The interstellar medium with HIFI

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Introduction

The study of the interstellar medium (ISM) is critical for an understanding of both star formation and the evolution of galaxies. HIFI is a unique instrument to accomplish this, since for local sources most important spectral structures are obscured by the Earth atmosphere.

The formation of new stars in galaxies releases such large amounts of radiative and kinetic energy in the interstellar medium that matter continuously cycles between the dense and diffuse phases of the medium. The chemical evolution of matter in space and the formation of stars must be investigated within this broad context. Gas phase abundances of elements such as Si and Fe show that a significant fraction of matter accreted onto dust in molecular clouds is released back to the gas within the low density phases of the ISM. At the opposite, the detection of numerous molecular clouds at high Galactic latitude and of large abundances of molecules in the diffuse ISM show that the condensation of gas from the warm to cold phases is easily followed by the formation of molecules. Molecular abundances in these low column density molecular clouds are not readily explained with state of the art gas phase chemistry and alternative formation processes may be effective. For instance, The decrease of turbulent line widths from the warm phases to atomic clouds and from atomic to molecular clouds suggests that the condensation process of clouds goes with a dissipation of turbulent kinetic energy. The dissipation process may be able to greatly enhance the abundance of some species (e.g. CH^+).

The proposal is organised as follows :

Section 1 deals with the ISM structure, the role of HIFI for studying physical and chemical processes in the Warm and dense ISM is described in Section 2, Section 3 presents observations probing the transition from atomic to molecular gas, especially the formation of hydrides, while complex molecules are the subject of Section 4.

1 ISM structure

1.1 HIFI niche for studying the ISM phases

The diffuse ISM in galaxies has a major contribution to their global emission in the main cooling lines such as C^+ or N^+. It is one of the most poorly known step in the evolutionary cycle of interstellar matter from stellar interiors to dense protostellar clouds and has therefore bearings to the evolution of galaxies. For these reasons, the diffuse ISM warrants further studies and HIFI is particularly well suited for them, as we show below.

A global description of the structure of the ISM is missing and the overall structure of the ISM remains elusive, in particular the volume filling factor of the various phases (hot, warm ionized medium WIM, warm neutral medium WNM and cold neutral medium CNM), the amount of small scale structure present in each of them, the density contrasts and perhaps most importantly the thermal pressure of each of these phases, and its variation with the distance z to the galactic plane. The link between the various phases (e.g. are they in thermal pressure balance ?) is likely to be related to their formation mechanism and has to be established. Is the hierarchy of structures observed in the coldest component (that of molecular clouds) a fossil of thermal/gravitational instabilities developed initially in a placental warm medium at 10^4 K? The structure of the ISM may thetrefore be related to that of the coldest self-gravitating components, and ultimately to the process of star formation.

The structure and physics of the diffuse ISM has also important bearings to (i) understanding the gaseous structure of one of the many screens between the Cosmic Background (CBG) and the Sun, and therefore that of the dust distribution which affects the continuum measurements of the CBG, (ii) the evolution of the Galaxy since the WNM and CNM contains each a significant fraction of the mass of the ISM in our Galaxy, (iii) the large observed porosity of the neutral medium to UV photons and (iv) understanding the first steps of interstellar chemistry.

Over the years dedicated efforts have been conducted and significant progresses have been performed in the understanding of the ISM, in particular with the HST/GHRS, COBE/FIRAS and ISO/LWS and

ISOCAM instruments. The capabilities of HIFI will allow new breakthroughs thanks to its high angular resolution, its high frequency resolution (velocity being the only means accessible to identify different gaseous components on a same line of sight) and its sensitivity. Some aspects of the foreseen investigation possibilities are described in the following.

Thermal pressure determinations as derived from [CI] fine structure lines and molecular line observations vary from tracer to tracer. The thermal pressure derived from [CI] absorption lines in the general ISM is $P_{th}/k \sim 3\times10^3$ K cm^{-3} (Jenkins & Shaya 1979, Jenkins & Tripp 2001) with large excursions above this value, while recent observations of molecules in absorption against extragalactic sources provide $P_{th}/k \sim 2 \times 10^4$ K cm^{-3} (Lucas & Liszt 1994). If large pressure differences exist, shocks propagating into the coldest phases should be present. Small scale density structures are also prominent in the spectra of nearby lines of sights (Pan et al. 2001, Andrews et al. 2001).

HIFI will extend the present observations of the [CI] fine structure lines to low column densities HI clouds. In such clouds most of the gas carbon is ionised and C is only a minor constituent. However carbon abundances derived from UV absorption studies (Jenkins & Tripp 2001) show that the [CI] fine structure emission lines can be measured with HIFI. Thanks to the high spectral resolution of HIFI we can use the information on the level population, and from the line profiles to determine the gas pressure for each of the velocity components of the clouds which is a fundamental information to understand the origin of clouds structure. An illustration of a possible target field is shown in Figure 1.1 from Miville-Deschênes et al. (2002). The HI emission there reveals conspicuous small scale filaments, the width of which has not been quite resolved by the instrument (DRAO interferometer, resolution 1'). Such a small scale structure in the HI emission seems to be found in many directions.

High spectral resolution observations of the [CII] fine structure line will allow the separation of the contribution of the cloud phase from that of the warm ionized medium (WIM) and, together with Hα and HI emission spectra, the thermal and non-thermal contributions to the observed line widths. The narrowest velocity components in HI clouds have velocity widths of 3 kms^{-1} (FWHM) which are close to the expected thermal width for gas at a few 100 K. For the corresponding [CII] emission components we expect to see a narrowing of the lines due to the higher mass of carbon. [CII] line emission for an HI cloud with a column density of $N(H) \sim 5\times10^{20}$cm^{-2} is estimated to be $I(CII) \sim 10^{-6}$ erg cm^{-2} s^{-1} sr^{-1} (Matsuhara et al. 1997), while the WIM contribution is $I_{WIM}(CII) = 4 \times 10^{-7}$ erg cm^{-2} s^{-1}sr^{-1} assuming $I(CII)/N(H) = 3 \times 10^{-26}$ erg s^{-1} H^{-1} (Gry et al. 1992) and all the carbon in the gas phase. The velocity information will be a critical input to disentangle the relative contributions of the CNM and WIM to the line intensity. Maps in the [CII] line will also help in understanding the small scale structure of the WIM. Warm components are presumably more smoothly distributed, but CaII absorption lines against binary stars (Meyer and Blades 1996; Watson and Meyer 1996) suggest that small scale structure also exists in the WIM. The [NII] line at 205 μm is expected to be 0.06 times weaker than the [CII] line in the WIM and will therefore be detected by HIFI only up to a few degrees from the plane. It is an excellent tracer of ionized gas, with no contamination from any other phase of the ISM.

The comparison of [NII], [CII] and HI emission spectra will permit the investigation of the degree of association between the so-called cold (or cloud)($T<$ a few 100 K) and warm intercloud ($T\sim$ 8000 K) neutral phases of the interstellar medium and the role of thermal instability in the formation of small scale density structure within the diffuse ISM (Hennebelle & Pérault 2000). The warm neutral gas does not contribute to the [CII] emission while both the cold and warm neutral phases contribute to the HI emission. The [NII] observations allow subtraction of the fraction of [CII] from ionized gas.

With the gas temperature and pressure estimates deduced from the neutral carbon lines, it might be possible to derive the carbon abundance from the [CII] line intensity. We will be able to correlate variations in the carbon depletion with local physical conditions and dust extinction and emission properties including observations of the dust emission spectrum with PACS and SPIRE. Such measurements will open a completely new perspective on the cycling of carbon between dust grains, small aromatic hydrocarbon particules, CO and atomic carbon. Indeed, Miville-Deschênes et al. (2002) show evidences for correlation between the abundance of the very small dust particles responsible for the mid-IR emission, and the gas velocity structure.

Observations of the emission lines of the ISM as described above should be also performed in fields surrounding the lines of sight studied in absorption in the UV by the HST and FUSE. The absorption studies give access to abundances and Doppler broadening for many atomic and ionic species but they are limited to a spectral resolution of about 3 km s^{-1} (HST) and the spatial information is almost non existent. However they provide unique information on the abundances and ionization state of numerous IS 'components' i.e. defined by a common absorption velocity. Some of the components are neutral and clearly associated with the WNM, and some are at least partially ionized, the origin of the ionization being not always clear. Some of these components in the lines of sight to halo stars should correspond to the extended Hα emitting layer in the Galaxy but its identification is not straightforward, especially because of the lack of spatial information of UV observations and the lack of spectral resolution of Hα observations.

1.2 proposed observations

For each source we propose to map small fields using the OTF mode in order to have a description of the small scale structure, and to have global information to compare with previous large scale observations (IRAS, ISO). For [CII] and [NII], we use a system temperature of 1800 K and adapt the frequency resolution to the expected line width. The expected [CII] line strength is 10^{-6} erg $\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ for high latitude clouds, and 4×10^{-4} erg $\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$ for a line of sight across the Galactic Plane at $b = 0.5°$. This corresponds to line integrated intensities of 0.14 K kms^{-1} ($\delta v = 2$ km s^{-1}) and 60 K kms^{-1} ($\delta v = 30$ km s^{-1}) respectively. The ionised nitrogen line at 205 μm is about 10 times weaker than [CII], but has broader features.

Adopting a velocity resolution of 1 kms^{-1} for [CII] and 4 kms^{-1} for [NII], a single pixel is detected at the 3σ level in 900s (high latitude), 30s (Galaxy, [CII] and [NII]).

We need to observe both [CI] lines as well, covering the same area in the 492 GHz line, and observing a few positions in the 809 GHz line. The estimated line strength is 0.1 $Kkms^{-1}$ for the 492 GHz line in a high latitude cloud and 6 $Kkms^{-1}$ across the Galaxy. The 809 GHz line is very sensitive to the gas pressure. In diffuse clouds, it is weaker than the 492 GHz line, by a factor of 10 approximatively.

We adopt use a system temperature of 233 K for 492 GHz and 454 K for 809 GHz, and select a frequency resolution of 1 MHz (or 0.6 km s^{-1}) at 492 GHz. For the high latitude fields, the requested integration time per pixel is 120 s for the 492 GHz [CI] line. The 809 GHz lines requires 4 hours integration per position.

For the Galaxy fields, the signal is expected to be stronger over a larger velocity coverage than for the HLCs and we plan to decrease the integration time by a factor of two in the plane. Since the lines, if they follow the latitude dependence of the emission measure, decrease by a factor 3 between $b = 0$ and $b = 2°$, the integration time for fields at larger latitude will be similar than for HLCs.

To cover a 4'×4' field in the [CII] line, a map of 40 × 40 positions with a sampling of 6" is required. For the high latitude clouds, the spatial resolution will be degraded to 30" to be comparable to the [CI] data. We give the integration time for a total of 64 points. For the lines of sight through the Galaxy, we compute the integration time for a spatial resolution of 20 arcsec (144 independant points)

We list below the requested integration times to observe one field of size $M \times N$ in arcminutes, with a resolution δv and a final rms σ once the angular resolution has been smoothed to 30" for the HLCs and 20" for the galaxy at $b = 0$. Frequency switching is used for the HLC fields.

- High latitude [CII] : 16 hours $(M \times N/4' \times 4')(14\mathrm{mK}/\sigma)^2(3\mathrm{kms}^{-1}/\delta v)^2$
- High latitude [CI] : 5 hours $(M \times N/4' \times 4')(12\mathrm{mK}/\sigma)^2(3\mathrm{kms}^{-1}/\delta v)^2$
- Galaxy [CII] : 1.2 hour $(M \times N/4' \times 4')(60\mathrm{mK}/\sigma)^2(4\mathrm{kms}^{-1}/\delta v)^2$
- Galaxy [NII]: 1.2 hour $(M \times N/4' \times 4')(60\mathrm{mK}/\sigma)^2(4\mathrm{kms}^{-1}/\delta v)^2$
- Galaxy [CI] : 2.5 hours $(M \times N/4' \times 4')(17\mathrm{mK}/\sigma)^2(3\mathrm{kms}^{-1}/\delta v)^2$

Adding at least one 809 GHz [CI] point, the total time per field is thus 25 hours (high latitude) and 9 hours (Galaxy, $b = 0$). The total satellite time will be at least a factor of two larger due to various overheads.