Herschel: the first science highlights

LETTER TO THE EDITOR

Herschel observations of FIR emission lines in brightest cluster galaxies[*]

A. C. Edge[1], J. B. R. Oonk[2], R. Mittal[3], S. W. Allen[4], S. A. Baum[3], H. Böhringer[5], J. N. Bregman[6], M. N. Bremer[7], F. Combes[8], C. S. Crawford[9], M. Donahue[10], E. Egami[11], A. C. Fabian[9], G. J. Ferland[12], S. L. Hamer[1], N. A. Hatch[13], W. Jaffe[2], R. M. Johnstone[9], B. R. McNamara[14], C. P. O'Dea[15], P. Popesso[5], A. C. Quillen[16], P. Salomé[8], C. L. Sarazin[17], G. M. Voit[10], R. J. Wilman[18], and M. W. Wise[19]

[1] Institute for Computational Cosmology, Department of Physics, Durham University, Durham, DH1 3LE, UK
   e-mail: alastair.edge@durham.ac.uk
[2] Leiden Observatory, Leiden University, PB 9513, Leiden 2300 RA, The Netherlands
[3] Chester F. Carlson Center for Imaging Science, Rochester Institute of Technology, Rochester, NY 14623, USA
[4] Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, 452 Lomita Mall, Stanford, CA 94305-4085, USA
[5] Max-Planck-Institut für extraterrestrische Physik, 85748 Garching, Germany
[6] University of Michigan, Dept. of Astronomy, Ann Arbor, MI 48109, USA
[7] H H Wills Physics Laboratory, Tyndall Avenue, Bristol BS8 1TL, UK
[8] Observatoire de Paris, LERMA, CNRS, 61 Av. de l'Observatoire, 75014 Paris, France
[9] Institute of Astronomy, Madingley Rd., Cambridge, CB3 0HA, UK
[10] Michigan State University, Physics and Astronomy Dept., East Lansing, MI 48824-2320, USA
[11] Steward Observatory, University of Arizona, 933 N. Cherry Avenue, Tucson, AZ 85721, USA
[12] Department of Physics, University of Kentucky, Lexington KY 40506, USA
[13] School of Physics and Astronomy, University of Nottingham, University Park, Nottingham NG7 2RD, UK
[14] Department of Physics & Astronomy, University of Waterloo, 200 University Avenue West, Waterloo, Ontario, N2L 3G1, Canada
[15] Department of Physics, Rochester Institute of Technology, 84 Lomb Memorial Drive, Rochester, NY 14623-5603, USA
[16] Department of Physics and Astronomy, University of Rochester, Rochester, NY 14627, USA
[17] Department of Astronomy, University of Virginia, PO Box 400325, Charlottesville, VA 22904-4325, USA
[18] School of Physics, University of Melbourne, Victoria 3010, Australia
[19] ASTRON, Netherlands Institute for Radio Astronomy, PO Box 2, 7990 AA Dwingeloo, The Netherlands

ABSTRACT

The question of how much gas cools in the cores of clusters of galaxies has been the focus of many, multiwavelength studies in the past 30 years. In this letter we present the first detections of the strongest atomic cooling lines, [CII], [OI] and [NII] in two strong cooling flow clusters, A1068 and A2597, using *Herschel*-PACS. These spectra indicate that the substantial mass of cold molecular gas ($>10^9\,M_\odot$) known to be present in these systems is being irradiated by intense UV radiation, most probably from young stars. The line widths of these FIR lines indicate that they share dynamics similar but not identical to other ionised and molecular gas traced by optical, near-infrared and CO lines. The relative brightness of the FIR lines compared to CO and FIR luminosity is consistent with other star-forming galaxies indicating that the properties of the molecular gas clouds in cluster cores and the stars they form are not unusual. These results provide additional evidence for a reservoir of cold gas that is fed by the cooling of gas in the cores of the most compact clusters and provide important diagnostics of the temperature and density of the dense clouds this gas resides in.

Key words. galaxies: clusters: intracluster medium – galaxies: elliptical and lenticular, cD

1. Introduction

The cooling process at the cores of galaxy clusters is highly complex: recent *XMM-Newton* and *Chandra* observations indicate that the cooling rates are reduced by an order of magnitude below the simple cooling flow models at temperatures below $\sim 2 \times 10^7$ K (Peterson & Fabian 2006). These X-ray observations, when linked with the detection of radio jet inflated bubbles in the

cores of many of the strongest cooling flows (see McNamara & Nulsen 2007, for a review), suggest that the strong suppression of gas cooling is related to energy injection into the intracluster medium by the action of jets and related AGN activity.

The detection of substantial masses of molecular gas in the cores of the most rapidly cooling clusters through CO lines (Edge 2001; Salomé & Combes 2003) and warm H_2 molecular lines in the NIR and MIR (Jaffe & Bremer 1997; Egami et al. 2006) indicates that not all cooling is suppressed and this cooled gas may provide the fuel for future AGN activity. These tracers of molecular gas appear to correlate with the strength of optical

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lines from ionised gas (Crawford et al. 1999; Edge 2001) and the dust continuum at MIR and sub-mm wavelengths (O'Dea et al. 2008). However, the excitation of these various emission lines and the relative importance of energy input from star formation, AGN, cosmic rays and/or the intracluster medium is poorly constrained (Ferland et al. 2009).

One as yet unexplored diagnostic of the properties of the cold gas are the atomic cooling lines found in the FIR, [CII], [OI] and [NII]. The unprecedented sensitivity of *Herschel* (Pilbratt et al. 2010) to FIR line emission offers the opportunity to assess the ionisation and density of the colder gas for the first time with the [CII] line and two principle [OI] lines. The authors were awarded 140 h of time in an open time key program (PI Edge) to investigate the FIR line and continuum properties of a sample of 11 brightest cluster galaxies (BCGs) in well-studied cooling flow clusters selected on the basis of optical emission line and X-ray properties. The full goals of the project are to observe at least five atomic cooling lines for each object that cover a range in density and temperature behaviour and obtain a fully sampled FIR spectral energy distribution for systems where significant star formation is expected. In this paper we present the Photodetector Array Camera and Spectrometer (PACS, Poglitsch et al. 2010) spectroscopy for the two targets observed in the science demonstration phase (SDP), Abell 1068 ($z = 0.1386$) and Abell 2597 ($z = 0.0821$). In a parallel paper (Edge et al. 2010), we present the FIR photometry for these clusters.

The two clusters observed have quite contrasting multiwavelength properties. A1068 is a strong MIR source (O'Dea et al. 2008) with a bright CO detection (Edge 2001) but a weak radio source (McNamara et al. 2004). A1068 lies just below the luminosity threshold of a ULIRG ($10^{12} L_\odot$) and exhibits some contribution from an AGN (Crawford et al. 1999; O'Dea et al. 2008). On the other hand, A2597 is a relatively weak MIR source (Donahue et al. 2007) with a weak CO detection (Salomé, priv. comm.) but a powerful radio source (Sarazin et al. 1995). The implied FIR luminosity of A2597 of $8.8 \times 10^9 L_\odot$ is a factor of around 30 below that of A1068 ($3.5 \times 10^{11} L_\odot$) and, in addition, the fractional contribution from an AGN in the MIR is also lower.

2. Observations

We have observed the [CII] and [OI] lines at 157.74 μm and 63.18 μm for A1068 and A2597 with the PACS spectrometer on *Herschel*. These are the primary cooling lines of the cold gas at a temperature $T < 40$ K (Kaufman et al. 1999). In addition for A2597 we observed the [NII], [OI] and [OIII] lines at 121.90 μm, 145.52 μm and 88.36 μm. These lines are used to constrain the excitation and temperature of this gas. Table 1 gives a summary of the observations.

All spectral line observations were taken in *PACS chopped line scan (standard faint line)* mode with chopping-nodding. The *simple pointed observations* mode was used for all observations. The data were reduced following the PACS data reduction guide (PDRG) using the PACS line spectroscopy script for point source chop/nod mode as presented by the PACS ICC team during the *Herschel* science demonstration phase data processing workshop at ESAC in december 2009. The reduction was performed within the *Herschel* Interactive Processing Environment (HIPE) version 2.0.0 (Ott 2010), build RC 3. We have processed the data from level 0 (raw channel data) to level 2 (calibrated spectra) in a number of steps as outlined in the PDRG. Level 0 to 1.0 processing removes the telescope specific structures from the data. The slopes of the raw channel data are fitted and removed. The

signal is converted from data units to volts per second. Sky coordinate information is added and bad pixels and glitches are removed from data. The data is flatfielded and flux calibrated by applying the ground based nominal response function as recommended in the PACS spectroscopy performance and calibration (PSPC) document. This ground based response calibration is known to yield overestimated fluxes and following the PSPC we divide our fluxes by 1.3 and 1.1 in the blue and red bands. The accuracy of this flux calibration for the PACS spectrometer, at the time of writing, is about 50 percent within a given spectral band (PSPC).

During the final stage of the reduction, level 1.0 to 2.0, the data are spectrally and spatially rebinned into a $5 \times 5 \times$ lambda cube. Using the standard 5×5 spatial rebinning each spatial pixel (spaxel) has a projected size of $9.4'' \times 9.4''$ on the sky. The spectral rebinning is performed using the recommended weak line density i.e. oversamp=1 and upsamp=4. Values between 1 and 10 were tried for the upsamp and oversamp parameters to test the robustness of the line profiles. We find that the line profiles do not change significantly for this range in values.

3. Results

The [CII] 157 μm and [OI] 63 μm lines are detected at a signal to noise greater than 30 for both A1068 and A2597. The much weaker [NII] 122 μm and [OIb] 145 μm lines are detected at the $3-5\sigma$ level for A2597. The [OIII] 88 μm line was not detected in A2597, an upper limit for this line is given in Table 2.

The line spectra are fitted by a model consisting of; (i) a linear function to determine the continuum flux, and (ii) a single Gaussian function to determine the line flux. Continuum subtracted line spectra are shown for the central spaxel in Fig. 1 for A1068 and Fig. 2 for A2597. The fitted line centers agree well with the redshift of CO in the BCG and the fitted *FWHM* line widths indicate gas with velocities of $300-500$ km s^{-1}.

The [CII] and [NII] lines in the central spaxel of both objects are well described by a single Gaussian. However, the [OI] 63 μm lines, where the PACS spectral resolution is best, have profiles indicative of weak ($2-3\sigma$) deviations from a single Gaussian function. The [OI] line in A1068 hints at a two-component structure in the form of a narrow core component on top of a broad underlying component comparable to the CO(2−1) profile in Edge (2001). Both [OI] lines observed in A2597 appear to have their dominant flux component at the systemic redshift of the BCG and a weaker component offset by about +250 km s^{-1} which is also seen in the CO data (Salomé, priv. comm.). We attribute the shared structure of these atomic and molecular lines to gas kinematics rather than self-absorption as the observed emission is from a large number of clouds that have much narrower intrinsic line width.

The resolution of PACS at the observed wavelengths varies from about $5''$ for the [OI] 63 μm line to about $14''$ for the [CII] 157 μm line. We have investigated line emission in all 25 spaxels of the PACS FoV. In all cases the line flux is dominated by the central spaxel. Summing up the flux in all 25 spectra and comparing it to the flux in the central spaxel shows no evidence of excess line flux as compared to what is expected from a point source. In order to properly recover the full beam line fluxes we have applied point source corrections (Appendix A of the PSPC document) to the central spaxel integrated line fluxes. The results are listed in Table 2. This spatial resolution matches the best sub-mm interferometry results for CO (Edge & Frayer 2003; Salomé & Combes 2004) which implies that most of the

Table 1. Log of *Herschel*-PACS observations.

Cluster	Redshift	Line	Wavelength (μm)	Obsid	Bandwidth (km s^{-1})	Resolution (km s^{-1})	Beam Size
A1068	0.1386	[CII]	179.61	1 342 186 308	1200	201	13.5″/33 kpc
		[OI]	71.94	1 342 186 307	600	55	5.4″/13 kpc
A2597	0.0821	[CII]	170.78	1 342 187 125	1100	218	12.8″/20 kpc
		[OI]	68.41	1 342 187 124	550	68	5.1″/7.8 kpc
		[NII]	131.94	1 342 188 942	1200	281	9.9″/15 kpc
		[OIb]	157.56	1 342 188 704	1200	241	11.8″/18 kpc
		[OIII]	95.61	1 342 188 703		108	7.2″/11 kpc

Table 2. Spectral line results for *Herschel*-PACS observations.

Cluster	Redshift	Line	Integrated Line Flux (10^{-18} W m^{-2})	Velocity offset (km s^{-1})	measured *FWHM* (km s^{-1})	instrinsic *FWHM* (km s^{-1})
A1068	0.1386	[CII]	104.7 ± 1.8	$+25 \pm 55$	378 ± 40	320 ± 55
		[OI]	64.8 ± 0.2	$+25 \pm 50$	356 ± 40	352 ± 55
A2597	0.0821	[CII]	58.5 ± 1.9	$+15 \pm 60$	463 ± 40	408 ± 55
		[OI]	54.7 ± 0.2	$+40 \pm 55$	411 ± 40	405 ± 55
		[NII]	3.8 ± 1.3	$+30 \pm 60$	578 ± 90	505 ± 110
		[OIb]	3.3 ± 1.3	-57 ± 65	484 ± 90	420 ± 110
		[OIII]	<2.9	$-$	$-$	$-$
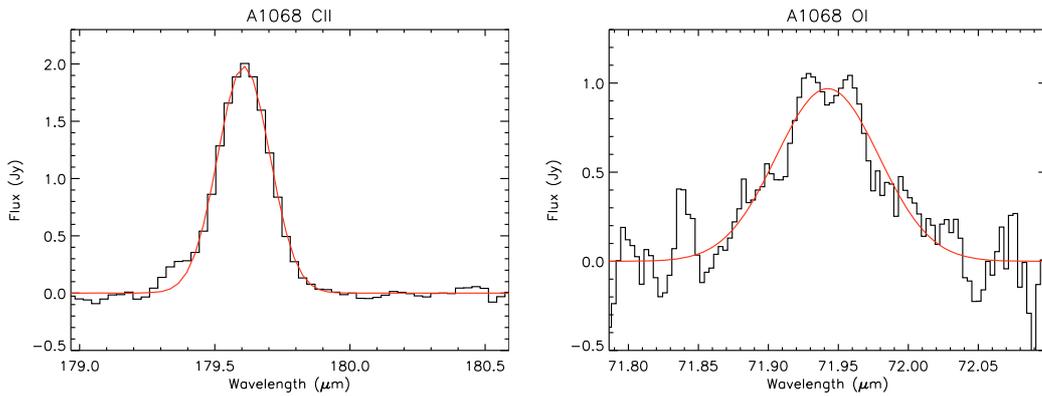
Fig. 1. *Herschel*-PACS spectra of [CII] and [OI] in A1068.

emission is on scales <5″ so we believe our PACS line fluxes can be compared to literature values without large beam corrections.

4. Discussion

The primary result from the SDP observations for this project is that the atomic cooling lines are present in both observed clusters. This first detection of these lines in cluster cores reinforces the importance of the cold gas in these environments. However, there are a number of questions that these detections raise.

How do the properties of the FIR lines compare to local LIRGs/ULIRGs? There have been several studies of local galaxies with ISO and high redshift galaxies using ground-based instrument that cover [CII] and [OI] (Malhotra et al. 1997; Maiolino et al. 2005; Hailey-Dunsheath et al. 2010). These studies show that the ratio of [CII] to FIR luminosity is a function of luminosity with relatively less [CII] emission for the most FIR luminous sources. Using the FIR data from Edge et al. (2010), we calculate the [CII] to FIR luminosity ratios are $10^{-2.4}$ and $10^{-1.9}$ for A1068 and A2597, respectively. The [CII]/FIR ratios of these two galaxies are comparable to those measured for galaxies of similar $L_{\rm FIR}$ (see Fig. 2 of Maiolino et al. 2005). In particular, the [CII] to FIR luminosity ratio is lower for the

more FIR luminous of the two galaxies. The ratio of [CII] to [OI] shows less variation (1.62 and 1.07) and is again consistent with other comparable galaxies (Luhman et al. 2003). Also our CO(1−0) to FIR luminosity ratios of $10^{-5.7}$ and $10^{-5.6}$ for A1068 and A2597 are consistent with star-forming local galaxies (Malhotra et al. 1997). So, despite potential differences in excitation, pressure and metallicity, the relative intensity of the atomic and molecular lines to the FIR luminosity do not distinguish the BCGs studied here from other FIR bright galaxies.

How do the dynamics of atomic and molecular lines compare? The relative velocity width of the atomic lines compared to the CO and MIR H$_2$ lines can provide important diagnostics for the dynamics and energetics of the various gas tracers. From the line width alone the resolution corrected line *FWHM* widths for the [CII] and [OI] lines are ≈330 km s^{-1} and ≈400 km s^{-1} for A1068 and A2597 respectively. This compares to 243 ± 13 km s^{-1} (Edge 2001) and 292 ± 45 km s^{-1} (Salomé, priv. comm.) for CO(2−1) for A1068 and A2597. In each case the FIR lines are a factor of ∼1.35 broader. This is not due to any instrumental broadening in the PACS instrument as the two lines sampled have similar intrinsic line width despite being observed at very different resolution. Instead, this difference is more likely to be related to the lines being emitted from different regions
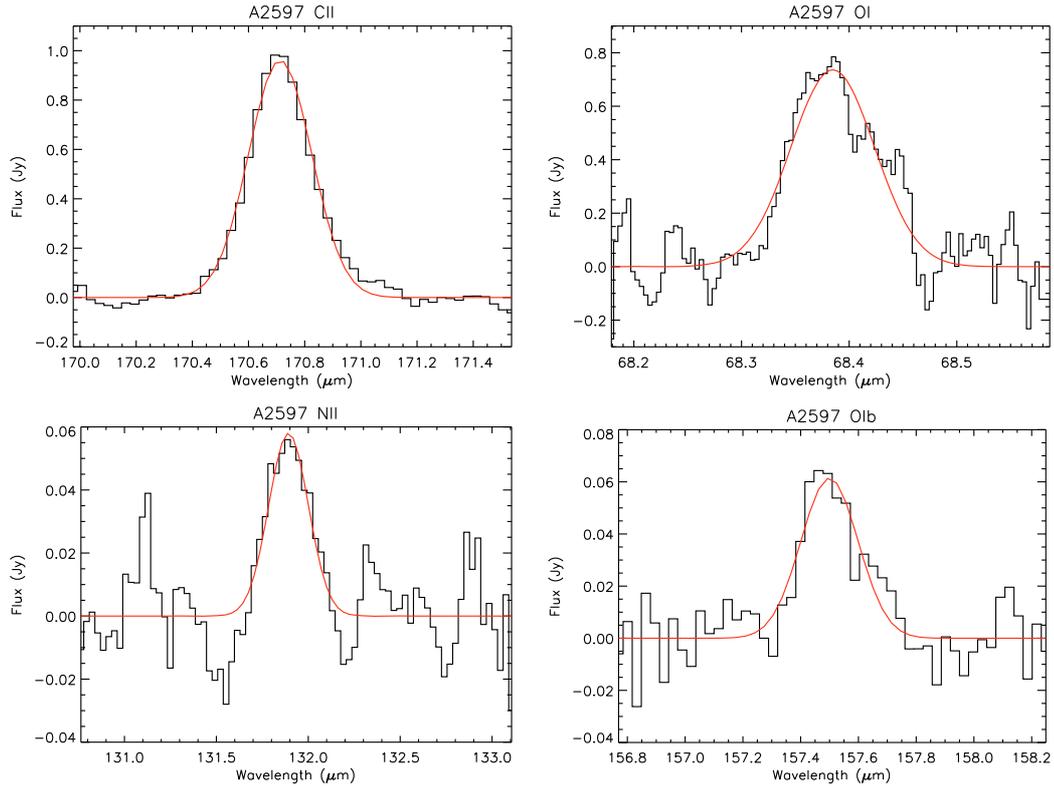
Fig. 2. *Herschel*-PACS spectra of [CII], [OI] (63 μm), [NII] and [OIb] (145 μm) in A2597.

within the BCG or in shocks. However, this clearly needs to be tested in more systems and through direct comparison of the [CII] and [OI] extent with that of CO.

How do the FIR line ratios constrain the gas properties? The relative strength of the FIR lines can constrain several key properties of the gas phase that dominates the emission. The main constraint we can determine directly from our current data is from the [CII] 158 μm and [OI] 63 and 145 μm lines for A2597. Kaufman et al. ([1999]) present photodissociation region (PDR) model predictions for the [OI] 145 μm/63 μm and [CII] 158 μm to [OI] 63 μm line ratios. Combining these two constraints for our observed [OI] 145 μm/63 μm ratio of 0.06 ± 0.02 and [OI] 63 μm to [CII] 158 μm ratio of 0.94 ± 0.05, we estimate a density of $10^{3.3 \pm 0.5}$ cm^{-3} and an incident FUV flux of G_0 of 150−1000 Habing units. These values of G_0 imply intrinsic FUV luminosities of ≈ 2−5×10^{43} erg s^{-1} if the clouds subtend 3−5 kpc. This is comparable to the observed FUV luminosities of these galaxies once dust absorption is taken into account (O'Dea et al. [2004]).

5. Conclusions

These initial results from *Herschel* indicate that atomic cooling lines are present in the brightest cluster galaxies in cooling flow clusters. The intensity and velocity width of these lines is consistent with all the other observed tracers of cold gas in these systems implying they originate from the same population of clouds. The only apparent exception to this in our current observations is that the FIR lines appear to be systematically broader than the CO lines impling that the *relative* intensity of these lines varies with position within the BCG. The results that will come from our open time key project for 11 BCGs will expand greatly on those presented here with more lines and a greater

range of BCG properties. Beyond this, the potential for *Herschel* to illuminate the properties of the cold gas that may fuel cold nuclear accretion in more distant clusters and local groups is vast.

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