have spectra with an excellent velocity resolution and to detect the [^{13}CII] hfs satellites at high S/N**

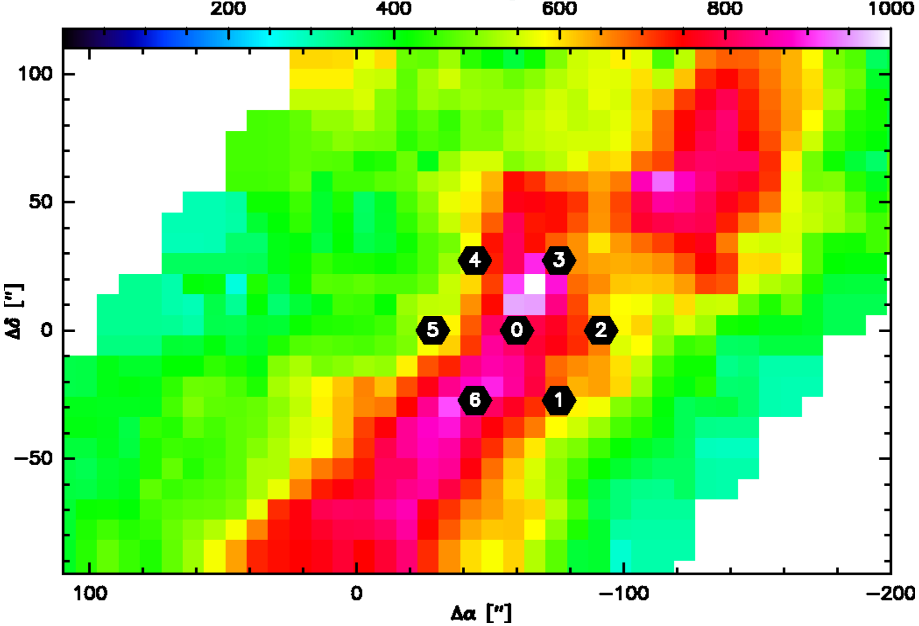




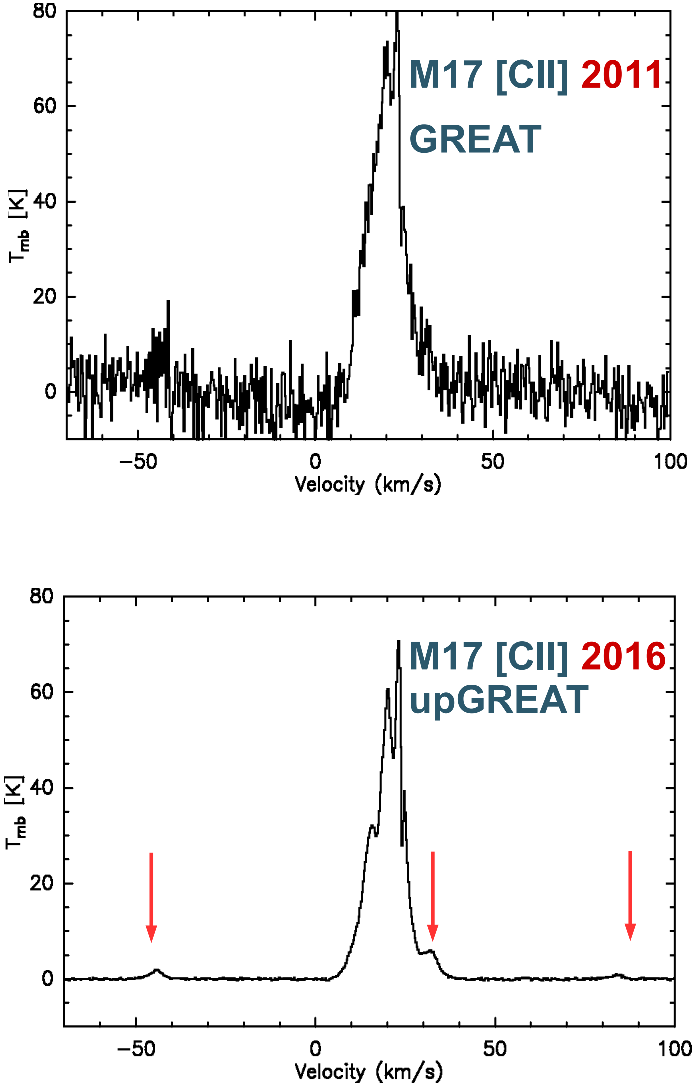
example spectra, showing the technological progress, i.e. the much improved sensitivity

Observational Data

- The M17 SW observation were done in June 2016
- Orientation of the array adjusted to cover interesting areas: the peak of emission and complex profiles of [CII] seen in previous observations (2011)



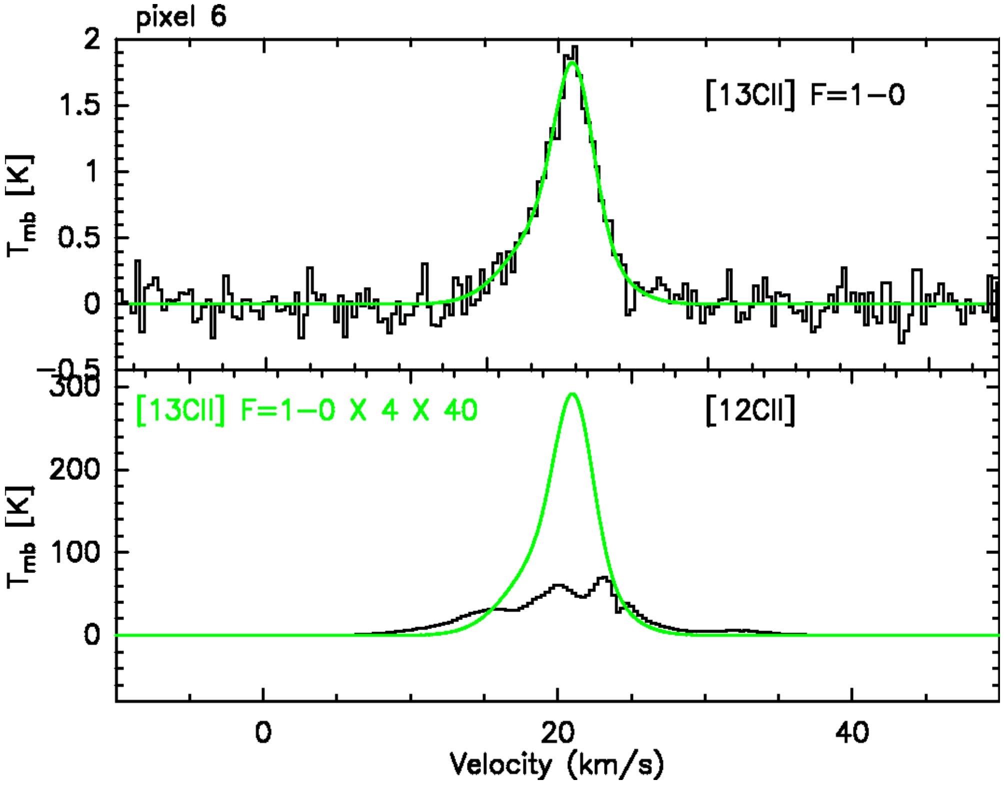
M17SW [^{12}CII] integrated intensity (2011) and upGREAT array positioning



example spectra, showing the technological progress, i.e. the much improved sensitivity

Observed Data

- All [^{13}CII] hfs satellites are well detected for all seven positions.
- Using an abundance ratio of [^{12}CII]/[^{13}CII] of 40 for M17, the [^{13}CII] scales up to 4 times higher intensity than the [^{12}CII] emission.
- The [^{13}CII] and the [CII] line profile don't match.
- Clear evidence that
  - The [CII] line is heavily affected by optical depth effects
  - the [CII] is absorbed by high column density foreground material



M17SW composite spectra

Analysis

- **Following the analysis of Graf et al. 2012, we apply a multicomponent analysis of the [^{12}CII] and [^{13}CII] emission simultaneously.**
- **We use a number of background sources corresponding to the object we want to model, and a number of foreground layers to model the absorption dip in the background emission.**
- **We perform a Least-Squares fit to the radiative transfer equation.**

$$\tau = \frac{h B_{lu} N(C^{+})}{\delta v} \frac{1-e^{-h\nu/kT_{ex}}}{1+\frac{g_u}{g_l} e^{-h\nu/kT_{ex}}}$$

$$T_{mb} = \{\sum_i J_\nu(T_{bgi}) * (1-e^{-\tau_{bgi}})\} e^{-\sum \tau_{fgi}} + \sum_i J_\nu(T_{fgi}) * (1-e^{-\tau_{fgi}})$$

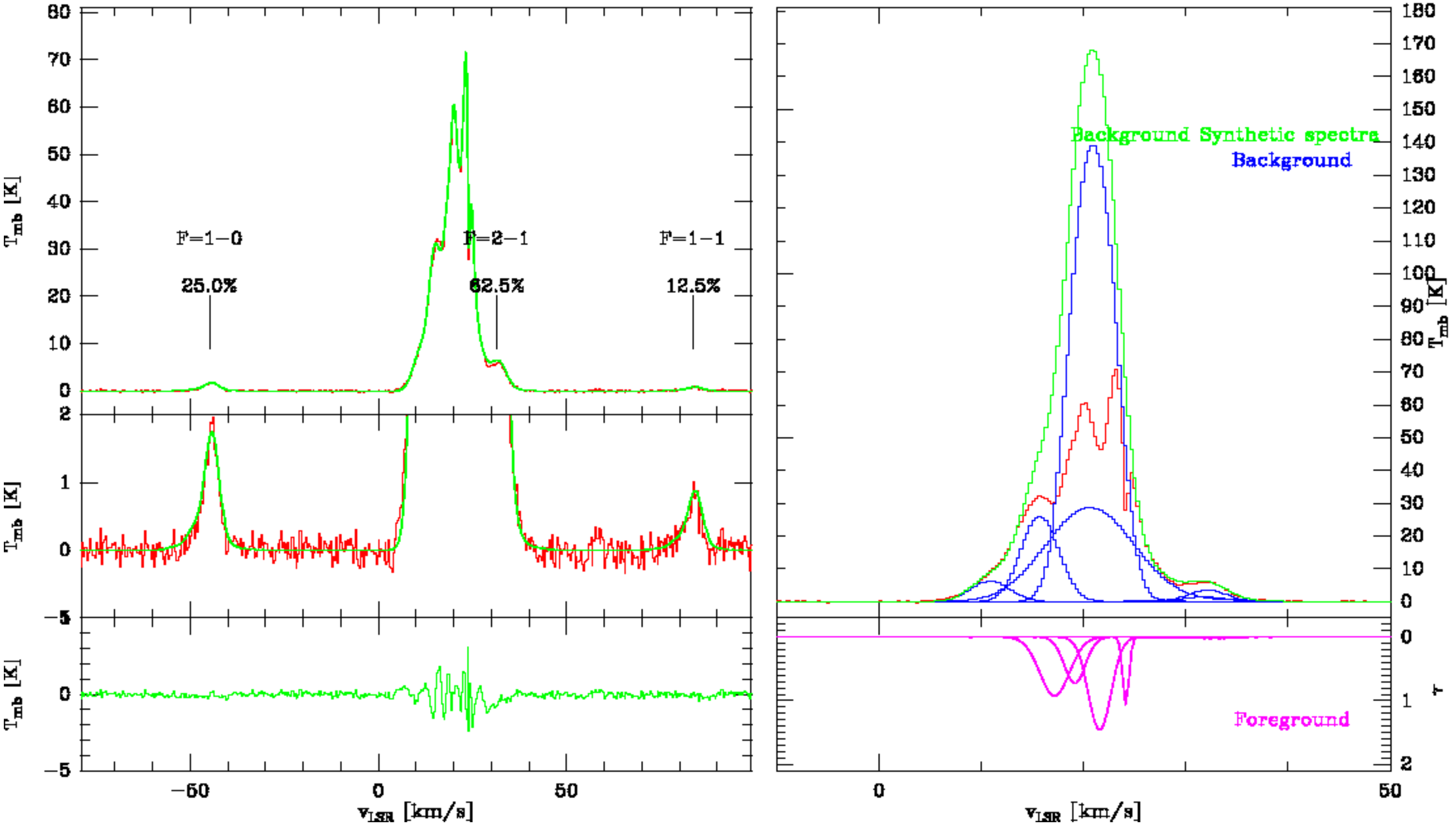
Background emission

Foreground absorption

Foreground emission

Analysis

- We find a solution through an iterative process (as the problem is degenerate)
- First we fit the [^{13}CII] satellite emission masking the [^{12}CII] emission using a fixed temperature of 200 K for the background
- Next the [^{12}CII] background emission not covered by the [^{13}CII] using a temperature of 200 K
- Finally the absorption features using a fixed temperature of 30 K



Analysis

Positions	No. Back.	No. Fore.	Chi square	Background N(CII) cm^{-2}	Back. N(CII) converted to A_ν *	Foreground N(CII) cm^{-2}	Fore. N(CII) converted to A_ν *
Position 0	4	6	1.8	9.15E18	50.8	2.01E18	11.2
Position 1	5	4	1.2	8.01E18	44.5	1.65E18	9.2
Position 2	4	5	0.47	5.64E18	31.3	2.97E18	16.5
Position 3	4	2	3.5	4.37E18	24.3	7.7E17	4.3
Position 4	5	5	6.2	7.56E18	42	1.26E18	7.0
Position 5	4	3	6.6	3.04E18	16.9	3.9E17	2.2
Position 6	5	4	0.85	7.68E18	42.7	1.79E18	9.9

- **It is a complex fitting with multiple components in the Background and Foreground**
- **It is important to remark that the solutions necessary for fitting the line profiles are difficult to reconcile with any simple model scenario**
- **For the Background we obtain very high A_v, between 16.9 and 50.8, and for the Foreground between 4.3 and 16.5**
- * $$\frac{N(CII)\times 10^{4}}{1.8\times 10^{21}} = A_v$$

Conclusions 1

- Our observations and analysis confirm the long standing suspicion (Russell et al. 1980, Langer. et. al. 2016), already proven for the single case of Orion-B (Graf et al. 2012) that [^{12}CII] emission might be heavily affected by high optical depth in the main isotopic line:
  - all our [^{13}CII] observations up to now show high opacity of the main line, and indications of foreground self-absorption (only M17 shown here)

- Both the extremely high column densities of warm background gas (M17, Orion-B) as well as the nature of the low-excitation foreground gas are difficult to explain with the present PDR-model context and ISM phases
  - Classical Scenario of 1 A_v for [CII] doesn't fit with 50 A_v calculated here (50 layers of [CII]?)
  - High column density could be obtained through high magnetic fields, compressing the gas and raising the density (Pellegrini et. al. 2007) ??
  - X-ray emission could create cold [CII] in the molecular core of the PDR clump (reference needed) ??

Conclusions 2

- Any kind of spatial and spectral correlation analysis to disentangle the [CII] emission coming from atomic, molecular and ionized regions has to take into account optical depth effects, because they change the profile of the [CII] line, mimicking separate velocity components.

- This scenario of a warmer background gas being absorbed by cold foreground changes the way we should analyze and interpret the [CII] data (in terms of physical quantities)
  - integrated line intensities without velocity resolution (incoherent instruments, extragalactic grand-average spectra) have to be regarded with great caution!

Thank you for your attention

M17 [CII] vs [OI]