

## **FIR/SUBMM SPECTROSCOPY WITH HERSCHEL: FIRST RESULTS FROM THE VNGS AND H-ATLAS SURVEYS**

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**Abstract.** The FIR/submm window is one of the least-studied regions of the electromagnetic spectrum, yet this wavelength range is absolutely crucial for understanding the physical processes and properties of the ISM in galaxies. The advent of the Herschel Space Observatory has opened up the entire FIR/submm window for spectroscopic studies. We present the first FIR/submm spectroscopic results on both nearby and distant galaxies obtained in the frame of two Herschel key programs: the Very Nearby Galaxies Survey and the Herschel ATLAS.

**Key words:** galaxies: ISM – infrared: galaxies – submillimeter: galaxies

### **1. INTRODUCTION**

The FIR/submm represents one of the least-studied regions of the electromagnetic spectrum, yet this wavelength range is absolutely crucial for understanding the physical processes and properties of the ISM in galaxies (see Tielens & Hollenbach 1985). One of the most fundamental issues in ISM studies is to address what factors control the heating and cooling processes in different phases of the ISM evolution. FIR/submm spectroscopy is a unique tool to answer this question, as the FIR/submm window contains important cooling lines of different phases of the ISM. The fine-structure line of singly ionized carbon [C II] at 158  $\mu\text{m}$  is the most important cooling line of the neutral ISM of normal star-forming galaxies. Other important atomic fine-structure lines include the [O I] lines at 63 and 145  $\mu\text{m}$  and the [C I] lines at 370 and 609  $\mu\text{m}$ . The FIR/submm window also contains a number of atomic fine-structure lines that trace ionized gas, such as the [N II] lines at

122 and 205  $\mu\text{m}$ , and the [O III] lines at 52 and 88  $\mu\text{m}$ . Finally, it contains a large variety of high- $J$  rotational transitions of different molecules, including CO, HCN,  $\text{HCO}^+$ ,  $\text{H}_2\text{O}$  and many others. The low- $J$  transitions (typically up to  $J = 4 - 3$ ) of many molecules can be observed with ground-based radio and submm telescopes, but they only trace the cooler gas and not the warmer gas that can dominate the cooling of the molecular ISM. The mid- to high- $J$  transitions, which are either difficult to observe or completely inaccessible from the ground, have a large span in critical densities, making them excellent tracers of the physical conditions of gas over a wide range in temperatures and densities. They are also excellent probes to distinguish between different energy sources responsible for the excitation of the gas, for example starbursts or AGN (e.g., Spaans & Meijerink 2008).

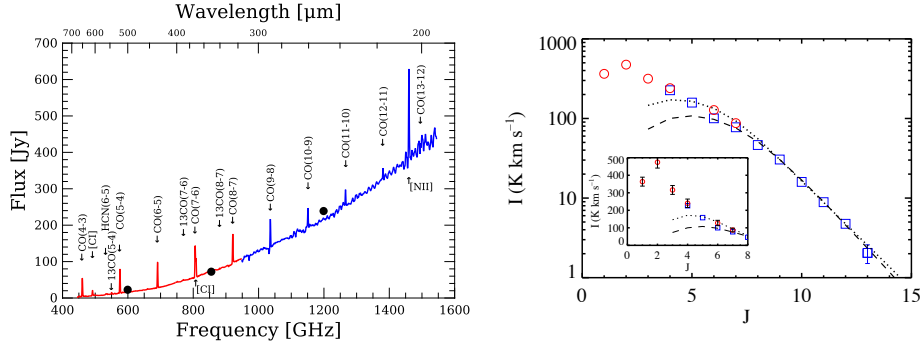
The main difficulty with FIR/submm spectroscopy is the fact that the earth atmosphere is almost completely opaque to FIR/submm radiation, such that these observations need to be performed from the stratosphere or from space. The first FIR spectroscopic observations were done with KAO, COBE and balloons in the 1980s and early 1990s. A major step forward was the launch of ISO with its LWS spectrograph, which made studies of large samples of galaxies of different types possible (e.g., Brauher et al. 2008). The wavelength region longwards of 200  $\mu\text{m}$  remained closed, however, until the advent in 2009 of the Herschel Space Observatory (Pilbratt et al. 2010). Herschel has three instruments onboard, which cover the FIR/submm wavelength region with unprecedented sensitivity and spatial resolution. PACS (Potglitsch et al. 2010) operates either as an imaging photometer or an integral field spectrometer over the spectral band from 55 to 210  $\mu\text{m}$ . SPIRE (Griffin et al. 2010) performs simultaneous imaging in three bands centered at 250, 350 and 500  $\mu\text{m}$ , and contains an imaging Fourier Transform Spectrometer (FTS) which covers simultaneously its whole operating range between 194 and 671  $\mu\text{m}$ . Finally, HIFI (de Graauw et al. 2010) is a high-resolution heterodyne spectrometer with a resolution up to  $10^7$  that can cover the wavelength region from 157 to 625  $\mu\text{m}$ .

In this paper, we present a number of recent FIR/submm spectroscopy results on both nearby and distant galaxies obtained in the frame of two Herschel key programs: the Very Nearby Galaxies Survey and the Herschel ATLAS. It should be noted that these results are just the first results, and that many more of them (both detailed studies on individual objects and more statistical studies on larger samples) are expected to come out in the next few years.

## 2. SPECTROSCOPY OF NEARBY GALAXIES

### 2.1. The Very Nearby Galaxies Survey

The Very Nearby Galaxy Survey (VNGS) is a Herschel Guaranteed Time Key Project focusing on twelve galaxies within 25 Mpc and the archetypal starburst galaxy Arp 220. The galaxies show a diverse range of masses and properties, from low-mass, late-type galaxies such as NGC 2403 to the radio galaxy Cen A. For all targets, a wealth of ancillary data at virtually all wavelengths are available. The design of the survey incorporates photometry and spectrometry with both PACS and SPIRE. The survey aims to gain a detailed understanding of the processes that regulate the ISM, and how these processes vary with the environment within different galaxies. The detailed study of these resolved galaxies will not only act as a benchmark for studies of more distant galaxies, but will also bridge the gap



**Fig. 1.** *Left:* Apodized spectrum of M82 corresponding to a  $43.4''$  beam. Filled circles show SPIRE fluxes measured in the same beam. *Right:* Comparison of the best fitting NLTE radiative transfer model (dotted line) with our CO line intensities. The model shown by a dashed line was obtained by using only  $J \geq 7 - 6$  CO lines. Open squares are the SPIRE FTS data, open circles are ground-based data from Ward et al. (2003). The inset highlights the deviations from models at the lower  $J$  end.

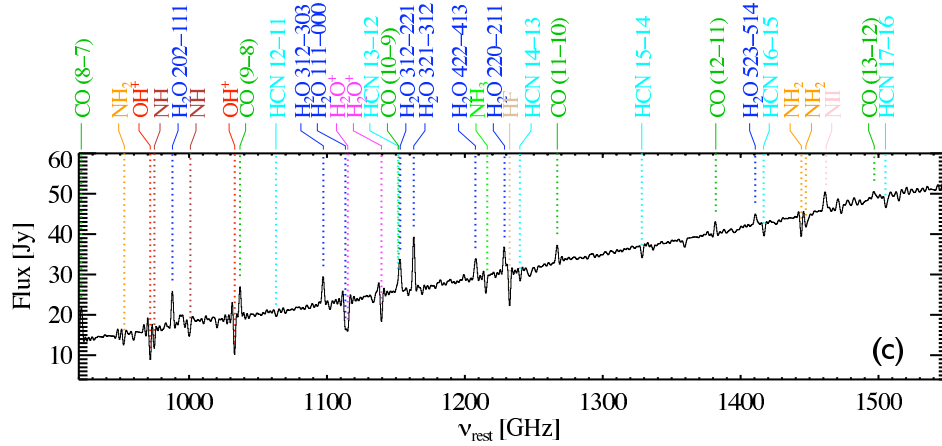
between surveys of distant objects and the extensive galactic surveys which have superior physical resolution but by their nature are limited to observations of one galaxy.

The first results from the VNGS were mainly photometric studies. These include the determination of the nature of dust heating in M81, M83 and NGC 2403 (Bendo et al. 2010, 2011), an attempt to separate Galactic cirrus emission from extragalactic dust emission in M81 (Davies et al. 2010), a study of the dust distribution and heating mechanisms in and around M82 (Roussel et al. 2010) and a detailed look at extragalactic dust clouds around the radio galaxy Cen A (Auld et al. 2011). Here we focus on two spectroscopic studies with the SPIRE FTS of two VNGS galaxies: the starburst galaxy M82 (Panuzzo et al. 2010) and the ULIRG Arp 220 (Rangwala et al. 2011).

## 2.2. The starburst galaxy M82

At a distance of 3.9 Mpc, M82 is the most well-studied starburst galaxy in the local universe, and it is widely used as a starburst prototype in cosmological studies. The ISM of this galaxy has been mapped using ground-based observations, in particular the lowest- $J$  CO rotational lines that provide constraints on the physical state of the cold molecular gas. With a molecular gas content of  $\sim 1.3 \times 10^9 M_\odot$  (Walter et al. 2002), it served as a perfect target for SPIRE FTS performance verification. M82 was observed in the high spectral resolution point-source mode, on 2009 September 21; the total integration time was 1332 s.

Figure 1 (left) shows the entire SPIRE FTS spectrum of M82, which displays a prominent CO emission-line ladder (from  $J = 4 - 3$  to  $J = 13 - 12$ ) along with several molecular lines from HCN and  $^{13}\text{CO}$ , and atomic fine-structure lines from [C I] and [N II]. The CO line intensities were modeled using the NLTE radiative transfer code RADEX (van der Tak et al. 2007). We generated a grid of models with different values in kinetic temperature, gas density and CO column density. Our modeling (Figure 1, right) strongly indicates that the observed CO emission is coming from very warm gas with a total mass of  $1.2 \times 10^7 M_\odot$  and a kinetic temperature of 540 K. Theoretical models predict that, at these temperatures,  $\text{H}_2$



**Fig. 2.** The spectrum of Arp 220 between 920 and 1550 GHz, corresponding to roughly half of the frequency range observed with SPIRE FTS. Different line identifications are indicated.

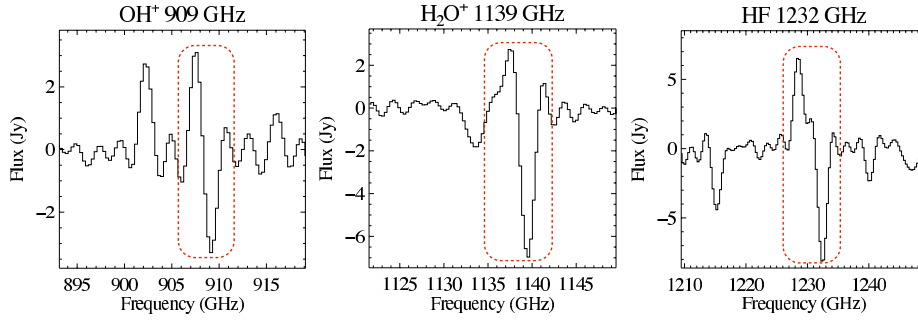
will be the dominant coolant compared to CO: in the case of M82, the SPIRE detected molecular gas is expected to radiate about  $3 \times 10^7 L_{\odot}$  in  $H_2$  lines. This is in good agreement with values derived from ISO and Spitzer MIR spectroscopy (Rigopoulou et al. 2002; Beirão et al. 2008).

The heating source of this warm molecular gas is not easy to uncover. A first possibility are UV-powered PDRs, but this can be disregarded as the observed CO lines in M82 are far too luminous compared to PDR models. Hard X-rays from an AGN have the potential for heating molecular gas in an XDR, but there is no strong evidence for an AGN in M82. Moreover, with a strong XDR component, such as seen in Mrk 231 (van der Werf et al. 2010), the spectral line energy distribution becomes flat at high  $J$  instead of decreasing as in M82. Another scenario is heating via the enhanced cosmic ray density generated by the high supernova rate in the nuclear starburst (Suchkov et al. 1993), but the energy input per mass in M82 is too low to match the observed cooling. The most probable heating mechanism is turbulence from stellar winds and supernovae. A large velocity gradient is required in order to reach the observed cooling rate of  $2.6 L_{\odot}/M_{\odot}$ , but given the powerful stellar winds in the M82 starburst, this may not be unreasonable.

### 2.3. The ULIRG Arp 220

Arp 220 is the nearest Ultra Luminous Infrared galaxy (ULIRG) at a distance of about 77 Mpc. It is one of the most popular templates for studies of high- $z$  dusty galaxies. It has two merging nuclei separated by  $\sim 1$  arcsec, and together they have a large reservoir of molecular gas ( $\sim 10^{10} M_{\odot}$ ). Arp 220 has been observed extensively over the years across the electromagnetic spectrum. The extreme star formation environment in this galaxy provides an excellent laboratory to understand the processes affecting star formation and possibly AGN feedback.

Arp 220 was observed with the SPIRE FTS in the high spectral resolution, single pointing mode on 2010 February 13. The total on-source integration time was 10 445 seconds. The spectrum (Figure 2) shows the far-infrared (FIR) continuum and the detection of several key molecular and atomic species. We detect



**Fig. 3.** P-Cygni profiles detected in  $\text{OH}^+$ ,  $\text{H}_2\text{O}^+$  and HF lines, suggesting molecular outflow in Arp 220.

a luminous CO emission ladder from  $J = 4 - 3$  to  $J = 13 - 12$  and several water transitions with total water luminosity comparable to CO. In addition to the emission line features, the spectrum also shows several absorption features. Most surprising are the detections of five very high- $J$  HCN lines in absorption; their low- $J$  transitions are detected in emission with ground-based observatories (Greve et al. 2009). Such high- $J$  transitions of HCN have never been detected before in external galaxies, in emission or absorption. Strong absorption lines are also detected from hydrides, including three transitions of  $\text{OH}^+$ , one of  $\text{CH}^+$  and four of  $\text{H}_2\text{O}^+$ . The detections of  $\text{OH}^+$  and  $\text{H}_2\text{O}^+$  are very important in Arp 220 for modeling the water transitions because they are the major intermediaries in the ion-neutral chemistry network producing water in the ISM, and their detection is very difficult from current ground-based observatories.

We again used RADEX to interpret the CO spectral line energy distribution. Our modeling strongly indicates that the mid- $J$  to high- $J$  CO lines are tracing warm molecular gas with a kinetic temperature of about 1350 K, whereas the low- $J$  transitions are tracing cold gas at about 50 K. The mass of the warm gas is about 10% of the cold molecular gas but dominates the luminosity as well as the cooling over the cold CO. The temperature of the warm molecular gas is in excellent agreement with the temperature derived from  $\text{H}_2$  rotational lines observed from Spitzer, implying that CO is still a good tracer of  $\text{H}_2$  at these high temperatures. Similar as for M82, we can rule out PDRs, XDRs and cosmic rays as possible sources of this warm molecular gas. The mechanical energy from supernovae and stellar winds can satisfy the energy budget required to heat this gas but we still do not know the exact mechanism that heats this gas. We also used NLTE modeling to interpret the HCN spectral line energy distribution. The transitions from emission to absorption takes places somewhere between  $J = 4 - 5$  and  $J = 12 - 11$ . These high- $J$  lines are populated via infrared pumping of photons at  $14 \mu\text{m}$ . The condition for infrared pumping to populate  $J = 17 - 16$  level requires an intense radiation field with  $T > 350$  K.

One of the most striking results from the SPIRE FTS data is the detection of a massive molecular outflow, that could be driven by a hidden AGN or starburst activity in Arp 220. Observations of massive molecular outflows in galaxies can significantly improve our understanding of the connection between AGN/starbursts-feedback and galaxy evolution. It is believed that the energy injection from an AGN or starbursts can quench star formation by expelling the molecular gas out of the galaxy, transforming gas-rich blue galaxies to gas-poor red galaxies. However,

the evidence for massive molecular outflows had been missing, until recently, when it was discovered in Mrk 231 and NGC 1266. The signature of a molecular outflow in Arp 220 was seen in the P-Cygni profiles of  $\text{OH}^+$ ,  $\text{H}_2\text{O}^+$  and  $\text{H}_2\text{O}$  (Figure 3). Unfortunately our FTS spectra could not fully resolve this outflow and we were only able to provide a lower limit on the mass of the outflow ( $\sim 10^7 M_\odot$ ) and an upper limit on the velocity ( $\sim 250 \text{ km s}^{-1}$ ). A high resolution follow-up with HIFI and ALMA is required to accurately characterize this outflow.

### 3. SPECTROSCOPY OF GRAVITATIONALLY LENSED HIGH- $z$ GALAXIES

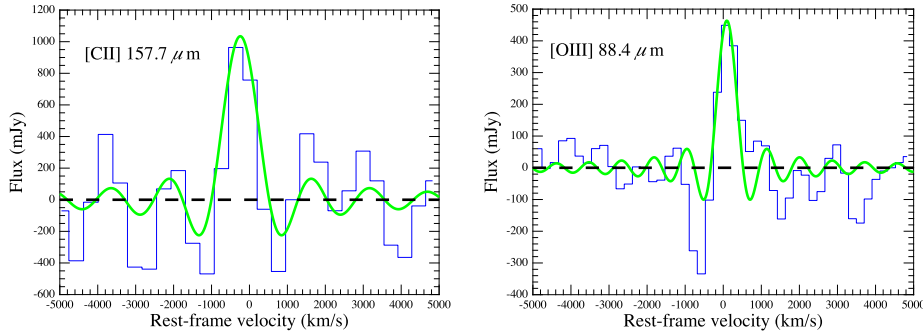
#### 3.1. The H-ATLAS survey

The Herschel ATLAS (H-ATLAS, Eales et al. 2010) is the largest open-time key project that will be carried out on the Herschel Space Observatory. It is surveying  $570 \text{ deg}^2$  of the extragalactic sky, 4 times larger than all the other Herschel extragalactic surveys combined, in five FIR/submm continuum bands. The main scientific goal of the H-ATLAS is to provide measurements of the dust masses and dust-obscured star formation for tens of thousands of nearby galaxies, the FIR/submm equivalent to the SDSS photometric survey. However, the H-ATLAS has many other science goals, ranging from studying cirrus and debris discs in our own Milky Way (Thompson et al. 2010; Bracco et al. 2011) and detailed studies of nearby galaxies (Baes et al. 2010) to cosmological studies (Maddox et al. 2010; Clements et al. 2010).

One of the most fascinating results of H-ATLAS is the detection of a significant number of gravitationally lensed objects in the distant ( $z > 2$ ) Universe. This is possible in such a shallow but large area survey because of the combined effects of a strong negative K-correction and steep number counts in the SPIRE  $500 \mu\text{m}$  waveband. Objects brighter than  $100 \text{ mJy}$  at  $500 \mu\text{m}$  will be a mixture of lensed high-redshift galaxies, nearby galaxies and flat-spectrum radio sources, and current models predict that H-ATLAS will detect some 350 strongly lensed objects at  $500 \mu\text{m}$  at  $z > 1$  (Negrello et al. 2007; Eales et al. 2010). High- $z$ , bright submm galaxies open a new possibility for the detailed study of the physical conditions of the interstellar medium, at restframe FIR/submm wavelengths: the important atomic emission lines shift towards submm wavelengths where they can be observed with SPIRE FTS, whereas the high- $J$  molecular lines, particularly the CO lines, shift towards radio wavelengths, where they can be observed with ground-based radio interferometers. The H-ATLAS consortium has set up a substantial programme of follow-up observations of candidate gravitational lenses, using both ground-based telescopes (IRAM, EVLA, SMA, GBT, Keck, ...) and space missions (Herschel, Spitzer, HST).

#### 3.2. The gravitationally lensed submm galaxy SDP.81

One of the best-studied H-ATLAS gravitational lenses so far is H-ATLAS J090311.6+003906 (SDP.81), detected first in the H-ATLAS Science Demonstration Phase field. A combination of radio and optical spectra shows that this source is a submm galaxy at  $z = 3.04$ , lensed by an elliptical galaxy at  $z = 0.30$  (Negrello et al. 2010; Frayer et al. 2011). SMA imaging reveals the submm morphology, consistent with a lensing event, with multiple peaks distributed around the position of the foreground elliptical galaxy (Negrello et al. 2010). Detailed lens modeling based on multi-wavelength data, including deep Keck and Spitzer imaging, re-



**Fig. 4.** Continuum subtracted regions around the [C II] 157.7  $\mu\text{m}$  (left) and [O III] 88.4  $\mu\text{m}$  (right) lines of SDP.81. The SPIRE FTS data are shown as a histogram and the best fit sinc function is also shown as the solid line.

vealed that the magnification factor is  $25 \pm 7$ , and that the submm galaxy has a high dust obscuration ( $A_V \sim 4.4$ ) and a star formation rate of  $\sim 75 M_\odot \text{yr}^{-1}$  (Hopwood et al. 2011).

In order to study its ISM, we observed SDP.81 with the EVLA and SPIRE FTS on 2010 July 17-18 and 2010 June 1, respectively (Valtchanov et al. 2011). The most prominent features in the FTS spectrum of SDP.81 are the [O III] 88  $\mu\text{m}$  and [C II] 158  $\mu\text{m}$  lines (Figure 4). The EVLA observations reveal a clear detection of the CO(1-0) line, which is redshifted to 28.53 GHz, into the EVLA's new Ka-band receivers. The line intensities of these lines, combined with the continuum fluxes, were analysed using the PDR models of Kaufman et al. (1999). The best fitting models indicate a PDR cloud-ensemble density  $n \approx 2000 \text{ cm}^{-3}$  and a far-UV ionizing field strength  $G_0 \sim 200$ . These characteristics are similar to other high- $z$  star-forming galaxies. The radio observations provide supporting evidence to the hints from the ISM lines, that part the ionization field in the galaxy may be due to an AGN.

#### 4. SUMMARY AND CONCLUSIONS

The FIR/submm domain is a fascinating region to study the physics of the ISM, as it contains a large variety of tracers of both dust emission and the different gas phases. The launch of the Herschel Space Observatory has finally opened up this region for systematic spectroscopic studies. We have presented a number of new spectroscopic results obtained with Herschel in the frame of the VNGS and H-ATLAS key programmes. Concerning nearby galaxies, we have presented, based on an impressive CO ladder, the detection of warm and dense molecular gas in M82 and Arp 220, probably heated by mechanical energy from the starburst. Moreover, in Arp 220, we have detected many molecular species (including hydrides) which support the evidence for a hidden AGN, and we have interpreted the observed P-Cygni profiles in various molecular lines as a massive molecular outflow. Concerning distant submm galaxies, we have discussed the case of SDP.81, a submm galaxy at  $z = 3.04$  lensed by a foreground elliptical with a magnification of about 25. We have presented SPIRE FTS and radio spectroscopy of this lensed submm galaxy and demonstrated that these measurements are unique probes of the ISM of high- $z$  galaxies. The results we presented are just the first results obtained in

the frame of the VNGS and H-ATLAS surveys, and many more results (both detailed studies on individual objects and more statistical studies on larger samples) are expected to come out in the next few years.

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