

LETTER TO THE EDITOR

# First detection of the Methylidyne cation ( $\text{CH}^+$ ) fundamental rotational line with the *Herschel*/SPIRE FTS $\star$

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Received March 31, 2010; accepted May 4, 2010

## ABSTRACT

*Aims.* To follow the species chemistry arising in diverse sources of the Galaxy with *Herschel*.

*Methods.* SPIRE FTS sparse sampled maps of the Orion bar & compact HII regions G29.96-0.02 and G32.80+0.19 have been analyzed.

*Results.* Beyond the wealth of atomic and molecular lines detected in the high-resolution spectra obtained with the FTS of SPIRE in the Orion Bar, one emission line is found to lie at the position of the fundamental rotational transition of  $\text{CH}^+$  as measured precisely in the laboratory (Pearson & Drouion 2006). This coincidence suggests that it is the first detection of the fundamental rotational transition of  $\text{CH}^+$ . This claim is strengthened by the observation of the lambda doublet transitions arising from its relative, CH, which are also observed in the same spectrum. The broad spectral coverage of the SPIRE FTS allows for the simultaneous measurement of these closely related chemically species, under the same observing conditions. The importance of these lines are discussed and a comparison with results obtained from models of the Photon Dominated Region (PDR) of Orion are presented. The  $\text{CH}^+$  line also appears in absorption in the spectra of the two galactic compact HII regions G29.96-0.02 and G32.80+0.19, which is likely due to the presence of  $\text{CH}^+$  in the the Cold Neutral Medium of the galactic plane. These detections will shed light on the formation processes and on the existence of  $\text{CH}^+$ , which are still outstanding questions in astrophysics.

**Key words.** *Herschel*, SPIRE, FTS, methylidyne,  $\text{CH}^+$ , CH, Orion, G29.96-0.02, G32.80+0.19

## 1. Introduction

Molecules and radicals with C and H as constituents are expected to be the first chemical building blocks. The methylidyne cation ( $\text{CH}^+$ ) was discovered at visible wavelengths 70 years ago by Douglas & Herzberg 1941, shortly after the discovery of the methylidyne (CH) radical by Swings & Rosenfeld (1937). Since that time there has been intense debate surrounding the chemistry of this species (Bates and Spitzer 1951).  $\text{CH}^+$  far-IR detections were reported by Cernicharo et al. (1997) for the J=2-1 to 4-3 transitions in the NGC7027 PDR using Infrared Space Observatory spectra. Falgarone et al. (2005) report the probable detection of  $^{13}\text{CH}^+(1-0)$  in absorption against a galactic source. CH N=2-1 transitions have been detected by Stacey et al. (1987) and Polehampton et al. (2005) toward SgrB2 and by Liu et al. (1997) in NGC7027.  $\text{CH}^+$  is commonly detected in the visible and found to correlate with rotationally excited  $\text{H}_2$  (Lambert and Danks 1986), which argues for its formation in energetic regions. One of the underlying questions is whether  $\text{CH}^+$  formation proceeds via a still undefined reaction or, following the consensus in the literature, via ISM conditions liberating sufficient energy (shock chemistry, turbulence, UV pumping) to overcome activation barriers, thereby strongly enhancing the otherwise hindered endothermic reac-

tion rate for  $\text{C}^+ + \text{H}_2 \rightarrow \text{CH}^+ + \text{H}$ , with a  $\sim 0.4\text{eV}$  barrier.  $\text{CH}^+$  formation has been evoked as a result of shock chemistry (Pineau des Forets et al. 1986, Draine and Katz 1986 and citations). Species produced in shocks, however, should display velocity differences from the source producing the shocks. The  $\text{CH}^+$  absorption profiles measured to date are found to lie at the same velocity as CH (Gredel (1997)), which has been taken as an argument against shock chemistry production. UV pumping, leading to vibrationally excited  $\text{H}_2$  (Stecher and Williams 1972), is not expected to be significant in the diffuse ISM, on the grounds that the mean UV field is not strong enough to generate the observed excited  $\text{H}_2$ . However, the laboratory measured  $\text{C}^+ + \text{H}_2(v=1) \rightarrow \text{CH}^+ + \text{H}$  reaction (Hierl et al. 1997), may support such a route to  $\text{CH}^+$  formation in PDRs (e.g. Agundez et al. 2010). Among the propositions, turbulence models are gaining support in  $\text{CH}^+$  chemistry (Godard et al. 2009 and references therein). In this letter we present the first detection of the fundamental rotational transition of  $\text{CH}^+$ , along several lines-of-sight, in different and distinct regimes of the ISM and discuss the potential of SPIRE FTS observations to constrain the CH chemistry in such sources.

## 2. Observations with the SPIRE FTS

The SPIRE FTS measures, simultaneously, the source spectrum across two wavebands: SLW, covering  $14.9 - 33.0 \text{ cm}^{-1}$  ( $303 - 671 \mu\text{m}$ ) and SSW covering  $32.0 - 51.5 \text{ cm}^{-1}$  ( $194 - 313 \mu\text{m}$ ). Each

$\star$  *Herschel* is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.

**Table 1.** Observations summary

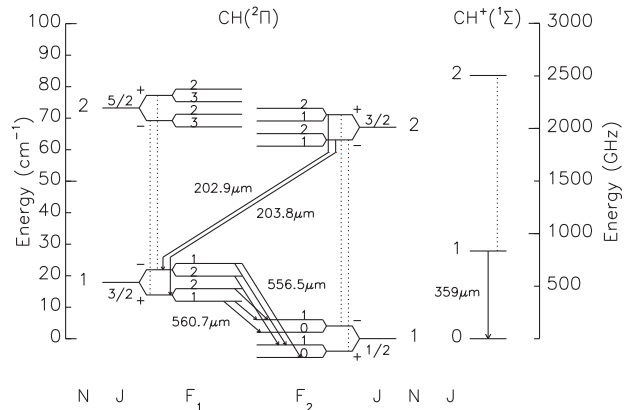
Source	Obs. date	Ra	Dec	Int(s)
HD37041	09/09/13	05h35m22.83s	-05d24'57.67"	266.4
G29.96-0.02	09/09/13	18h46m04.07s	-02d39'21.88"	266.4
G32.80+0.19	09/09/21	18h50m30.87s	00d02'00.85"	266.4

band is imaged with a hexagonal bolometer array with pixel spacing of approximately twice the beam-width. The FWHM beam-widths of the SLW and SSW arrays vary between 29-42" and 17-21" respectively. The source spectrum, including the continuum, is obtained by taking the inverse transform of the observed interferogram. For more details on the ESA *Herschel* Space Observatory, the SPIRE FTS, and the FTS calibration and data reduction procedures, the reader is referred to the articles by Pilbratt et al. (2010), Griffin et al. (2010), and Swinyard et al. (2010), respectively, in this volume. Our observations are part of the *Evolution of Interstellar dust* key project of the SPIRE consortium (Abergel et al. 2010). The source data presented here include the Orion Bar as well as the G29.96-0.02 and G32.80+0.19 compact HII regions. A short observation log is given in Table 1. For example, G29.96-0.02 was observed with the high-resolution mode of the SPIRE FTS on the 13th of September, 2009 at 19:49 (*Herschel* observation ID, 1342183824). Two scan repetitions were observed giving an on-source integration time of 266.4 seconds. The unapodized spectral resolution was  $0.04 \text{ cm}^{-1}$  (1.2 GHz). After apodization (using extended Norton-Beer function 1.5; Naylor and Tahic 2007) the FWHM of the resulting instrument line shape is  $0.0724 \text{ cm}^{-1}$  (2.17 GHz). While unapodized FTS spectra provide the highest spectral resolution, the instrument line shape, which in the case of an ideal FTS is the classical sinc function, is characterized by relatively large secondary oscillations having negative lobes. An iterative spectral line fitting routine has been developed to extract line parameters from unapodized FTS spectra. This algorithm fits a continuum (either a low order polynomial or a blackbody variant) and a series of lines using the Levenberg-Marquardt least squares method. The fitting procedure weights the spectral intensity at a given frequency of an averaged spectrum by the statistical uncertainty at that frequency. The fitting routine returns the line centres, intensities, and widths together with their associated errors. The transitions of methylidyne and its cation accessible to the FTS are summarized in Fig 1 and Table 2.

### The Orion Bar

The recorded spectra for  $^{12}\text{CH}^+$  are overlaid on published maps by Lis et al. (1998) in Fig. 2. The position of the O6  $\theta^1$  Ori C exciting star is also shown on the map. The expected geometry along the line of sight can be found in Fig.3 from Pellegrini et al. (2009) and in references therein. A cut through the expected best exposed projected line of sight is displayed (Fig. 2, left panel) and the integrated fluxes along this cut are shown in the right panel. Estimates of the column density corresponding to the positions shown in Fig. 2, which have been derived assuming thermal equilibrium with a mean Orion Bar temperature ( $\sim 85 \text{ K}$ ), determined from ground based observations (Hogerheijde et al. 1995), are given in Table 3. This table also presents abundance values for temperatures of 50 and 200 K, which probe different optical depths in the PDR. As noted above,  $\text{CH}^+$  is highly reactive, easily destroyed by collisions and is not expected to be found in thermal equilibrium in the pres-

ence of strong UV pumping. Detailed analysis and interpretation of the measured fluxes is ongoing, but is beyond the scope of this letter.

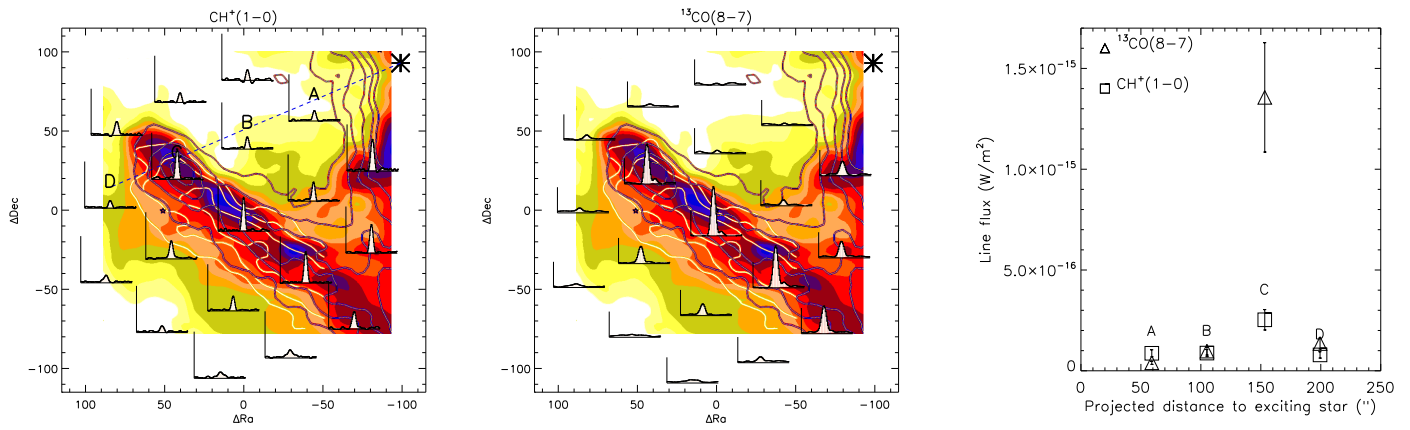

**Fig. 1.** Energy diagram for CH and  $\text{CH}^+$  in the SPIRE FTS range. Expected transitions are shown with arrows. Dotted lines are transitions lying at higher frequencies accessible by other *Herschel* instruments.

**Table 2.**  $\text{CH}^+$  and CH transitions in the SPIRE/FTS range

Freq (GHz)	Transition	$A(\text{s}^{-1})^a$	Ref
$\text{CH}^+$	$J = 1 \leftarrow 0$		
835.079043(1.0)	$1 - 0$	$5.96 \times 10^{-3}$	c
CH	$N = 1 J = 3/2 \leftarrow 1/2$		
532.721333 (100)	$F1 = 1+ \leftarrow F2 = 1-$	$2.1 \times 10^{-4}$	b
532.723926 (40)	$F1 = 2+ \leftarrow F2 = 1-$	$6.2 \times 10^{-4}$	b
532.793309 (50)	$F1 = 1+ \leftarrow F2 = 0-$	$4.1 \times 10^{-4}$	b
536.761145 (50)	$F1 = 2- \leftarrow F2 = 1+$	$6.4 \times 10^{-4}$	b
536.781945 (50)	$F1 = 1- \leftarrow F2 = 1+$	$2.1 \times 10^{-4}$	b
536.795678 (50)	$F1 = 1- \leftarrow F2 = 0+$	$4.2 \times 10^{-4}$	b
CH	$N = 2 \leftarrow 1 J = 3/2 \leftarrow 3/2$		
1470.6861(30)	$F2 = 1- \leftarrow F1 = 2+$	$8.8 \times 10^{-4}$	d
1470.6890(30)	$F2 = 1- \leftarrow F1 = 1+$	$4.4 \times 10^{-3}$	d
1470.7356(30)	$F2 = 2- \leftarrow F1 = 2+$	$4.8 \times 10^{-3}$	d
1470.7385(30)	$F2 = 2- \leftarrow F1 = 1+$	$5.3 \times 10^{-4}$	d
1477.2901(30)	$F2 = 1+ \leftarrow F1 = 1-$	$4.4 \times 10^{-3}$	d
1477.3104(30)	$F2 = 1+ \leftarrow F1 = 2-$	$8.8 \times 10^{-4}$	d
1477.3630(30)	$F2 = 2+ \leftarrow F1 = 1-$	$5.3 \times 10^{-4}$	d
1477.3832(30)	$F2 = 2+ \leftarrow F1 = 2-$	$4.7 \times 10^{-3}$	d

<sup>a</sup>calculated using CDMS data parameters; <sup>b</sup>Amano (2000); <sup>c</sup>Pearson & Drouin (2006); <sup>d</sup>Brown & Evenson (1983)

One of the striking features when comparing these plots is the prominence of  $\text{CH}^+$  with respect to the  $^{13}\text{CO}(8-7)$  transition fluxes at the A and B positions, away from the Bar, probably corresponding to the surface of the cavity perpendicular to the line of sight. This tendency is reversed on the Bar (C position). From a preliminary analysis of  $^{13}\text{CO}$  SLW data along the A and B line of sight, an excitation temperature of  $85 \text{ K}_{-45}^{+15}$  is derived from the rotational diagram, corresponding to  $N_{\text{B}}(^{13}\text{CO}) = 4.5 - 16.9 \times 10^{15} \text{ cm}^{-2}$ . We chose to focus on the B line of sight to avoid the effects of vignetting which are known to occur on the outer ring of bolometers. Such column densities would correspond to  $A_{\text{V}}$  in the range 1-6 at most, and fractional abundances in the range  $2 - 7 \times 10^{-10}$  for  $\text{CH}^+$ . We compare these estimates with a Meudon PDR code (Le Petit et



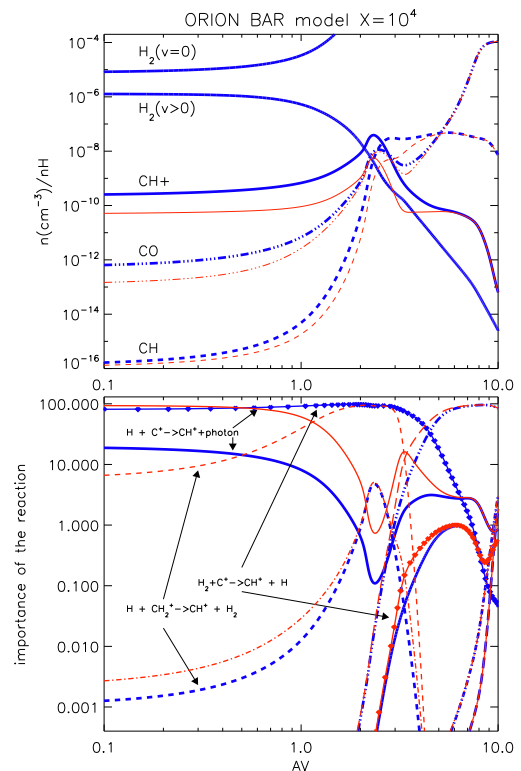
**Fig. 2.** Left panel:  $^{12}\text{CH}^+(1-0)$  continuum subtracted FTS spectra in the Orion bar region, overlaid on previous observations by Lis et al. (1998), which combine dust and gas emission. The color map is the  $^{12}\text{CO}(6-5)$  emission, the contours extending over the whole map are the continuum emission at  $350\mu\text{m}$  and the contours displayed only for  $\Delta\text{R}_a$  above  $-50$  correspond to  $^{13}\text{CO}(6-5)$  emission. The Orion PDR exciting star is also shown and a cut passing through the bar discussed in the text. The stratification of the PDR appears clearly on Lis et al. (1998) data, where the  $^{12}\text{CO}$  color map tracing hot gas is displaced toward the star with respect to  $^{13}\text{CO}$  contours tracing the dense molecular regions. Middle panel: same as  $\text{CH}^+$  map for  $^{13}\text{CO}(8-7)$ . Right panel: line fluxes along the cut presented in left panel for  $^{13}\text{CO}$  and  $\text{CH}^+(1-0)$

al. 2006) model applied to the Orion Bar environment, described in more detail in Habart et al. (2010).  $\text{CH}^+$  abundances in A and B are only marginally compatible with a classical Orion PDR model (Fig. 3, red curves), whereas taking into account the vibrationally excited  $\text{H}_2$  states (blue curves) where about 6% of  $\text{H}_2$  is in an excited vibrational state, enhances the formation rate by a factor of about 30 at low  $A_V$ . The relative importance of the  $\text{CH}^+$  production reactions, for both models, is shown in the lower panel of Fig. 3. At low to moderate  $A_V$ , corresponding to the front and surface of the PDR, in the model using only thermal rates, the radiative association reaction of  $\text{H} + \text{C}^+$  dominates (blue curves). This reaction is, however, superseded by the  $\text{H}_2 + \text{C}^+$  ion molecule reaction when the activation barrier can be overcome by the vibrational excitation of  $\text{H}_2$  (red curves).

The fact that the  $\text{CH}^+$  ion is seen extended all around the bar in the lower  $A_V$  regions and in high abundance seems to support the importance of excited  $\text{H}_2$  in the  $\text{CH}^+$  formation route. At lower frequencies, a pair of lines is observed at the position of the lambda-doublet CH transitions as shown in Fig. 4. In estimating the abundance of CH and  $\text{CH}^+$  it has been assumed that the opacity is negligible with the species thermalised at the temperatures noted. Only the spectra on the Bar are shown. The signal-to-noise ratio of these two lines will improve as the SPIRE FTS data processing is improved and with deeper observations toward Orion. Higher signal-to-noise is required to ensure that potential contributions from  $\text{HCO}^+$  and  $\text{HOC}^+$  line emission to this spectral region are considered, particularly for the higher frequency component.

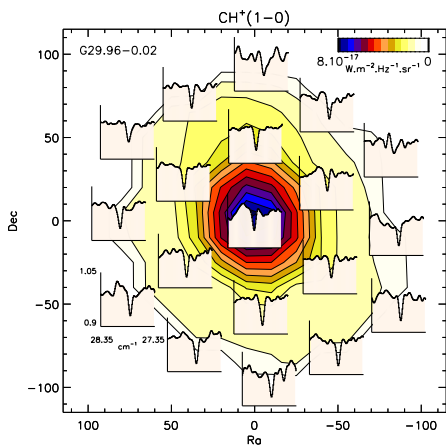
#### G29.96-0.02 and G32.80+0.19

G29.96-0.02 and G32.80+0.19 are two ultra compact HII regions (e.g. Wood and Churchwell 1989), located near the Galactic plane. A global analysis of G29.96-0.02 SPIRE/FTS data can be found in this issue (Kirk et al. 2010). Both HII regions display a  $\text{CH}^+$  absorption line at a few percent of the continuum level. From a study of the line-to-continuum ratio maps shown in Fig. 5, it appears that for each continuum level across the maps, the amount of absorption remains essentially the same, within the signal-to-noise limits for the outer pixels. This sug-

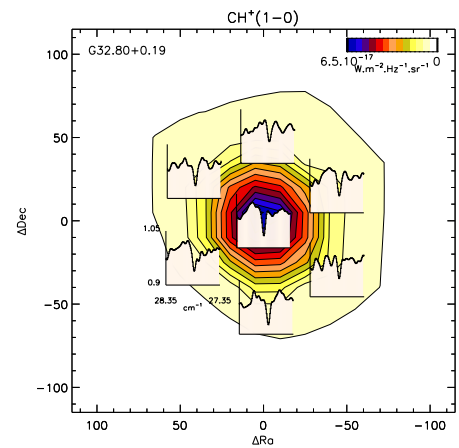


**Fig. 3.** Orion Bar isochore PDR model, using the Meudon code, as a function of the visual extinction normal to the front. The adopted PDR parameters are an incident flux of  $\chi = 10^4$  and a density of  $n_{\text{H}} = 10^5 \text{ cm}^{-3}$ . The upper panel shows model results in which the state by state vibrational excitation of  $\text{H}_2$  in  $v \geq 1$  (thick blue line) is considered as an internal energy involved in overcoming potential energy barriers, notably for the  $\text{H}_2 + \text{C}^+$  reaction. The thin red line shows the results for the classical PDR model. The lower panel is a fractional representation of the relative importance of the methylidyne cation production reactions as a function of  $A_V$ .

gests that the methylidyne ion is, as expected from its electronic visible absorption transitions, present in the foreground diffuse interstellar medium in relative high abundances. The apodized



**Fig. 5.** Left panel: G29.96-0.02 CH<sup>+</sup>(1-0) continuum divided transmittance spectra, overlaid on the continuum intensity map at the same frequencies, extending away from the ultra compact HII source. Right panel: same for the G32.80+0.19 HII region. The outer detectors are vignetted so have been omitted.



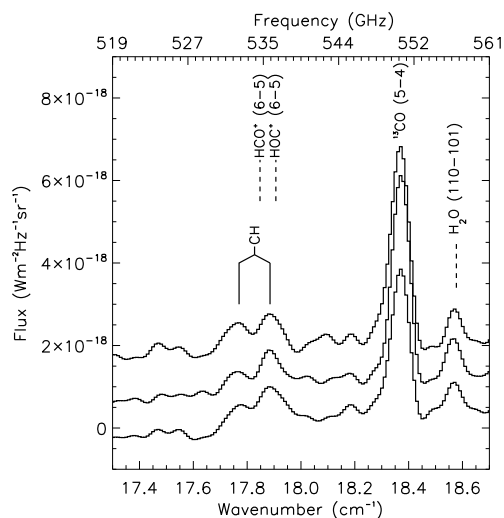
**Table 3.** Column densities along the cut

Position	<sup>13</sup> CO (10 <sup>15</sup> cm <sup>-2</sup> )	CH <sup>+</sup> (10 <sup>12</sup> cm <sup>-2</sup> )	CH(10 <sup>12</sup> cm <sup>-2</sup> )
A	1.2(85K) 1.3(200K) 5.6(50K)	2.2(85K) 3.8(200K) 1.9(50K)	
B	4.8(85K) 3.1(200K) 13.8(50K)	2.2(85K) 3.8(200K) 1.9(50K)	
C	67.4(85K) 43.5(200K) 191.7(50K)	6.4(85K) 11(200K) 5.5(50K)	≤ 4.5(85K) 8.4(200K) 3.6(50K)
D	6.7(85K) 4.3(200K) 19.1(50K)	2.0(85K) 1.7(50K)	

The angular size assumes a filled gaussian beam of 36'' at CO, CH<sup>+</sup> transition frequencies and 33.9'' at CH ones.

resolution of the spectra is 0.0724 cm<sup>-1</sup>, corresponding to about 780 km s<sup>-1</sup> for the considered CH<sup>+</sup> transition. Although the absorptions appear shallow, at the SPIRE/FTS resolution, a 5% absorption corresponds to a saturated line about 38 km s<sup>-1</sup> wide. This is consistent with the velocity dispersion of the foreground ISM as seen in HI absorption (e.g. Fish et al. 2003, Fig.1). This precludes us from deriving stringent column densities at this level of analysis.

In subsequent observations with the SPIRE FTS the CH<sup>+</sup> line has also been measured in the planetary nebula NGC7027 (Wesson et al. 2010) and in the ultra luminous infrared galaxy MRK231 (Van der Werf et al. 2010). The SPIRE FTS promises



**Fig. 4.** Continuum subtracted spectra of the 3 positions on the Orion bar, displaying a doublet as expected for CH.

to yield a harvest of methylidyne data from a wide variety of sources.

### 3. Conclusions

We have presented the first detection of the lowest rotational transition of the methylidyne cation CH<sup>+</sup> in an astronomical source. We have also shown strong evidence for the detection of the lambda doublet emission from the CH molecule. The detection of CH<sup>+</sup> in a variety of environments shows that spectral mapping of this and other species will provide a powerful probe of the physics of the interstellar medium. These results have only been made possible by the sensitivity and broad spectral coverage of the SPIRE FTS.

*Acknowledgements.* SPIRE has been developed by a consortium of institutes led by Cardiff Univ. (UK) and including Univ. Lethbridge (Canada); NAOC (China); CEA, LAM (France); IFSI, Univ. Padua (Italy); IAC (Spain); Stockholm Observatory (Sweden); Imperial College London, RAL, UCL-MSSL, UKATC, Univ. Sussex (UK); Caltech, JPL, NHSC, Univ. Colorado (USA). This development has been supported by national funding agencies: CSA (Canada); NAOC (China); CEA, CNRS, CNRS (France); ASI (Italy); MCINN (Spain); SNSB (Sweden); STFC (UK); and NASA (USA). DAN acknowledges support from NSERC. The authors thank Jacques LeBoufflot and Guillaume Pineau des Forêts for their assistance with the analysis/modeling of the Orion Bar.

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