Observations and diagnostic use of highly redshifted fine structure lines

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Abstract. The diagnostic use and detectability of luminous fine structure lines from high redshift galaxies is reviewed in the light of results from COBE concerning the Milky Way and from ISO on low redshift galaxies. At the highest luminosities ($L > 10^{12} L_\odot$) the [C\textsc{ii}] 158 $\mu$m line is somewhat less luminous with respect to the bolometric luminosity than for lower luminosity objects. Thus, surveys for this line must emphasize depth. The [C\textsc{ii}] line will be the principal spectroscopic probe of the deep universe for the MMA and FIRST. A deep search for [C\textsc{ii}] 158 $\mu$m emission from the dusty $z = 4.693$ quasar BR 1202–0725 is presented. The resulting $3\sigma$ upper limit implies that for this object $L_{[\text{CII}]}/L_{\text{FIR}} < 0.0006\%$, a highly significant result indicating that distant luminous objects may represent a natural extension towards higher luminosities of the ultraluminous infrared galaxies at low redshift.

1. Introduction

Warm, neutral interstellar gas cools mainly through emission in low excitation fine structure lines, principally the [C\textsc{ii}] 158 $\mu$m and [O\textsc{i}] 63 $\mu$m lines. Star forming galaxies therefore emit copious amounts of radiation in these lines, as shown observationally by observations with the KAO (e.g., Stacey et al. 1991) and the ISO satellite (e.g., Malhotra et al. 1997). The brightest of these lines exceed the brightest CO lines by one to two orders of magnitude in luminosity. These lines, which lie mostly in the far-infrared (FIR) region, are therefore expected to be detectable out to very large distances where they are redshifted into the submillimeter region, and their detection has long been recognized as a key aim of extragalactic submillimeter spectroscopy. The discovery of luminous CO emission lines in a number of high-$z$ objects has intensified searches for fine structure lines, which, as principal coolants, carry substantial diagnostic information on the heating sources involved, which may be immense, optically obscured starbursts.

In this review, I first discuss the current state of knowledge on the properties of these lines in the Milky Way and local galaxies. I briefly address the detectability and diagnostic use of these lines at high $z$ with future instrumentation. Finally I present the deepest search so far for redshifted [C\textsc{ii}] 158 $\mu$m emission, which provides for the first time a highly significant upper limit, and may provide a link between dusty, luminous high-$z$ objects and ultraluminous infrared galaxies (ULIRGs) in the local universe.

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Table 1. Luminosities of fine structure lines in the Milky Way. $L_{\text{FIR}} = 10^{10} L_\odot$ is the far-infrared luminosity of the Milky Way.

| Line   | $\lambda_0$ [\(\mu\text{m}\)] | $v_0$ [GHz] | $L_{\text{line}}$ [$L_\odot$] | $L_{\text{line}}/L_{\text{FIR}}$ |
|--------|---------------------------------|-------------|--------------------------------|----------------------------------|
| [C\text{ii}] | 158                             | 1900        | $5 \cdot 10^7$ | 0.5\%                          |
| [O\text{i}] | 63                              | 4745        | $2 \cdot 10^7$ | 0.2\%                          |
| [N\text{ii}] | 122                             | 2459        | $8 \cdot 10^6$ | 0.08\%                         |
| [N\text{ii}] | 204                             | 1461        | $5 \cdot 10^6$ | 0.05\%                         |
| [C\text{i}]  | 370                             | 809         | $3 \cdot 10^5$ | 0.003\%                        |
| [C\text{i}]  | 609                             | 492         | $2 \cdot 10^5$ | 0.002\%                        |

Figure 1. Expected integrated emission line fluxes of the Milky Way as a function of redshift for $H_0 = 75$ km s\(^{-1}\) Mpc\(^{-1}\) and $q_0 = 0.5$ (left panel) and $q_0 = 0.1$ (right panel), calculated as described in Van der Werf and Israel (1996). Drawn lines indicate atmospheric windows accessible from the ground: 75 – 500 GHz (some narrow inaccessible frequency ranges have been ignored), 630 – 700 GHz, and 800 – 900 GHz; dashed lines denote regions inaccessible due to atmospheric opacity.
2. The Milky Way at low and high redshift

The first accurate determinations of the global luminosities of luminous fine structure lines in the Milky Way have been provided by the FIRAS experiment on the COBE satellite (Wright et al. 1991). These luminosities are summarized in Table 1, together with a much more uncertain luminosity of $[\text{O} \text{i}]$ 63$\mu$m, which has not been measured by FIRAS, but estimated from the possible FIRAS detection of $[\text{O} \text{i}]$ 145$\mu$m, using a $[\text{O} \text{i}]$ 63$\mu$m/145$\mu$m ratio of 20, and which agrees with the estimate by Stacey (1989).

Given these luminosities, it is easy to calculate the apparent integrated emission line fluxes for the Milky Way as a function of redshift. The expected fluxes are presented in Figure 1.

It is clear that the $[\text{C} \text{ii}]$ line is going to be the most important spectroscopic probe of the deep universe in this frequency region, once sufficiently sensitive facilities become available. Using currently expected sensitivities for the MMA (assuming a total collecting area of 7000 m$^2$), for $q_0 = 0.5$ the Milky Way will be detectable as a point source for the MMA in an 8 hour synthesis at any redshift where the line is shifted into a transparent atmospheric window. Mapping will be more difficult (because the emission is divided into a number of beams, and because of cosmological surface brightness dimming), but should still be routinely possible in objects somewhat more luminous than the Milky Way, or in longer integrations. $[\text{N} \text{ii}]$ and in particular $[\text{O} \text{i}]$ measurements will be limited to more luminous objects in specific redshift intervals. The $[\text{C} \text{i}]$ lines from the Milky Way will only be detectable out to $z \sim 1$. The $[\text{C} \text{ii}]$ line will not be accessible to the MMA at $z < 1$, but this redshift range will be covered by the heterodyne instrument HIFI on the FIRST satellite.

3. Diagnostic use of cooling lines

Since the low excitation fine structure lines are major cooling lines, their fluxes should scale to zeroth order with the heating rate, and hence with the FIR luminosity $L_{\text{FIR}}$. KAO observations (Crawford et al. 1985; Stacey et al. 1991) confirmed this behaviour for the $[\text{C} \text{ii}]$ line, which carries typically 0.5% of the FIR luminosity for $L_{\text{FIR}} \lesssim 10^{11} L_\odot$. Detection of these lines at high redshift will provide powerful diagnostics.

1. The $[\text{C} \text{ii}]$ line originates at the UV-exposed surfaces of molecular clouds (photon-dominated regions or PDRs). It becomes a particular powerful diagnostic in combination with CO lines, since the $[\text{C} \text{ii}]$/CO line ratio is independent of beam filling factor, and thus provides an extinction-free measurement of the UV luminosity per unit molecular mass, i.e., of the star forming efficiency. Combining this result with a star formation rate and dust mass determined from $L_{\text{FIR}}$ provides a characterization of the star forming properties of distant galaxies (Crawford et al. 1985; Stacey et al. 1991).

2. The $[\text{O} \text{i}]$ line also arises in PDRs, and, combined with $[\text{C} \text{ii}]$, provides an independent measure of the UV field strength.
3. The [C\textsc{ii}] lines also arise at molecular cloud surfaces, and may be used to trace the mass of UV-exposed gas.

4. The [N\textsc{ii}] lines, with a formation potential of only 14.53 eV, and low critical density and upper level temperature, are ideal probes of the general low excitation ionized medium.

4. Lessons from local galaxies

The recent discovery of high redshift objects with FIR luminosities up to \(10^{14} L_\odot\) and the detection of CO emission in several of these have led to the suggestion of immense, optically obscured starbursts at high redshift. Application of the simple scaling of \(L_{\text{[C\textsc{ii}]}}\) with \(L_{\text{FIR}}\) suggested in the preceding section results in [C\textsc{ii}] fluxes for these luminous objects that should already be observable with present instrumentation. However, searches for redshifted [C\textsc{ii}] 158 \(\mu\)m (Isaak et al. 1994; Ivison et al. 1998) and [N\textsc{ii}] 205 \(\mu\)m emission (Ivison and Harrison 1996) have not yielded any detections and the only reliably detected fine structure line at high redshift so far is the [C\textsc{i}] 609 \(\mu\)m detection of the gravitationally lensed “Cloverleaf quasar” (Barvainis et al. 1997).

Recent FIR spectroscopy of low redshift galaxies with the ISO Long Wavelength Spectrograph (LWS) has shed new light on these results. As shown by Malhotra et al. (1997), the ratio \(L_{\text{[C\textsc{ii}]}}/L_{\text{FIR}}\) falls dramatically below 0.5% for galaxies with high star formation rates, which typically have \(L_{\text{[C\textsc{ii}]}}/L_{\text{FIR}} \sim 0.05\%. The most outstanding example of this phenomenon is the prototypical ULIRG Arp 220, where the [C\textsc{ii}] line is strongly suppressed with respect to the continuum (Fischer et al. 1998). While the origin of this effect is still debated (optically thick [C\textsc{ii}] emission, dust absorption at 158 \(\mu\)m, and suppressed [C\textsc{ii}] emission in dense PDRs may all play a role), it is evident that at the luminosities characterizing ULIRGs the [C\textsc{ii}] luminosity does not scale with \(L_{\text{FIR}}\) anymore, but is suppressed by about a factor of 10 with respect to the lower luminosity scaling (Luhman et al. 1998). The behaviour of other fine structure lines is even more complicated: in Arp 220, [O\textsc{i}] 63 \(\mu\)m (and many lines of OH, H\_2O, NH\_3 and CH) is in absorption (Fischer et al. 1998)! In the somewhat less luminous starburst galaxy NGC 3690, both [C\textsc{ii}] and [O\textsc{i}] are bright, and neither Arp 220 nor NGC 3690 shows [N\textsc{ii}], but the latter object has [N\textsc{iii}] emission (Fischer et al. 1998). In contrast, the modest nearby starburst galaxies M82 and NGC 253 show both [N\textsc{ii}] and [N\textsc{iii}] emission (Hur et al. 1996).

While it will be some time before these results can be placed in their proper physical context, a number of phenomenological conclusions relevant to high-\(z\) observations of these lines can already be drawn.

1. In objects with luminosities up to \(\sim 10^{12} L_\odot\), the [C\textsc{ii}] 158 \(\mu\)m line carries about 0.5% of \(L_{\text{FIR}}\). In more luminous objects this fraction decreases to about 0.05%.

2. On the other hand, in low-metallicity objects such as the Magellanic clouds, the [C\textsc{ii}] line carries about 1% of \(L_{\text{FIR}}\) and this fraction may increase to about 3% in individual star forming regions in these objects.
(Israel et al. 1996). This behaviour results from the easier photodissocia-
tion of CO in low metallicity galaxies, and may positively affect detection 
rates for high-z objects.

3. The nitrogen lines are affected by excitation conditions, and in the absence 
of detailed further information, upper limits will be extremely difficult to 
interpret. In addition, at high redshift the strengths of the nitrogen lines 
may be affected by abundance effects.

4. [O i] 63 µm may be affected by radiative transfer effects. Consequently, 
detections of this line will be difficult to interpret.

It is important to note that the use of [C ii] emission as a cosmological 
probe for the MMA is not compromised by these results, since the MMA will be 
able to probe sufficiently far to the faint end of the luminosity function. Only 
for ultraluminous objects flux predictions have to be lowered in the light of the 
ISO results. These results also imply that blind surveys for extragalactic [C ii] 
emission (see e.g., Stark 1997 for predictions of detection rates) should emphasize 
survey depth rather than survey volume, until the luminosity function is probed 
to sufficiently faint levels at the highest redshift of interest.

5. A deep search for [C II] emission from BR 1202−0725 at z = 4.69

Even with the more pessimistic flux predictions discussed in Section 4, the most 
luminous high-z objects might be detectable in redshifted [C II] 158 µm emis-
sion in a long integration with presently available instrumentation. We have 
therefore obtained a very deep spectrum of the dusty z = 4.69 radio-quiet QSO 
BR 1202−0725 (Van der Werf and Israel, in preparation). This object shows 
strong submillimeter dust emission (McMahon et al. 1994; Isaak et al. 1994), 
with \( L_{\text{FIR}} \sim 10^{14} L_\odot \) (\( H_0 = 75\, \text{km}\, \text{s}^{-1}\, \text{Mpc}^{-1}, q_0 = 0.1 \) is adopted here and in 
the remainder of this paper). Luminous CO emission was detected by Ohta et 
al. (1996) and Omont et al. (1996) and provided an accurate redshift of 4.693, 
so that the [C ii] 158 µm line is redshifted to a frequency of 333.8375 GHz, where 
the atmosphere is transparant. The JCMT was used to search for this line dur-
ing several observing runs between December 1993 and April 1997, using first 
the B3(i) single-channel SIS receiver, and later the B3 dual-channel SIS receiver. 
The DAS autocorrelator spectrograph was used as backend. Since at the start 
of this project the CO detection (and hence the precise redshift) was not avail-
able yet, a range of frequencies had to be scanned. This situation underlines 
the need for very wideband systems (e.g., Isaak, these proceedings) for future 
observations of fine structure lines from distant objects. The observations were 
done with double beam switching, so that the source appeared alternately in the 
signal and reference beams of the chopping secondary mirror. The subbands of 
the DAS were merged using SPECX, and further processing was done in CLASS. 
All scans were visually inspected and those with curved baselines or zeropoint 
offsets were discarded, leaving a total integration time of about 50 hours on 
source. In order to safeguard against spurious broad features, horizontal base-
lines were subtracted from all individual frequency settings before merging these 
into a final composite spectrum (cf., Ivison et al. 1998). The resulting spectrum 
is shown in Figure 2.
Figure 2. Final combined spectra of [C II] 158 μm emission from BR 1202−0725 at $z = 4.693$. The top panel shows the full spectral range covered, at a frequency resolution of 1.513 MHz (velocity resolution 1.36 km s$^{-1}$); for reasons of presentation, the most noisy sections have not been plotted. The central panel shows a blow-up of the most sensitive section of the spectrum, centered on the expected frequency of the line, which is taken as the zeropoint of the indicated velocity scale. The bottom panel shows the same section, smoothed to 40 MHz frequency resolution (36 km s$^{-1}$ velocity resolution), and converted into flux density units.

The [C II] line is not detected. Assuming a Gaussian line with a FWHM of 220 km s$^{-1}$ (as measured by Ohta et al. 1996 for the CO $J = 5\rightarrow4$ line), the $3\sigma$ upper limit to the integrated flux is 9.5 Jy km s$^{-1}$, so that $L_{[\text{C II}]} < 6.3 \times 10^9 L_\odot$, and $L_{[\text{C II}]}/L_{\text{FIR}} < 0.006\%$. Another useful diagnostic ratio, with CO $J = 1\rightarrow0$, can be estimated from the CO $J = 5\rightarrow4$ measurements, noting that the CO excitation properties are likely similar to those in the Cloverleaf quasar (Omont et al. 1996), and using the estimate by Barvainis et al. (1997) for the CO $J = 1\rightarrow0/J = 5\rightarrow4$ ratio of the Cloverleaf. The resulting $3\sigma$ upper limit is $L_{[\text{C II}]}/L_{\text{CO}(1\rightarrow0)} < 4000$.

These results can be put in perspective using Table 2, which is based on data from Stacey et al. (1991), Nakagawa et al. (1993), Solomon et al. (1997), and Luhman et al. (1998). It is evident that the low $L_{[\text{C II}]}/L_{\text{FIR}}$ ratio, which is at least a factor of 8 smaller than in local ULIRGs, is a highly significant result.
Table 2. Empirical luminosity ratios for various types of objects.

| Object          | $L_{\text{[CII]}}/L_{\text{CO(1–0)}}$ | $L_{\text{[CII]}}/L_{\text{FIR}}$ |
|-----------------|--------------------------------------|----------------------------------|
| Milky Way       | 1400                                 | 0.5%                             |
| Starburst galaxies | 4100                               | 0.5%                             |
| ULIRGs          | 1700                                 | 0.05%                            |
| Orion region    | 7000                                 | 0.1%                             |
| LMC             | 23000                                | 1%                               |
| 30 Dor          | 77000                                | 2.5%                             |

The low $L_{\text{[CII]}}/L_{\text{CO(1–0)}}$ ratio is consistent with this result, without providing an additional constraint. Table 3 indicates that we should go at least a factor of 3 deeper before the same $L_{\text{[CII]}}/L_{\text{CO(1–0)}}$ ratio is reached as in local ULIRGs. Such sensitivities are beyond the reach of presently available instrumentation, but will be available with the MMA. These results suggest that distant, dusty hyperluminous objects such as BR 1202–0725 represent a natural extension towards higher luminosities of the local population of ULIRGs. Hence, the study of local ULIRGs will also shed light on the role and properties of distant hyperluminous objects, whether they are powered by active nuclei or immense bursts of star formation.

6. Conclusions

Redshifted fine structure lines form powerful diagnostics of the physical conditions in the neutral interstellar gas in distant galaxies. The $\text{[CII]}$ 158 $\mu$m will form the principal spectroscopic probe of the deep universe for the MMA, which (for $q_0 = 0.5$) will be able to detect this line from galaxies down to Milky Way luminosities at every redshift where the line is shifted into a transparent atmospheric window. A deep search for redshifted $\text{[CII]}$ 158 $\mu$m emission from the dusty $z = 4.693$ quasar BR 1202–0725 has resulted in highly significant 3$\sigma$ upper limit $L_{\text{[CII]}}/L_{\text{FIR}} < 0.0006\%$, at least factor 8 lower than ULIRGs at low $z$, and a factor of 80 lower than luminous starburst galaxies, suggesting that hyperluminous, dusty high redshift objects such as BR 1202–0725 represent an extension towards higher luminosities of the population of ULIRGs in the local universe.

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