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EXTREME [CII] LINE COOLING IN RADIO-GALAXIES: A SIGNATURE OF TURBULENT DISSIPATION IN ACTIVE GALACTIC NUCLEI?

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Abstract. Observations by the *Spitzer Space Telescope* have revealed a population of radio galaxies with enhanced infrared molecular hydrogen (H_2) line cooling, above that expected by star formation heating alone. We present *Herschel* observations of these galaxies, which show unusually powerful [CII]$\lambda 158\mu$m line emission of very broad line-width. The C^+/PAH and C^+/FIR flux ratios are found to be extremely large, in most cases greatly in excess of that expected by photoelectric heating of the gas, and comparable in power to the mid-infrared H_2 lines. In contrast, [OI] emission is found to be quite weak. We show that the [CII] line emission mostly traces the molecular gas, and that a very large fraction of this gas is diffuse and warm. We also briefly discuss the possible heating sources of the gas (turbulent heating and/or cosmic rays). These results have profound consequences on our interpretation of FIR cooling lines at high-redshifts and on our understanding of dissipation of energy, feedback and energetics of galaxy formation in general. The fact that C^+ and H_2 can be strongly enhanced in shocks and turbulent systems in general will be of great importance for ALMA (and perhaps SPICA) observations which will extend *Herschel* observations to much higher redshifts, where the proportion of turbulently-heated molecular gas may be more important.

Keywords: AGN feedback, radio-galaxies, 3C 326, turbulence, interstellar medium, molecular gas

1 Introduction: what is the efficiency of AGN feedback at low redshifts?

AGN feedback is now widely postulated to regulate galaxy growth over cosmic time (e.g. Springel et al. 2005), in particular to reconcile the predicted mass functions with observations (Benson et al. 2003) showing that most massive local galaxies have old stellar populations (e.g. Thomas et al. 2005; Croton et al. 2006). At high redshifts, AGN-driven winds are invoked to clear out the reservoir of cold molecular gas, which quenches the starburst associated with the early phase of massive galaxy formation (e.g. Silk & Rees 1998; Nesvadba et al. 2006). At lower redshifts, AGN feedback is also needed to complement starburst-driven feedback in order to heat the gas over long timescales, thus regulating star formation and limit gas accretion (e.g. Begelman & Cioffi 1989).

The energy released by the central supermassive black hole is in principle enough to balance the gas cooling and remove the gas from the dark matter halo of a galaxy. However, it is not clear what is the efficiency of this process. What fraction of the AGN energy goes into: (1) the heating of the X-ray emitting cocoon of tenuous gas? (2) the heating of the cold molecular gas? (3) the driving of mass-loaded outflows? What is the dynamical coupling efficiency of the AGN mechanical energy to the different phases of the host interstellar medium (ISM)? These are the questions we are trying to address with detailed observations of low-redshift radio-galaxies.

2 Herschel observations of powerful, turbulent radio-galaxies

Local radio-loud galaxies are ideal candidates to study how the AGN energy is dissipated and distributed amongst the gas phases since we can estimate the mechanical energy of their jets with a relatively good accuracy, and the spatial scale over which this energy is deposited (which can reach Mpc scales, e.g. Machalski et al. 2008).

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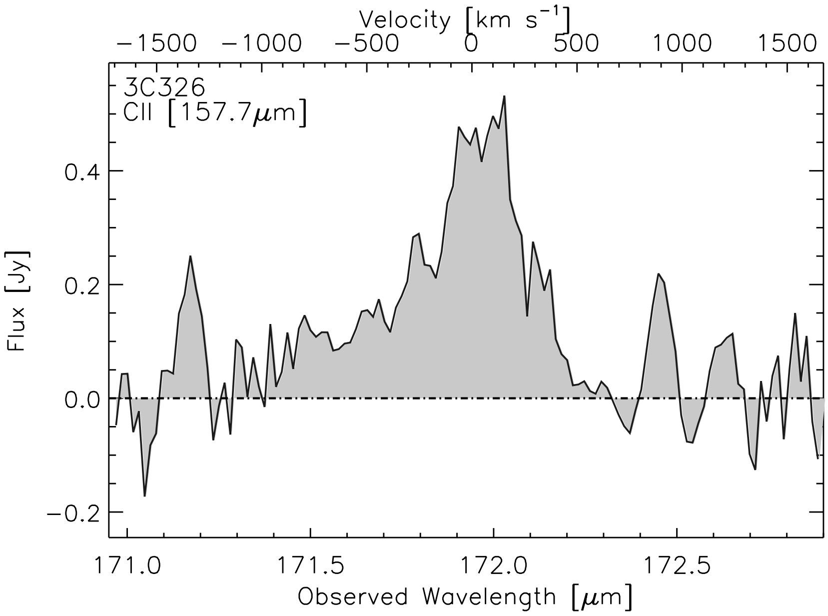

Fig. 1. [CII]λ158 spectrum in 3C326 N observed with *Herschel/PACS* (from Guillard et al. 2013a). The total line flux is 1.2×10^{-17} W m^{-2}, corresponding to a line luminosity of 6.2×10^{7} L$_\odot$ for a redshift of $z = 0.0895$. A clear blue-shifted broad wing is detected, with a velocity shift of -445 km s^{-1} with respect to the narrower component (after Gaussian decomposition).

We observed the [CII]λ158μm and [OI]λ63μm lines with the PACS far-infrared spectrometer (Poglitsch et al. 2010) onboard the *Herschel* Space Observatory (Pilbratt et al. 2010) in a sample of nine powerful radio-galaxies known to have outflows of HI gas (Morganti et al. 2005) and bright, shock-excited rotational H_2 line emission (Guillard et al. 2012). The PACS observing mode and data reduction are discussed in Guillard et al. (2013b). In the following we briefly summarize the observational results.

In all radio-galaxies* we detect bright [CII] lines, with fluxes ranging from 10^{-17} to 3×10^{-16} W m^{-2}, corresponding to line luminosities of $10^{7} - 5 \times 10^{9}$ L$_\odot$. The [CII] lines are all very broad, with intrinsic FWHM ranging from 400 to 1200 km s^{-1}. 3/7 galaxies show significant blue-shifted wings or very broad symmetric components underlying a narrower line. The example of the 3C 326 galaxy, one of the most extreme object in terms of H_2 turbulent heating (Ogle et al. 2010; Nesvadba et al. 2010), is shown in Figure 1, and discussed in details in Guillard et al. (2013a).

3 [CII] line cooling and turbulent heating

The [CII]λ158μm line is the main coolant of the cold neutral medium ($T \approx 100-300$K, $n_{\rm H} \approx 10^2 - 3\times10^3$ cm^{-3}) heated by UV radiation, and therefore controls the balance between the ≈ 5000 K gas and the cold neutral medium. This makes [CII] a key line diagnostic to probe the formation of cold gas.

The masses of [CII]-emitting gas, derived from the observed [CII] luminosity and the theoretical C$^+$ cooling rate, range from 2.5×10^{7} to 1.2×10^{10} M$_\odot$ (Guillard et al. 2013b) for a gas temperature of 100 K and a hydrogen density of $n_{\rm H} = 6000$ cm^{-3} (equal to the [CII] critical density with H_2 as collision partner). A gas temperature is 100 K is optimal for [CII] line emission. At higher temperatures Oxygen cooling starts to take over, and lower temperatures are below the excitation temperature of the transition†. So any deviation from this temperature would require more gas mass to account for the [CII] line emission. The comparison of these masses to the observed gas masses in the different ISM phases shows that the molecular gas is the only reservoir of gas containing enough mass to produce the [CII] emission, the masses of ionized and atomic gas being too low. Therefore, a large fraction of the molecular gas in those radio-galaxies is warm ($T > 100$ K), which is in

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*Except two galaxies 3C 293 and 4C 12.50 which do not have [CII] measurements.

†$^2P_{3/2} \rightarrow ^2P_{1/2}$, $E_{ul}/k = 92$ K.

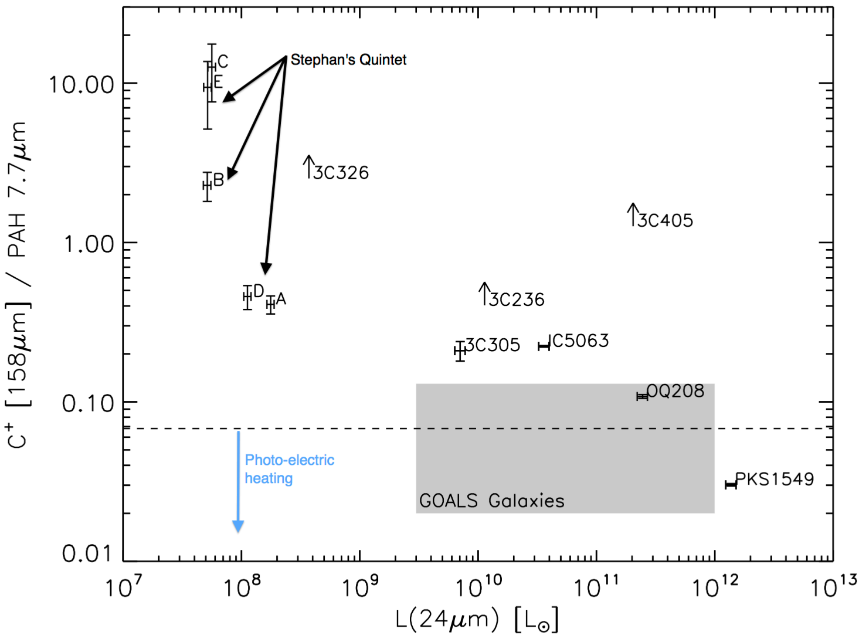

Fig. 2. [CII]$\lambda 158\mu$m to PAH 7.7μm flux ratio as a function of the monochromatic 24μm luminosity (observed by *Spitzer/IRS*, from Guillard et al. 2012). The dashed line is the upper limit on the C^+-to-PAH ratio compatible with photoelectric heating of the gas. 5/7 galaxies are clearly above that limit. The grey area shows the rage of ratios observed in the GOALS sample (Díaz-Santos et al. 2013). The letters denote different regions of the Stephan's Quintet shock region, (Appleton et al. 2013). This diagnostic appears to be highlight the enhancement of the C^+ emission due to the dissipation of turbulent energy.

agreement with the large amounts of warm H_2 gas detected (Ogle et al. 2010), sometimes comparable to the H_2 masses derived from CO observations (Nesvadba et al. 2010).

The weakness of the [OI] and CO lines in those radio-galaxies, except for 3C 405, suggest that the average molecular gas density is moderate, with $10^2 < n_{\rm H} < 10^4$ cm^{-3} (Guillard et al. 2013a,b). Together with the constraint on the gas temperature discussed above, this suggests that the average pressure of the warm H_2 is relatively low ($5 \times 10^4 < P/k < 5 \times 10^5$ K cm^{-3}).

What is the main heating source of the [CII]-emitting gas? In star-forming galaxies, the excitation of the [CII] line mostly arises from the collisions between C^+ and the warm gas (mostly H and H_2 partners) heated by the photo-electric effect from PAH molecules (dominant) and small grains (e.g. Bakes & Tielens 1994). Therefore, the [CII]-to-PAH luminosity ratio is a direct measure of the efficiency of photoelectric heating, which is a few percent. Figure 2 shows that 6/7 radio-galaxies studied here have unusually large [CII]/PAH ratios, showing that UV photons cannot be the main source of heating of the [CII]-emitting gas. Extreme [CII]/PAH ratios have also been detected in other systems like galaxy interactions (Stephan's Quintet, Appleton et al. 2013, and the Taffy galaxies, Peterson et al. in prep.).

Nesvadba et al. (2010) and Ogle et al. (2010) argued that the dissipation of turbulent energy is the primary heating source of the warm H_2 gas in those radio-galaxies. Since the [CII] line emission is mostly coming from the molecular gas, we assume that the [CII] line is tracing the kinematics of the H_2 gas. Indeed, the [CII] line and the ro-vibrational H_2 1-0S(3) line observed by Nesvadba et al. (2011) have remarkably similar profiles (see the discussion about the 3C 326 line kinematics in Guillard et al. 2013a). The turbulent kinetic luminosity associated with the H_2 gas velocity dispersion alone is a factor of > 2 higher than the total [CII]+H_2 cooling rate for all galaxies, so turbulent heating is energetically plausible (Guillard et al. 2013a), and we interpret the [CII] line emission within this framework of turbulent dissipation. In general, since the jet is perpendicular to the disk plane, this turbulent energy is likely to be injected over a spatial scale comparable to the vertical scale height of the disk, and can maintain high values of the disk thickness (Guillard et al. 2013a). This vertical turbulent support can stabilize the molecular disk against fragmentation into bound, star-forming clumps, and is a possibility to explain why some of these sources have heavily suppressed star formation activity (Nesvadba et al. 2010).

We note that cosmic ray heating, although energetically possible at high ionization rates ($10^{-14} < \zeta < 5 \times 10^{-12}$ s^{-1}), would require high gas densities ($n_{\rm H}$ larger than a few 10^3 cm^{-3}) for the gas to remain molecular (see discussion in Ogle et al. 2010), which is not suggested by the weakness of the [OI] and CO lines (see above). Therefore, cosmic rays may not be the main heating source in the diffuse molecular gas. However, cosmic rays must play an important chemical role in maintaining a high fractional abundance of C^+, the CO molecules being dissociated by secondary electrons (Mashian et al. 2013; Guillard et al. 2013a).

4 Conclusions and implications on the interpretation of high redshift observations

We detect strong [CII] line emission in a small sample of radio-galaxies chosen to show signs of jet-driven outflows, at levels brighter than what is expected from star formation. We show that the molecular gas is the only mass reservoir capable of explaining the observed [CII] luminosity, and that the bulk of this gas is warm ($T \approx 100$ K) and diffuse ($10^2 < n_{\rm H} < 10^4\,{\rm cm}^{-3}$). We interpret the [CII] observations in the framework of turbulent dissipation, believed to be the heating source of the warm H_2 gas, and offering a natural link between the [CII] and rotational H_2 line observations by *Spitzer*. The dissipation of a small fraction of the jet mechanical energy ($\approx 10\%$) can maintain large amounts of H_2 gas ($10^8 - 5 \times 10^{10}$ M$_\odot$) at low pressure, thus in a physical state not favourable for star formation. This suggests that AGN-driven turbulence in the H_2 gas plays a key role in the way the AGN mechanical energy is dissipated and star formation regulated.

Bright [CII] line emission in turbulence-dominated systems – boosted by shocks (Lesaffre et al. 2013) or vortices (Godard et al. in prep.), and above levels expected from star formation alone – may have important impact on our interpretation of far-infrared line cooling in gas at high-redshifts. Dissipation of turbulence is likely to be a generic feature of early stages of galaxy build-up, and we may have already some first observational signatures of that dissipation at $z \approx 2$ through enhanced H_2 line emission (Ogle et al. 2012) and perhaps also [CII] (Seymour et al. 2012).

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