Feeding the spider with carbon

[CII] emission from the circumgalactic medium and active galactic nucleus

C. De Breuck1, A. Lundgren1, B. Emonts2, S. Kolwa3,4, H. Dannerbauer5,6, and M. Lehnert7

1 European Southern Observatory, Karl Schwarzschild Straße 2, 85748 Garching, Germany
2 National Radio Astronomy Observatory, 520 Edgemont Road, Charlottesville, VA 22903, USA
3 Inter-University Institute for Data Intensive Astronomy, Department of Astronomy, University of Cape Town, Rondebosch 7701, South Africa
4 Physics Department, University of Johannesburg, 5 Kingsway Ave, Rossmore, Johannesburg 2092, South Africa
5 Instituto de Astrofísica de Canarias (IAC), 38205 La Laguna, Tenerife, Spain
6 Universidad de La Laguna, Dpto. Astrofísica, 38206 La Laguna, Tenerife, Spain
7 Université Lyon1, ENS-Lyon, CNRS, Centre de Recherche Astrophysique de Lyon UMR5574, 69230 Saint-Genis-Laval, France

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ABSTRACT

We present the detection of [CII] 158 µm emission from the Spiderweb galaxy at z = 2.1612 using the Atacama Pathfinder EXperiment (APEX). The line profile splits into an active galactic nucleus (AGN) and circumgalactic medium (CGM) component previously identified in CO and [CII]. We find that these individual [CII] components are consistent in terms of CO and far-IR luminosity ratios with the populations of other z > 1 AGN and dusty star-forming galaxies. The CGM component dominates the [CII] emission in the 10” APEX beam. Although we do not have spatially resolved data, the close correspondence of the velocity profile with the CO(1−0) detected only on scales of tens of kiloparsecs in CO(1−0) suggests that the [CII] emission is similarly extended, reminiscent of [CII] halos recently found around z > 5 galaxies. Comparing the first four ionization states of carbon, we find that the atomic [CI] emission is dominant, which increases its reliability as a molecular mass tracer. Our [CII] detection at 601.8 GHz also demonstrates the feasibility to extend the frequency range of ALMA Band 9 beyond the original specifications.

Key words. galaxies: high-redshift – galaxies: ISM – submillimeter: ISM

1. Introduction

The important role of the circumgalactic medium (CGM) as a reservoir feeding star forming gas to galaxies is now well established (e.g. Dekel et al. 2009). However, especially at high redshift, our knowledge of the CGM is still mostly limited to the brightest emission lines (e.g. Lyman-α), which mainly trace the warm gas and have the disadvantage of being poor tracers of the intrinsic velocity of the gas due to resonant scattering effects, and being ionized by a range of physical processes involving an active galactic nucleus (AGN), star formation, and shocks from inflows or outflows (Tumlinson et al. 2017; Daddi et al. 2021). A more direct way to study the link between the CGM and star formation is to observe cold gas containing molecular hydrogen, which is the fuel for forming stars. This cold gas can be detected in the (sub)millimetre using bright CO (e.g. Cicone et al. 2014; Emonts et al. 2016; Ginolfi et al. 2017; Li et al. 2021) or fine structure lines (e.g. Cicone et al. 2015; Fujimoto et al. 2020; Herrera-Camus et al. 2021). Most of these results, especially those using the [CII]158 µm line (hereinafter [CII]), appear to be tracing AGN or star formation driven outflows rather than an extended gas reservoir feeding the central galaxy. Most importantly, by its large spatial scale nature, any interferometer over-resolves a significant part of the extended CGM emission, in particular at the high observing frequencies of [CII] (Carniani et al. 2020; Novak et al. 2020; Decarli et al. 2021). This is where sensitive single-dish submillimetre (submm) telescopes can play an important role. Due to their limited collecting area, we can currently only target the brightest emission lines such as [CII].

In this Letter, we present Atacama Pathfinder EXperiment (APEX) [CII] observations of the Spiderweb galaxy at z = 2.1612, one of the best studied high redshift radio galaxies (HzRG), located at the centre of a protocluster (e.g. Pentericci et al. 2000; Miley et al. 2006). Emonts et al. (2013) first detected CO(1−0) in the Spiderweb galaxy using the Australia Telescope Compact Array (ATCA). Deeper observations showed that this emission splits into two components dominated by the AGN and the CGM, which is over-resolved in longer baseline observations with the Karl J. Jansky Very Large Array (VLA; Emonts et al. 2016). The extended CGM emission follows the diffuse UV light from young stars found with the Hubble Space Telescope (Hatch et al. 2008). While the CO(1−0) line traces the cold molecular gas, it is unfortunately rather faint. This is where the bright [CII] line presents a good alternative. However, at z = 2.1612, the [CII] line falls at 601.8 GHz, just below the edge of the ALMA Band 9 receivers, designed to cover 602 to 720 GHz (Baryshev et al. 2015). The upgraded version of this receiver installed in the Swedish ESO PI Instrument for

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APEX (SEPIA; Belitsky et al. 2018) has extended the frequency range to 578–738 GHz, which now allows one to observe the [CII] line in the Spiderweb galaxy. Throughout this Letter, we assume a \( \Lambda \)CDM cosmology with \( H_0 = 67.8 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_m = 0.308 \), and \( \Omega_\Lambda = 0.692 \) (Planck Collaboration XIII 2016). At \( z = 2.1612 \), this corresponds to a luminosity distance \( D_L = 17.5 \text{ Gpc} \) and a scale of 8.5 kpc/\( \text{mas} \).

2. Observations and data reduction

We observed the [CII] 158 μm (\( \nu_{\text{rest}} = 1900.539 \text{ GHz} \)) using the SEPIA (Belitsky et al. 2018) on the APEX telescope (Güsten et al. 2006). The data were obtained under ESO project E-0106.A-1003A-2020 during five nights in December 2020. The total on-source integration time centred on RA = 11h40m48s; Dec = −26°29′08″ was 4.3 h and the telescope time including all overheads and calibrations was 17.1 h. The precipitable water vapour (PWV) was in the range 0.3–0.6 mm, corresponding to a transmission 0.21 to 0.45 at the science frequency. While the CO redshift of 2.1612 used by Emonts et al. (2018) places the [CII] line at 601.204 GHz, we preferred to tune the receiver to 602.26 GHz in the lower side-band to centre the line in the middle of one of the two 4 GHz wide backend units, so as to avoid any edge effects affecting the line profile in the small overlap region between the two backends. We used the wobbler in symmetrical mode with an amplitude of 20″ and frequency of 1.5 Hz. Pointing and calibration was checked regularly against V Hya and IRC+10216 using the CO(1−0) line profile in the small overlap region between the two backends. Gullberg et al. (2016) found at least three spatially and spectrally separated components of the AGN host galaxy.

We detected the [CII] line with a velocity integrated intensity of 48 ± 11 Jy km s\(^{-1}\) in the range −500 to 500 km s\(^{-1}\), where 0 km s\(^{-1}\) corresponds to the sky frequency of 601.204 GHz (corresponding to \( z = 2.1612 \); Emonts et al. 2018). The spectral profile clearly deviates from a single Gaussian, and it consists of two main velocity components listed in Table 1.

The [CII] spectral profile reflects the different velocity components covered by the 10″ APEX beam. The CO and [CII] detected galaxies of Emonts et al. (2018) with velocities within the observed [CII] line are located 9″ to 22″ from the APEX pointing, which is well outside of the APEX beam. Other companion galaxies are located within the APEX beam, but none of them have velocities within the [CII] profile (Pentericci et al. 2000; Kurk et al. 2004; Kuiper et al. 2011). One exception could be a very tentative (\(<2\sigma\)) detection at 599.3 GHz, which is close to the expected \( z = 2.1701 \pm 0.0016 \) of source #5 of Kuiper et al. (2011), located at the eastern edge of the host galaxy.

The AGN-dominated region has been detected in a range of emission lines. In the rest-frame UV, the narrow-line region has a velocity width of \( \sim 2000 \text{ km s}^{-1} \) (Silva et al. 2018), while the Ha line has a width of 15 000 km s\(^{-1}\), which can only originate from the AGN broad-line region (Nesvadba et al. 2006, 2011; Humphrey et al. 2008). The non-resonant HeII1640 Å combination line is commonly used as the best tracer of the AGN systemic redshift \( z_{\text{AGN}} = 2.1623 \pm 0.0011 \) (Silva et al. 2018). This corresponds within the uncertainties with the \( z_{\text{CO VLA}} = 2.1617 \pm 0.0003 \) of the AGN component in the CO(1−0) line identified by Emonts et al. (2016). As the HeII line has a 3x higher FWHM than the CO(1−0) (Fig. 1), the latter can provide a more accurate redshift constraint, despite the limited signal-to-noise of the CO(1−0) data. In addition, as the [CII] predominantly traces the photo-dissociation regions, it is expected to originate from the same gas as the CO(1−0), while the HeII is tracing the more extended photo-ionized gas. We thus assume the CO(1−0) AGN redshift and the nominal redshift of the AGN.

The molecular and atomic gas in the Spiderweb galaxy show an even more complex structure. Gullberg et al. (2016) found at least three spatially and spectrally separated components

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1. We also performed baseline subtraction on individual backends and then combined the data, providing consistent results.
2. See http://www.apex-telescope.org/telescope/efficiency/index.php

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Table 1. Observational parameters of the Spiderweb galaxy.

| Component | Velocity Offset (^1) | \( I_{\text{CII}} \) (^2) | FWHM \((\text{km s}^{-1})\) | \( L_{\text{CII}} \) \((10^7 \ L_{\odot})\) |
|-----------|---------------------|-------------------------|-----------------|-----------------|
| CGM       | −234 ± 25           | 28 ± 9                  | 185 ± 85        | 5.3 ± 1.7      |
| AGN       | 144.6 (1)           | 20 ± 11                 | 340 ± 190       | 3.8 ± 2.1      |

Notes. (^1)Relative to \( z = 2.1612 \). (^2)Fixed to CO(1−0) redshift (Emonts et al. 2018).
detected in the [CII] 370 µm (3P2−3P1) line. Two of these components with velocity widths of 270 and 1100 km s\(^{-1}\) appear to be associated with the AGN, with an additional 230 km s\(^{-1}\) wide component offset by +360 km s\(^{-1}\). Emonts et al. (2018) found a very similar total profile in the [CII] 609 µm (3P1−3P0) and CO(4−3) lines. On more extended CGM scales (17−70 kpc), Emonts et al. (2016, 2018) found that the CO(1−0) is blueshifted by a few hundred km s\(^{-1}\) with respect to the CO(1−0) in the AGN. Figure 2 compares these AGN and CGM components of CO(1−0) with our [CII] velocity profile, and it illustrates a striking correspondence. We therefore interpret the narrow [CII] component at −234 km s\(^{-1}\) to originate from the CGM predominantly.

4. Discussion

Our [CII] detection is not only the first one reported in a HzRG, but also one of the few reported in the CGM of a massive high-redshift galaxy (e.g. Cicone et al. 2015). This allows us to compare the Spiderweb galaxy with other high-z galaxies, and to provide new insight into the physical conditions in the CGM.

We first compared the total [CII] luminosity of the Spiderweb galaxy with other sources. A key property is the FIR luminosity, integrated over the source based on Herschel observations. Seymour et al. (2012) report an IR (8−1000 µm) L\(_{\text{IR}}\) = 2 ± 0.3 × 10\(^{12}\) L\(_{\odot}\), splitting in 1.2 and 0.8 × 10\(^{11}\) L\(_{\odot}\) for the AGN and starburst (CGM) components, respectively. To convert from IR to FIR (42−5000 µm), we assumed L\(_{\text{IR}}\) = 0.5 × L\(_{\text{FIR}}\). This implies a L\(_{\text{CII}}\)/L\(_{\text{IR}}\) ≈ 9 × 10\(^{-4}\), which is close to the average for dusty star-forming galaxies (DSFG; Gullberg et al. 2015), but lower than for z ∼ 2 main sequence galaxies (Zanella et al. 2018). Separating both the dust and [CII] emission into AGN and CGM-dominated components, the ratios become 6 × 10\(^{-3}\) for the AGN and 1.3 × 10\(^{-3}\) for CGM component. These different L\(_{\text{CII}}\)/L\(_{\text{IR}}\) values are consistent with those for other high-z AGN and star-forming galaxies reported by Gullberg et al. (2015). We also note that with a 0.09% contribution to the L\(_{\text{IR}}\), the [CII] line uniquely affects the Herschel/500 µm photometry (Smail et al. 2011; Seymour et al. 2012). Interestingly, the star formation rate SFR = 1400 ± 150 M\(_{\odot}\) yr\(^{-1}\) (where the AGN component has been spectrally removed in the SED; Seymour et al. 2012) is exactly on the SFR–L\(_{\text{CII}}\) relation for high-z galaxies of De Looze et al. (2014), while for low metallicity galaxies, brighter [CII] emission would be expected. Overall, this suggests that the AGN is unlikely to be the dominant source powering the [CII] in the Spiderweb galaxy.

Both our APEX [CII] spectrum and the ATCA+VLA CO(1−0) spectrum allowed us to isolate the AGN and CGM components (Fig. 2, Table 1). Using L\(_{\text{CII}}\)/(CO(1−0)VLA = 0.08 ± 0.03 Jy km s\(^{-1}\) for the AGN (Emonts et al. 2016), we found L\(_{\text{CO}(1−0)}\),VLA = (9 ± 3) × 10\(^{8}\) L\(_{\odot}\) and L\(_{\text{CII}}\)/L\(_{\text{CO}(1−0)}\) ≈ 4200. This value is close to the 5200 ± 1800 found by Gullberg et al. (2015) for DSFGs. While this presents a consistent picture where the AGN has a negligible contribution to the cold dust as well as CO(1−0) and [CII] luminosities, it is important to consider the uncertainties in the separation of the AGN and CGM components in one or both of the lines. We trust the separation in CO(1−0) to be quite reliable as it is based on spatially resolved observations, which vary with distance from the AGN. Moreover, for the compact component near the AGN, Emonts et al. (2018) report a thermalized L\(_{\text{CO}(4−3)}\)/L\(_{\text{CO}(1−0)}\) ≈ 1, which is also consistent with AGN excitation. If the spatially isolated AGN component in CO(1−0) were off by a significant amount, this would also affect the CO(4−3) in a similar fashion, which is rather unlikely. We therefore conclude that the [CII] luminosity is dominated by the CGM at negative velocities with a possible contribution from the AGN mostly at positive velocities.

Our detection of [CII] in the CGM allows us to better characterize the CGM surrounding one of the most massive high-redshift sources known. Emonts et al. (2018) also separated the CGM component in [CII]−1 and CO(4−3), but those lines likely have more AGN residuals from the central point spread function than for CO(1−0) because the CO emission is thermalized and both [CII] lines are comparatively bright at the central AGN (Gullberg et al. 2016; Emonts et al. 2018). Conversely, on scales of the CGM, the molecular gas is subthermally excited and has a lower [CII] abundance relative to CO(1−0) compared to the AGN region (Emonts et al. 2018), meaning that the fraction of the emission coming from the CGM is larger, and thus easier to separate, in CO(1−0) than in CO(4−3) or [CII]. Our APEX [CII] detection thus confirms the presence of the CGM component at predominantly negative velocities in CO(1−0), but we lack a signal-to-noise ratio (S/N) to reliably measure the profile at positive velocities. To derive the CGM component in CO(1−0), we assumed L\(_{\text{CO}(1−0)}\),CGM = L\(_{\text{CO}(1−0)}\),ATCA−L\(_{\text{CO}(1−0)}\),VLA = 0.16 ± 0.09 Jy km s\(^{-1}\) (Emonts et al. 2016), yielding L\(_{\text{CO}(1−0)}\),CGM = (1.9 ± 1.0) × 10\(^{8}\) L\(_{\odot}\). This implies L\(_{\text{CII}}\)/L\(_{\text{CO}(1−0)}\),CGM ≈ 2800, which for optically thick CO emission suggests low [CII] excitation temperatures, unless the [CII] is also optically thick (Gullberg et al. 2015). Normalizing by the FIR luminosity, the CGM component in the Spiderweb galaxy falls in the region of nearby galaxies with average radiation fields G\(_{0}\) ∼ 3 and densities n ≈ 10\(^3\) cm\(^{-3}\), assuming the [CII] is mostly dominated by photo-dissociation regions (Stacey et al. 2010; Gullberg et al. 2015).

Although our APEX detection does not provide any spatial information, we predict that the [CII] in the Spiderweb galaxy is likely quite extended because it traces the more extended

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Fig. 2. Total [CII] spectrum (yellow histogram) with CO(1−0) from different regions overlaid in blue. In both panels, the CO(1−0) was scaled up in flux by a factor of 650 for easy comparison with [CII]. Left: CO(1−0) emission on scales of 17−70 kpc in the CGM around the Spiderweb galaxy. The CO(1−0) spectrum was made from low-resolution ATCA data with the central emission subtracted (see Emonts et al. 2018, for details). Right: CO(1−0) emission in the inner −6 kpc of the radio galaxy, from high-resolution VLA data (Emonts et al. 2016). The CO(1−0) emission on ~6−17 kpc scales around the AGN is not captured reliably in this figure due to the difference in resolution between the ATCA and VLA data.
component in CO(1−0). Moreover, extended [CII] emission has now been regularly observed in several high-redshift objects (Cicone et al. 2015; Fujimoto et al. 2020; Carniani et al. 2020; Rybak et al. 2020; Herrera-Camus et al. 2021). Given that the spatial scales can be several tens of kiloparsecs or more, even short-baseline observations at these high frequencies may not be able to detect the full extent of the CGM in [CII] emission. On the other hand, the APEX beam size of 10′′ corresponds to a physical scale of ~70 kpc, which is the same as the total extent of the cold molecular gas reservoir in the CGM observed in CO(1−0).

Our [CII] detection also completes a census of the first four ionization states of carbon. As mentioned earlier, Gullberg et al. (2016) and Emonts et al. (2018) reported [CI] emission consisting of several spatially and spectrally resolved components, where the AGN component is significantly brighter than the CGM component. The [CII] 1909 Å and CIV 1549 Å lines were first reported in the discovery spectrum of Röttgering et al. (1997), with a line ratio of CIV 1549Å/[CII] 1909 Å = 0.6 ± 0.2. Since then, only the CIV 1549 Å line has been observed at a higher S/N and spectral resolution (Kurk 2003; Hatch et al. 2008), suggesting a broad component in the CIV 1549 Å line, but with a total line flux about half of the one reported by Röttgering et al. (1997). We interpret this di

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