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Far-infrared spectroscopy with Herschel Space Observatory

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Abstract. We review results of some of the recent far-infrared spectroscopic observations of the interstellar medium in our Galaxy and in the nearby galaxy M33 using HIFI and PACS onboard the Herschel Space Observatory.

Keywords : infrared: ISM – ISM: clouds – ISM: molecules – Galaxies: individual M33

1. Introduction

The far-infrared (FIR) and sub-millimeter part of the electromagnetic spectrum tracing primarily temperatures between 30–100 K, is best suited to study the origin of galaxies, stars and planets which emit primarily in these wavelengths. A large number of atomic fine structure and molecular rotational transitions with a wide range of excitation energies ($\sim$ 1–1000 K) lie in the FIR and provide diagnostic tools for physical conditions, chemistry and kinematics of the interstellar clouds, star-forming regions, protoplanetary disks, envelopes of evolved stars etc.. The Herschel Space Observatory is a European Space Agency space observatory sensitive to the FIR and sub-mm wavebands (55-672 μm). Herschel, launched in 2009 is the largest infrared space telescope so far, carrying a single mirror of 3.5 metres in diameter (Pilbratt et al. 2010). The science payload for Herschel consisted of three instruments, the Photodetector Array Camera and Spectrometer (PACS, Poglitsch et al. 2010), the Spectral and Photometric Imaging REceiver (SPIRE, Griffin et al. 2010), and the Heterodyne Instrument for the Far Infrared (HIFI, de Graauw et al. 2010). Each of these instruments have spectroscopic capabilities.

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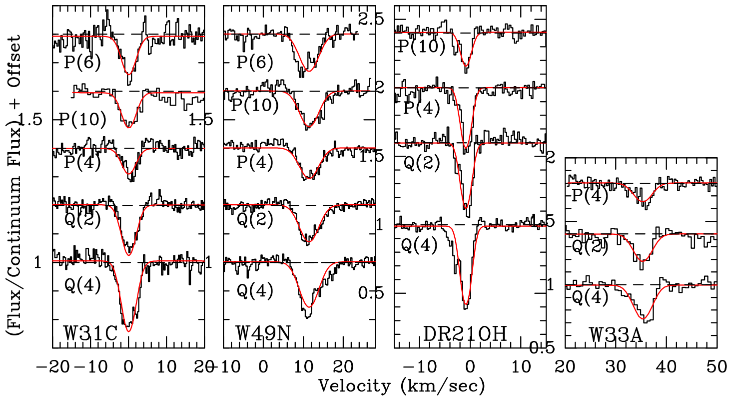

Figure 1. Ro-vibrational transitions of C_3 towards Galactic star forming cores. Histogram corresponds to the observed spectra and the smooth curve shows results of fitting of Gaussian profile to the observed spectra.

2. Spectroscopy of hydrides & carbon chains with HIFI

The high spectral resolution of HIFI and its sensitivity has made possible the observation of so-far inaccessible spectral lines of a large number of chemical species, exotic or otherwise. These chemical species include hydrides which play a central role in interstellar chemistry as significant reservoirs of heavy elements and small pure carbon chains which could be progenitors of more complex linear carbon molecules. Several ground state rotational transitions of hydrides like HF, CH, H_2O^+, OH^+ and ro-vibrational transitions of C_3 have been probed using HIFI as part of the key programme “PRobing InterStellar Molecules with Absorption line Studies" (PRISMAS) (P. I. M. Gerin). These observations have shown CH and HF to be potential surrogates for molecular hydrogen (Gerin et al. 2010; Neufeld et al. 2010a; Sonnentrucker et al. 2010). Highly reactive ions of OH^+, H_2O^+ and H_3O^+ originating from both the dense star forming cores and the diffuse foreground clouds detected towards the lines of sight to W31C, W49N, DR21, Sgr B2, and NGC 6334 (Gerin et al. 2010; Neufeld et al. 2010; Ossenkopf et al. 2010), provide strong support to the present understanding of gas-phase oxygen chemistry, in particular, to the formation of water vapor via gas-phase reactions. The abundance of these ionized hydrides also help to set a lower limit to the cosmic ray ionization in the diffuse gas. Owing to the improved laboratory measurements of the wavelengths of the FIR bending mode transitions of C_3 together with the high spectral resolution of the HIFI instrument, it has been possible for the first time to detect multiple transitions of C_3 in the warm dense envelopes of hot star forming cores like W31C, W49N, DR21(OH) and W51 (Fig. 1 Mookerjea et al. 2010, 2012). The sensitivity of the HIFI observations is not sufficient to detect C_3 in the diffuse ISM. Detailed chemical modeling involving warming up of CH_4 from grain mantles followed by gas-phase reactions reproduce the observed C_3 abundances (Hassel et al. 2011; Mookerjea et al. 2012).

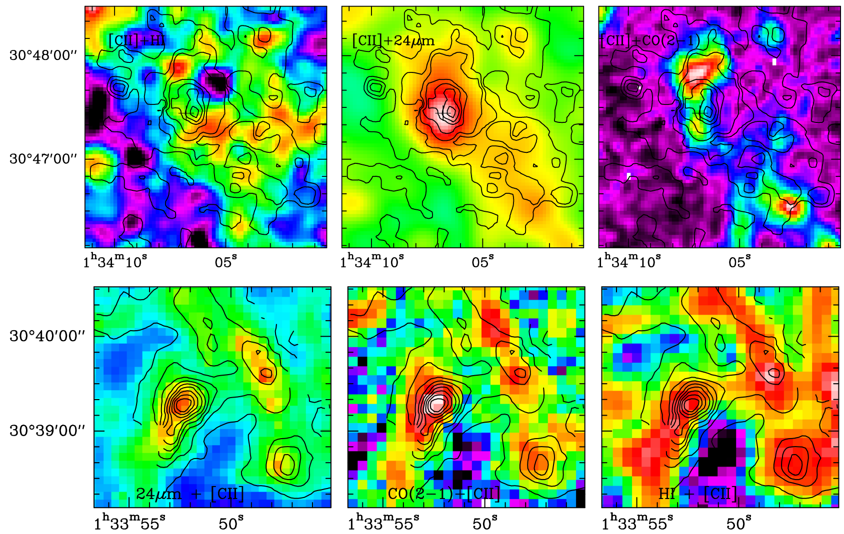

Figure 2. Comparison of [CII] with CO(2–1), HI and 24 μm continuum in BCLMP302 (top) and around M33 nucleus (bottom).

3. [CII] 158 μm in M33

Carbon, the fourth most abundant element, has an ionization potential of 11.3 eV (remains ionized where hydrogen is neutral) and is easily excitable with a $T_{ex} \sim 91$ K. Thus the 158 μm $^2P_{3/2}$–$^2P_{1/2}$ fine-structure transition of C^+, which is mostly optically thin, is one of the best candidates to trace the molecular ISM which is otherwise not traced by CO dark gas and is an excellent probe of the stellar radiation fields and their effects on the physical conditions of the neutral gas. C^+ is easy to detect, however, since it can arise from both ionized and neutral (atomic or molecular) ISM, use of this spectral line to derive the physical conditions of the emitting gas requires separation of the contribution of the different phases of the ISM to this emission. The high spatial and spectral resolution of HIFI onboard Herschel has made it possible to identify the contributions from the ionized, atomic and molecular phases of ISM to the [CII] emission at 158 μm.

As part of the open time key programme “Herschel M 33 extended survey" (HerM33es; Kramer et al. 2010) we have surveyed the major cooling lines, [CII], [OI], and [NII] as well as dust spectral energy distribution (SED) using all three instruments onboard *Herschel*, HIFI, PACS, and SPIRE. M33, a moderately inclined (i = 56°) galaxy, located at a distance of d= 840 kpc, with its recent star formation activity, together with the absence of signs of recent mergers, make M33 an ideal target to study the interplay of gas, dust, and star formation in the disk. Using PACS, several small [CII], [OI], and [NII] maps have been observed along the major axis of M33 (Nikola et al. in prep). On-the-fly perpendicular cuts have been observed in [CII] within each of these PACS maps using HIFI. [CII] has been detected throughout the regions observed along the major axis of M33 with PACS (Nikola et al. in prep), as well from the HIFI cuts (Mookerjea et al. 2010, Braine et al. 2012, Mookerjea et al. in prep.). Previous observations of [CII] in galaxies which are unresolved have indicated a strong correlation between [CII] and CO, suggesting PDRs to be the main contributors to [CII] emission (Stacey et al. 1991, Malhotra et al. 2001). The Galaxy-wide survey of [CII] emission using COBE on the other hand have shown a strong correlation between [NII] emission arising from diffuse ionized medium (Bennett et al. 1994). Based on the spatially resolved [CII] observations of M33, we have explored the correlation between [CII] and CO and HI, to understand the origin of [CII]. We find that while [CII] is indeed correlated well with CO emission in BCLMP691 as well as in the nucleus region, it is not so for BCLMP302. Thus the overall [CII]–CO correlation does not necessarily hold at length scales of individual molecular clouds and is dependent on local geometry etc. In all regions [CII] is strongly correlated with tracers of star formation such as $H\alpha$ and dust continuum emission. Comparison of line profiles of [CII], CO(2–1) and HI observed in M33 often show that [CII] has line widths intermediate between the broader HI and CO lines and there is a significant relative shift in the line centers of [CII], HI and CO. In BCLMP302 we used [NII] at $122\,\mu$m to estimate that $\sim$ 20–30% of the [CII] emission arises in the ionized medium. In the nucleus we find that 20% of the [CII] emission arises from the neutral atomic region also traced by HI. Velocity information obtained with HIFI have also resulted in the detection of [CII] from regions with conditions inappropriate to form CO, the so-called "dark gas".

References

Bennett C. L., et al., 1994, ApJ, 434, 587
Braine J., et al., 2012, A&A, 544, A55
de Graauw T., et al., 2010, A&A, 518, L6
Gerin M., et al., 2010, A&A, 521, L16
Gratier P., et al., 2010, A&A, 522, A3
Griffin M. J., et al., 2010, A&A, 518, L3
Hassel G. E., Harada, N., Herbst, E., 2011, ApJ, 743, 182
Kramer C., et al., 2010, A&A, 518, L67
Malhotra S., et al., 2001, ApJ, 561, 766
Mookerjea B., et al., 2011, A&A, 532, A152
Mookerjea B., et al., 2010, A&A, 521, L13
Mookerjea B., et al., 2012, A&A, 546, A75
Neufeld D. A., et al., 2010a, A&A, 521, L10
Neufeld D. A., et al., 2010b, A&A, 518, L108
Ossenkopf V., et al., 2010, A&A, 518, L111
Pilbratt G. L., et al., 2010, A&A, 518, L1
Poglitsch A., et al., 2010, A&A, 518, L2
Sonnentrucker P., et al., 2010, A&A, 521, L12
Stacey G. J., et al., 1991, ApJ, 373, 423