Mapping the ISM in nerbay galaxies with CCAT-prime: the example of M51

M. Ziebart, C. Buchbender, M. Röllig, R. Simon, J. Stutzki
I.Physikalisches Institut, Universität zu Köln

Context

We discuss the feasibility of sub-mm line observations of nearby galaxies with CCAT-prime/CHAI. As an example we use the M51 grand designed nearby spiral galaxy, for which complementary data exist, including the recent velocity resolved full map in the [CII] 158 µm line observed with upGREAT on SOFIA.

We note that M51 is not necessarily the best target for the southern CCAT-prime telescope, nevertheless we use it here because of the available complementary data in many tracers, including CO, HI, optical light, radio continuum, dust continuum and dense gas tracers.

We estimate the observing time for full maps of M51 in the emissions lines of [CI] (1-0) 609 µm, [CI] (2-1) 370 µm, CO J=4-3 650 µm and CO J=7-6 372 µm to be observed with the future 2x64 pixel CHAI receiver on the CCAT-prime telescope.

CCAT-prime

CCAT-prime, presently under construction, will be a 6 m diameter telescope operating at submm to mm wavelengths and sited at 5600 m elevation on Cerro Chajnantor in the Atacama desert of northern Chile.

The high altitude and dry site offers very good transmission up to the 350 µm atmospheric window. Under the best conditions, observations in the 200 µm window will be possible.

CCAT-p will be ideally suited, due to its high-site location, low error beam and large field of view, to probe tracers of the ISM and cloud/star formation over a range of environments in the Milky Way, the Magellanic Clouds and nearby galaxies.

The 6 m diameter of the CCAT-prime dish gives an angular resolution comparable to that of the SOFIA [CII] observations and the mm-wave low-J CO mapping with the IRAM 30m telescope. The resolution for the respective emission lines is:

- 16” for [CI] (2-1) & CO J=7-6
- 26” for [CI] (1-0) & CO J=4-3

Scientific Context

Investigations of the star formation activity, including the cloud formation, are relevant to understand galaxies evolution. The detailed investigation of the life cycle of Interstellar Mater (ISM) is an essential ingredient for these studies.

Observations show that star formation occurs inside Giant Molecular Cloud (GMCs) complexes, where the gas is mainly molecular, i.e. consist of H_2. The dense clouds assemble from lower density clouds which are largely atomic, i.e. consist of HI.

H_2 is not directly observable at the physical conditions in ISM clouds. For this reason the observations over the last 30 years have largely used the rotational excitation lines of CO as tracers for H_2-gas. CO has revealed many important properties of ISM clouds. It occurs in the central, UV shielded regions of the clouds.

The UV radiation from young, massive stars dissociates the molecules, and partially ionizes the carbon on the surfaces of dense clouds and in diffuse clouds. These so-called photon dominated regions (PDRs) thus show up as a transition layer from atomic to molecular H_2 gas, as well as CII/CI/CO. The latter is traced by the atomic fine structure lines [CII] 158 µm and both [CI] 370 and 609 µm emission lines.

[CII] 158 µm is thus a commonly used tracer of star formation activity, also out to high redshift galaxies, where the line is shifted into the ALMA frequency bands. In combination with other fine structure lines, its intensity provides a good measure of the density and average UV-field. It also traces the CO-dark molecular gas component in PDRs and diffuse clouds.

The [CI] intensity, on the other hand, resulting from a relatively thin transition layer between C+ and CO, is relatively weak and varies significantly with the detailed parameters of the cloud; PDR models also show that it sensitively depends on the details of the cloud internal structure and the microphysics included in the model. Hence, its intensity in comparison to the other PDR tracer lines allows a detailed understanding of the PDR-physics. To what extend [CI] traces CO-dark gas is an open issue, as the observations are difficult and sparse up to now.

Observationally, [CII] 158 µm can only be observed from space or from SOFIA. [CI] 370 µm and 609 µm, its frequencies being located at the edge of atmospheric submm-windows, can be observed from the ground at high observing sites.

The new CCAT-prime telescope at its superb location will thus drastically improve the possibilities to observe both [CI] lines, as well as the mid-J CO lines (J=4-3 and 7-6).

High spectral resolution observations of the PDR emission lines are essential in order to resolve the line profiles and thus identify individual emission components in the turbulent clouds and along the line-of-sight.

SOFIA/UpGREAT [CII] observation of M51

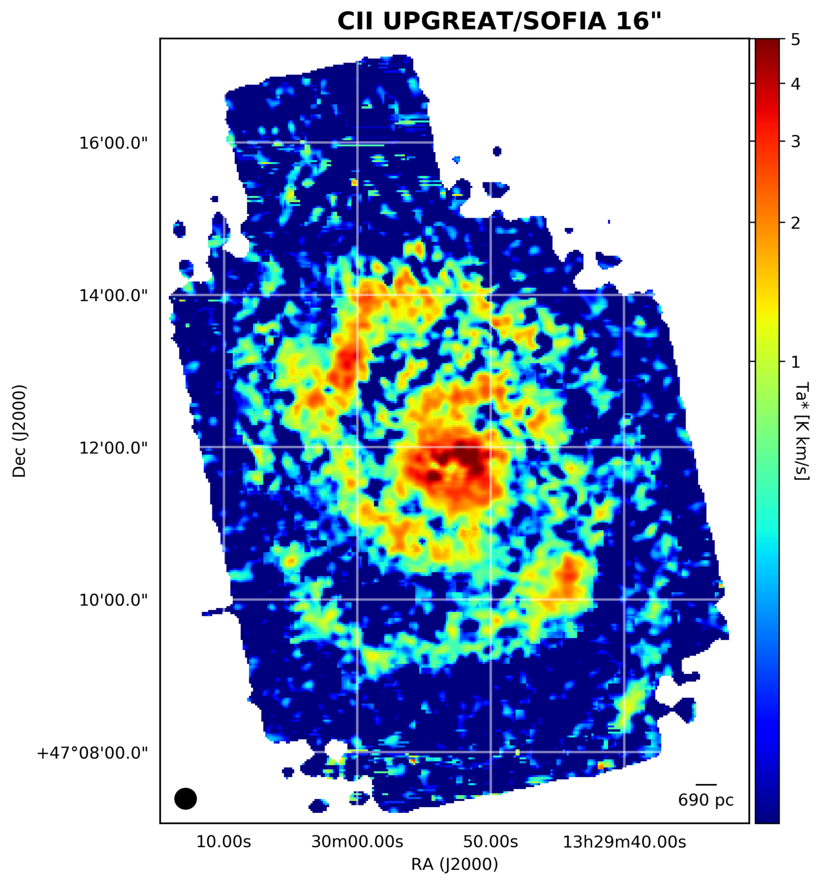

FIGURE 1: Integrated intensity map of [CII] emission in M51 (on Ta* scale in K km/s) measured with upGREAT/SOFIA in 30 hours observation time. The final map will have twice as much integration time. This image was observed in 17 flights over three upGREAT flight series in the time interval May2016 – February 2017. Last data was taken on 17. February 2017.

Spectrally resolved observations of [CII] 158 µm have been possible only over the last 7 years (except for a few pioneering observations), starting with the HIFI instrument on Herschel and now with upGREAT on SOFIA.

In Fig. 1. we present the integrated intensity of the velocity resolved full map of M51 in the [CII] 158 µm emission line observed with upGREAT on SOFIA. The angular resolution of 16” (~0.6 Kpc in M51) allows to separate the major structural features such as the spiral arms and the interarm-regions, as well as GMCs complexes and the central region of the galaxy.

Observed Line Intensities of [CI] and mid-J CO

The [CI] (1-0) and (2-1) integrated line intensities, as well as those of CO J=4-3 and J=7-6 in M51 were measured with the Herschel SPIRE instrument (Schirm at al. 2017). The observed average integrated intensities for a spiral arm/interarm regions in M51 are:

- $[CI]_{370}$ = 0.85 +- 0.08 K km/s
- $[CI]_{609}$ = < 3.50 +-1.60 K km/s
- CO_{650} = < 4.60 +-2.10 K km/s
- CO_{372} = 0.28 +- 0.07 K km/s

The observed line width of CO in arm regions of M51 is 30-40 km/s. Similar line widths are observed in [CII] 158 µm. The line widths of the [CI] emission are expected to be similar. This allows us to estimate the peak brightness of the lines. The CO 7-6 emission is expected to be confined to warm and dense spots and will not be extended across the map. Therefore, we scale the SPIRE intensity up by the ratio of beam solid angles.

From our [CII] observations we know that a velocity bin of 5 km/s is sufficient to resolve the major features in the line profile. This give a line peak intensities of

- [CI] (2-1) 370µm = 0.030 K
- [CI] (1-0) 609µm = 0.115 K
- CO J=4-3 650µm = 0.155 K
- CO J=7-6 372µm = 0.060 K (4 x SPIRE)

CCAT-p Observing Time Estimation

The dual-frequency CHAI receiver will allow for simultaneous observations of [CI] 370 µm and CO 7-6 in the high frequency channels (as these lines are only 2.7 GHz apart and fit into the 4 GHz wide IF band); the low-frequency channels can then observe either [CI] 609 µm or CO 4-3. Thus, the mapping observing time estimate is driven by the weak [CI] 370 µm line, which is also in the atmospheric windows with lower transmission.

The prospective CHAI receiver system temperatures for these conditions would be :

- T_{sys} [CI] (1-0) = 520 K
- T_{sys} [CI] (2-1) = 1050 K
- T_{sys} CO J=4-3 = 380 K
- T_{sys} CO J=7-6 = 1100 K

calculated with the average transmission at the 25% quartile (as these kind of observations will only be conducted at good weather) and at an average airmass of 1.5 (Elev=42°).

The observing time necessary to map the [CI] 372 um line with a signal to noise of S/N=5 in the 5 km/s velocity bins discussed above, and with full angular sampling is given by the radiometer equation

$$\tau = \frac{\alpha^2}{\Delta\nu} \frac{n_{obs}}{n_{pix}} \left(\frac{T_{sys}}{\Delta T}\right)^2$$

Since the lines are weak chopping will be necessary to achieve stable baselines (resulting in $\alpha \approx 2.2$; namely equal time ON- and OFF-source and 10% observing overhead).

For the other lines we show, which signal-to-noise we can reach in the same mapping observing time for the above peak intensities.

Line	S/N	τ [h]
[CI] (2-1) 370 μm	5	150
CO J=7-6 372 μm	10	
[CI] (1-0) 609 μm	44	100
CO J=4-3 650 μm	54	50

Conclusion

CCAT-prime with the CHAI heterodyne array receiver will allow for efficient mapping of the weak [CI] emission over large areas of the sky, as well as of the mid-J CO lines. It will thus be possible to map a large sample of nearby galaxies with decent spatial and full spectral resolution. In combination with complementary FIR and mm-wave line data, this will give important insight into the detailed physical conditions in star forming molecular clouds.