ABSORPTION MEASUREMENTS OF COLD HALO GAS: FIRST'S SENSITIVITY

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Abstract

We discuss the sensitivity of FIRST to detect cold gas in the outer Galaxy by line absorption against the thermal dust emission from nearby, bright galaxies. The analysis shows that some ten of these are sufficiently strong and extended for a successful absorption measurement. The spectral range of FIRST covers several important ground state transitions of abundant atomic and molecular species. These allow to probe a range of chemical (and physical) conditions of the potentially present cold halo gas, which are not accessible by or complementary to observations by other means.

Key words: Galaxies: halo – Interstellar Matter: Missing Mass – Mission: *FIRST*

1. Introduction

HI 21 cm observations detect interstellar matter far beyond the optical disk in external galaxies, and similarly outer Galaxy material can be traced in HI in the Milky Way. In fact, the rotation curve derived from HI is the best tracer of the mass distribution of the outer Milky Way, indicating a substantial contribution of dark matter beyond the solar circle (Blitz 1995, Fich & Tremaine 1991). One may speculate that a fraction of that material may be in the form of normal matter. There is, e.g. an indication that mergers need a reservoir of gaseous matter which cannot be accounted for by the typical mass contribution of the ISM in quiescent galaxies of corresponding type without activity, and hence might be brought in from the very outer regions of the disks during the interaction (Braine & Combes 1993).

Little is known about the physical and chemical composition of the interstellar matter in the halo and outer disk of the Milky Way. Even local material shows unexpected characteristics that become obvious only when traced in non common ways, as was shown by the recent analysis of mm-wave absorption measurements against quasars by Liszt & Lucas (2000). Due to the lack of heating sources in the outer Galaxy this material is probably cold; due to the lack of nuclear chemical processing through stars it may also be metal poor. It may well be that some of this material (and potentially even a large fraction) is present in the form of cold molecular clouds, thus being invisible in HI. As an extreme possibility "clumpscules" of dense H_2 have been proposed by Pfenninger & Combes (1995).

As the material is cold, it will not be detectable in emission in any of the standard tracers: H_2 itself has the lowest emission level at an energy 512 K above ground state and the lowest emission levels of all the abundant carbon and oxygen bearing species (i.e. the atomic fine structure and rotational levels of the corresponding hydrides) are also at least several 10 K above ground. Only CO, with the first rotational level just 5 K above ground might be excited. On the other hand, CO may not be the dominant form of gas phase carbon in cold, outer Galaxy molecular clouds, considering their potentially low metalicity and hence larger UV–penetration (similar to the ISM in metal poor dwarf galaxies (Madden et al. 1997, Bolatto, Jackson & Ingalls 1999).

The highest sensitivity for detecting cold, outer halo gas in the Milky Way is provided through absorption measurements against extragalactic background sources, as long as a sufficient number of them is available and is sufficiently bright in the telescope beam. Absorption profiles have been observed for the 3 mm ground state rotational transition of CO and other molecules, were mm-wave interferometers supply a sufficiently small beam to be reasonably filled by the strong but compact mm-emission from quasars (see Liszt & Lucas (2000) and references therein). The general problem in the mm-wave range is that the continuum sources are rather weak (at least in single dish beams): the non-thermal synchrotron and thermal free-free emission, dominant at longer wavelengths, is already down, whereas the sub-mm thermal dust continuum is still very optically thin.

The dust continuum, however, gets much brighter in the sub-mm and FIR. This fact, together with the relatively small beam of *FIRST* (and *SOFIA*) and the availability of many ground state transitions within the atomic fine structure and within the rotational levels of several hydrides of carbon and oxygen in *FIRST*'s spectral range stimulated this contribution.

2. Column Densities of Cold Halo Gas

Absorption measurements in the CO $J = 1 \rightarrow 0$ transition with mm-wave interferometers detect absorption profiles

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Table 1. Sub-mm and FIR transitions of abundant species and their column densities required to reach an optical depth of $\tau = 1$, assuming standard abundances in the ISM

species and	$N_{\mathrm{H}}(\tau = 1)$	remarks		
wavelength	[cm^{-2}]	$\chi = n_{\mathrm{x}}/n_{\mathrm{H}}$	excitations	E_{u}/k
HI 21 cm	1.8×10^{18}	1	$T_{ex} >> \frac{h\nu}{k}$	68 mK
CO $J = 1 \rightarrow 0$ 3 mm	6.4×10^{18}	10^{-4}	$T_{\mathrm{ex}} << \frac{h\nu}{k}$	5.5 K
[CI] 609 μm	4.7×10^{20}	10^{-4}	"	24 K
[CII] 158 μm	1.4×10^{21}	10^{-4}	"	91 K
[OI] 63 μm	6.2×10^{20}	3×10^{-4}	"	228 K
H_2 rot 28 μm	1.5×10^{24}	0.5	"	512 K
H_2 rovib 2.2 μm	3.7×10^{23}	0.5	"	6256 K

towards all of the limited number of sources that provide bright enough extragalactic background (see e.g. Liszt & Lucas 2000). These observations are sensitive to column densities ranging from 0.01 to about 2×10^{20} cm^{-2}, using the standard abundance of about 10^{-4} to convert from CO to H. This result empirically sets a range of column densities for which material in absorption can be expected to be detectable.

Taking the mass distribution derived from the rotation curve of the outer Galaxy, as derived from HI 21 cm observations, Fich & Tremaine 1991, we know that the mass enclosed between the solar circle and out to 20 kpc is about $1.35 \times 10^{11} M_{\odot}$, of which only a small fraction is traced by stellar light. The rest is attributed to "dark matter". Assuming for the moment (without implying that this is indeed the case) that this matter is present as ordinary matter, but undetectable in the usual tracers of local and inner Galaxy molecular clouds, this amount of material corresponds to an average volume density in a spherical distribution of $n = 0.2$ cm^{-3} and an average column density radially across the spherical shell between 8 and 20 kpc of some 10^{22} cm^{-2}. Thus, even a small fraction of this material might be detectable, if present as ordinary matter, and even at substantially lower metalicities (given the column densities that produce significant absorption, as discussed below).

The volume and column density increases if the distribution is flattened along the Galactic plane, rather than being spherical. One also has to consider a clumpy distribution of the matter: going to the extreme of putting all this material into the form of "clumpuscules" (as being introduced speculatively by Pfenninger & Combes 1995) with densities on the order of $n_{\mathrm{c},6} = 10^6$ cm^{-3} and radii of order $R_{\mathrm{c},2} = 0.02$ pc, one arrives at masses of $0.7 M_{\odot} R_{\mathrm{c},2}^3\ n_{\mathrm{c},6}$, a volume filling factor of around $\eta_{\mathrm{V}} = 2 \times 10^{-7}/n_{\mathrm{c},6}$, a clump column density of $8 \times 10^{22}\ R_{\mathrm{c},2}\ n_{\mathrm{c},6}$ and an average area filling factor for these clumps of $\eta_{\mathrm{A}} = 0.7/(R_{\mathrm{c},2}\ n_{\mathrm{c},6})$, i.e. still close to unity.

3. Source and Beam Geometry

In order to estimate the absorption line signal strength expected from cold halo material against extragalactic background sources one has to consider the general experience that molecular clouds show a complex structure, often referred to as clumpy. In relation to absorption measurements one should mention that in fact HI absorption measurement against QSOs with the milliarcsec resolution reachable by VLBI provide evidence for the smallest scale structure in the local ISM, with surprisingly high densities of the smallest scale structures (Faison et al. 1998).

Figure 1 shows a sketch of the geometry: the background continuum source fills part of the telescope beam (filling factor η_{c}); the clumpy foreground source covers part of the continuum source (filling factor η_{sc}), and partly extends over the beam area outside of the continuum source (filling factor η_{s}).

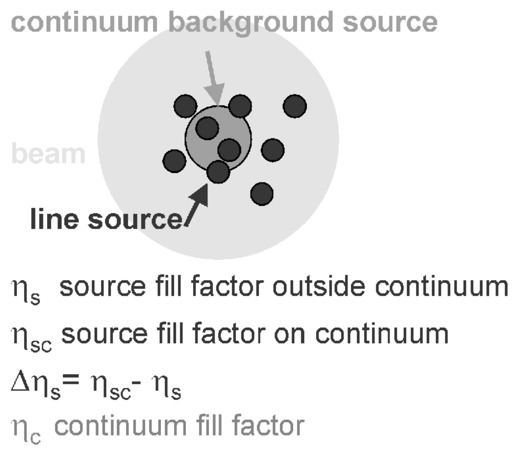

Figure 1. Beam and source geometry for line absorption measurements.

For an ON-OFF measurement with the off source field only showing the cosmic microwave background emission, the absorption signal on a Rayleigh–Jeans brightness temperature scale, normalized to the continuum brightness $T_{\mathrm{B,c}} = (1-\eta_{\mathrm{c}})\mathcal{J}_{\nu}(T_{\mathrm{cmb}})+\eta_{\mathrm{c}} T_{\mathrm{c}}$ is the appropriately weighted average of the signal from in front of the continuum source and from the rest of the beam:

Table 2. Instrument sensitivity and continuum flux levels needed for a 5 σ detection of a $\tau = 1$ absorption line at 1 km/s resolution, obtainable with HIFI. The sensitivity for the integrated line flux with PACS is comparable, but lacks the important velocity information. The continuum fluxes are scaled to 100 μm by assuming a $\lambda^{-1.5}$ dust emissivity law and an unresolved source.

species and wavelength	instrument	$T_{\rm sys}$[K] SSB	$\Delta T_{\rm sys}$[mK] SSB	beam– FWHM	$S_{\rm c}$[Jy] S/N=5	$F_\nu(100\,\mu{\rm m})$ [Jy] with $\lambda^{-3.5}$
[CII] 158 μm	HIFI	1300	70	12"	105	520
[CI] 609 μm	"	180	5	42"	6.5	3620
[OI] 63 μm	PACS	line flux (5 σ, 1 hr) 8×10^{-18} W m^{-2}			49	13

$$\frac{T_{\rm B}}{T_{\rm B,c}} = 1+\frac{\Delta T_{\rm B,l}}{T_{\rm B,c}} = \frac{1}{(1-\eta_{\rm c})\mathcal{J}_\nu(T_{\rm cmb})+\eta_{\rm c}T_{\rm c}} \times \Big\{(1-\eta_{\rm c})\,\mathcal{J}_\nu(T_{\rm cmb}) \left[1-\eta_{\rm s}\left(1-e^{-\tau_\nu}\right)\left(\frac{\mathcal{J}_\nu(T_{\rm ex})}{\mathcal{J}_\nu(T_{\rm cmb})}-1\right)\right] + \eta_{\rm c}T_{\rm c}\left[1-\eta_{\rm sc}\left(1-e^{-\tau_\nu}\right)\left(\frac{\mathcal{J}_\nu(T_{\rm ex})}{T_{\rm c}}-1\right)\right]\Big\} \quad (1)$$

where $T_{\rm c}$ is the RJ-continuum brightness temperature. This rather complex expression reduces to the result $\frac{T_{\rm B}}{T_{\rm B,c}} = e^{-\tau_\nu}$, as used in the analysis of mm-wave absorption signals against (point-like) quasars, under the assumptions that (i) the foreground covers the extent of the continuum source, $\eta_{\rm sc} = 1$, (ii) the beam average continuum is much stronger than the cosmic microwave background in the rest of the beam, $\eta_{\rm c}T_{\rm c} >> (1-\eta_{\rm c})\mathcal{J}_\nu(T_{\rm cmb})$, and (iii) that the excitation temperature is small compared to the continuum, $\mathcal{J}_\nu(T_{\rm ex}) << T_{\rm c}$.

For the FIR spectral range relevant for *FIRST*, we can safely neglect the cosmic background intensity ($\mathcal{J}_\nu(T_{\rm cmb}) = 0$) on the Wien side of the spectrum; also, restricting the discussion to cold material (or at least sub-thermal excitation) we may assume the excitation temperature to be small compared to the continuum, i.e. again condition (iii) from above, and obtain

$$\frac{T_{\rm B}}{T_{\rm B,c}} = 1-\eta_{\rm sc}\left(1-e^{-\tau_\nu}\right), \quad (2)$$

with $T_{\rm B,c} = \eta_{\rm c}T_{\rm c}$. For a strong line absorption signal we thus need a strong background continuum source, which is extended relative to the beam size, and a low excitation, foreground line source which covers at least a substantial fraction of the continuum.

4. Absorption Optical Depth

Depending on the type of radiative transition, the corresponding dipole or quadrupole moment, and the transition energy, different species reach an absorption optical depth of unity at different column densities. Table 1 shows a compilation for the most abundant species. The column density for which $\tau = 1$ is reached, has been converted to a corresponding H–column density assuming standard abundances. The halo gas may, of course, be expected to have lower metalicity, so that the abundance would have to be scaled accordingly.

Except for the HI 21 cm–transition, we have assumed an excitation temperature much smaller than the transition energy, corresponding to cold material (or at least sub-thermal excitation). The energy level spacing for the HI 21 cm–transition is so small, that the assumption of a level population proportional to the statistical weights of the levels (corresponding to infinite excitation temperature) is appropriate for all situations.

We have not included in Table 1 H_2–absorption in the UV, as has been observed from *Copernikus* and, most recently, from *FUSE* (Shull et al. 2000 and references therein). UV–absorption of H_2 allows to detect columns as low as 10^{14} cm^{-2} and thus is very easily confused by smallest amounts of material; in addition only a limited distance can be probed because of the strong dust extinction in the UV. Nevertheless, UV absorption measurements of H_2 are an important tool for studying the ISM distribution and they contribute important insight, in particular in combination with the potential sub-mm– and FIR observations discussed here.

One should note that the mid– and near–IR rotational and rovibrational ground state transitions of H_2 (admittedly not observable with *FIRST* in any case) require quite high column densities to reach $\tau = 1$. They are thus not suited for the detection of cold halo gas, although this alternative might at first sight look rather attractive for *SIRTF* or *SOFIA*, given the small beam at these wavelengths and the availability of many bright extragalactic continuum sources. These H_2 transitions are, however, well suited to study dense, massive star forming cores.

The spectral range covered by *FIRST* also includes several ground state transitions of the hydrides of abundant elements, in particular CH, CH^+, and OH. These have not been included in Table 1. Due to the large dipole moments of these transitions, they can provide strong absorption signals, compensating their lower abundance by their higher transition probabilities.

5. Sensitivity and Background Sources

The absorption lines from cold halo gas will have rather narrow line widths, so that the heterodyne resolution of *HIFI* is necessary to resolve the lines. The full velocity information is advantageous to associate the absorption clouds with other material, detected e.g. in HI emission, and to derive their position in the Milky Way from the rotation curve (which, however, is only poorly known in the outer Galaxy). We thus compile in Table 2 the instrument noise level achievable with *HIFI* for a 1 km/s resolution element in 1 hour total integration time (ON–OFF observing mode). Together with *FIRST*'s beam size we convert this into a continuum flux level needed for a 5 σ detection of a $\tau = 1$ absorption line.

As it turns out, the per pixel, per spectral resolution element integrated line flux sensitivity of PACS is rather comparable, so that similar continuum fluxes are needed to detect the integrated line absorption, with the velocity information however missing. This is relevant for those lines, that fall outside of *HIFI*'s wavelengths coverage, like e.g. [OI] 63 μm.

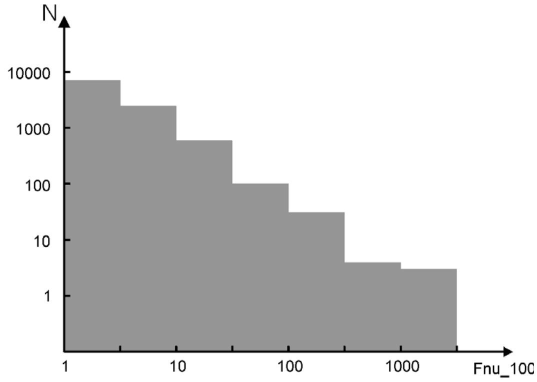

Figure 2. Flux distribution of extragalactic sources from the IRAS point source catalogue at 100 μm

Assuming a dust emissivity law exponent $\propto \lambda^{-1.5}$ and source sizes small compared to the beam, we extrapolate to the corresponding 100 μm fluxes necessary for absorption line detection. Both assumptions are on the conservative side. We can then compare with the number distribution of extragalactic continuum sources from the IRAS point source catalog. Figure 2 shows that we may expect on the order of 10 sources bright enough for detecting the [CII] 158 μm in absorption (following the estimates from Table 2). A close inspection of the distribution on the sky shows that indeed roughly half of them are located in the outer Galactic quadrants. For the longer wavelength [CI] 609 μm line the severe beam dilution within the large beam of *FIRST* likely does not allow an absorption detection. [CI]–absorption will, however, be an ideal target for interferometric observations with *ALMA* with its small beam size.

Similar to the [CI] absorption observed towards the Galactic center by Staguhn et al. (1997), absorption in cold halo gas might also be detectable against the line emission of extragalactic sources, provided that their LSR–velocity and velocity width cover the velocity interval expected for the halo gas. This is the case for several nearby star burst galaxies.

6. Summary

The dust continuum emission from nearby star-burst and other IR–bright galaxies, increasing rapidly with decreasing wavelength, provides strong and reasonably extended extragalactic background sources that can be exploited for the detection of cold halo gas in absorption. An estimate of the expected column densities of cold material in the outer Galaxy, the optical depths reachable with several ground state transitions accessible to *FIRST*, and the sensitivity of *FIRST*'s spectrometers, shows that absorption signals from cold halo gas might be detectable towards at least a handful of extragalactic FIR sources. At the longer wavelengths, the success of absorption observations might be marginal because of *FIRST*'s large beam, resulting in serious beam dilution of the background source.

Such observations, though demanding and potentially unsuccessful, may provide a unique possibility to detect the presence of a significant amount of cold halo material undetectable by any other means, if CO is not the dominant form of gas phase carbon due to its different physical and chemical composition. In complement with observations in other wavelengths ranges (sub-mm-interferometer–observations with *ALMA*, non-velocity resolved FUV H_2 absorption) *FIRST* will be able to cover an important niche in the parameter space accessible.

References

Blitz, L., 1995, in "Dark Matter", AIP Conf. Proc. 336, eds. S.S. Holt & C.L. Bennet, p. 101, AIP Press, New York.

Bolatto, A.D., Jackson, J.M., Ingalls, J.G., 1999, ApJ 513, 275.

Braine, J., Combes, F., 1993, A&A 269, 7.

Faison, M.D., Goss, W.M., Diamond, P.J., Taylor, B., 1998, AJ 116, 2916.

Fich, M., Tremaine, S., 1991, ARAA 29, 409.

Liszt, H., Leung, R., 2000, A&A, 355, 333.

Madden, S.C., Poglitsch, A., Geis, N., et al. 1997, ApJ 483, 200.

Pfenninger, D., Combes, F., 1995, in "Dark Matter", AIP Conf. Proc. 336, eds. S.S. Holt & C.L. Bennet, p. 161, AIP Press, New York.

Shull, J.M., Tumlinson, J., Jenkins, E.B. et al. 2000, ApJ 538, L73.

Staguhn, J., Stutzki, J., Chamberlin, R.A. et al. 1997, ApJ 491, 191.