Snapshot [C II] line survey of a uniform sample of high-redshift quasars selected at optical wavelengths

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ABSTRACT
It is proposed to observe the [C II] line and far-infrared continuum of a sample of 24 quasars at redshifts around 5.1. The sample is selected according to simple criteria from the uniform sub-sample of SDSS quasars and should be statistically representative. Because this survey optimally makes use of ALMA's high spectral sensitivity to point sources, only 15 minutes per target should allow good signal-to-noise measurement of the [C II] line and the far-infrared continuum corresponding to star-formation rates around 100 $M_\odot$/yr. The large statistical sample and good sensitivity would greatly expand our knowledge of star formation in hosts of black holes of mass $> 10^9\,M_\odot$ when the universe was only about $10^{9.1}$ years old. These observations would therefore be an exciting, efficient, low-risk programme to do at the beginning of ALMA's study of the high-redshift universe. To maximise the timely use of the data, I propose to waive the proprietary data period for this project.

1 INTRODUCTION

This proposal is motivated in part by considering how to construct an efficient, low-risk, observation programme which will allow ALMA to significantly contribute to high redshift astronomy immediately from Cycle 0. The requirements I considered were:

(i) Targeted, in position and in redshift, as opposed to a 'blind' search. Blind searches, although scientifically exciting, are likely to be very inefficient in Cycle 0 because they will be limited by sensitivity and/or observing overheads
(ii) Frequency/redshift range corresponding Band 7 or higher, i.e., in which ALMA Cycle 0 configuration has the greatest advantage compared to existing instruments
(iii) Sufficient number of sources to immediately be able to draw scientific conclusions from the observations
(iv) Sufficiently bright ($\equiv$ luminous, as I am concentrating on high-redshift) sources /spectral lines to make (iii) feasible in reasonable amount of time
(v) Well defined, uniform, source selection. This makes interpretation of results much easier and greatly improves the **long-term** value of the observations

The natural starting point given the these requirements is the sample of quasars from the Sloan Digital Sky Survey (Schneider et al. 2010). Since SDSS is a large-area survey (especially compared to existing mm/sub-mm surveys) it selects many of the most luminous objects in the Universe accessible to astronomy, and because candidate sources are selected optically, a large (and well understood) fraction of candidates have secure redshifts. The SDSS has discovered many of the highest-redshift quasars, some using specialised selection criteria. However, the catalogue of quasars selected according to **uniform** selection criteria (described by Richards et al. 2002) across the whole survey has a redshift limit of about $z \sim 5.4$ (see data by Shen et al. 2011).

Redshifts toward this catalogue limit, fortuitously, correspond to the usually very luminous [C II] $\lambda = 158\,\mu$m ionised carbon line being red-shifted in into the $850\,\mu$m atmospheric window in which ALMA has extremely high point-source spectroscopic sensitivity even in Cycle 0. As discussed below, the [C II] is line is one of the key emission lines from interstellar medium and rather than being just *a tracer* it contributes significantly to the overall energy balance of the gas phase ISM. This line is of substantial scientific interest and with advent of ALMA will be an increasingly important probe of the high-redshift universe.

In the sections below I show that ALMA will be able to observe the [C II] line from 24 quasars, uniformly selected from the SDSS, in only six hours of on-source time. The combination of well-defined and uniform selection, substantial number of sources, and high likelihood of good S/N detections would, I argue below, make a low-risk ALMA Cycle 0 observing project that would efficiently result in a significant improvement of our understanding of quasars, and their hosts, at high redshifts.

Since I believe the results of the proposed survey will be a good demonstration of ALMA capabilities, be of immediate interest for follow-up at a variety of wavelengths and by a variety of groups, and to encourage scientific programmes by individuals and small groups of researchers, I propose that the proprietary period for the data collected under this programme is waived.

2 EXISTING OBSERVATIONS

The [C II] line has so far only been detected in a handful of high-redshift ($z > 3$) quasars: Maiolino et al. (2005) measured $L_{[\mathrm{C\,II}]} = 10^{9.64}\,L_\odot$ from a quasar at $z \sim 6.4$, Iono et al. (2006) measured at $L_{[\mathrm{C\,II}]} = 10^{9.65}\,L_\odot$ at $z \sim 4.7$, Maiolino et al. (2009) measured with $L_{[\mathrm{C\,II}]} = 10^{9.66}\,L_\odot$ at $z \sim 4.4$, Wagg et al. (2010) measured $L_{[\mathrm{C\,II}]} = 10^{10.2}\,L_\odot$ at $z = 4.4$. This proposal is to observe to a sensitivity which would allow good detection of $L_{[\mathrm{C\,II}]} = 10^{9.1}\,\mathrm{L}_{\odot}$, i.e., more than three times fainter then the least luminous detection so far.

The proposed sample of 24 sources would therefore greatly expand the number of quasars with measured $L_{[\mathrm{C\,II}]}$ luminosities and would further benefit from well defined selection criteria. This step-change improvement that is made possible by ALMA is due to its much larger collecting area (a factor of 16 compared to APEX) and consequent improvement in spectral sensitivity to point sources (factor of 256 vs APEX).

Besides quasars, the [C II] line has been observed at high redshift in sub-mm selected galaxies, e.g., by Valtchanov et al. (2011) and De Breuck et al. (2011) and at intermediate redshift by for example Stacey et al. (2010). The [C II] line is therefore a well known and increasingly used probe of the energetics of the interstellar medium in galaxies.

3 SCIENTIFIC BACKGROUND

The interstellar medium and star formation in high-redshift quasar hosts have been already been the subject of substantial interest and there have been a number of studies, although these have generally limited to small numbers of objects due to sensitivity constraints. The main motivation for these studies may be summarised as follows.

The redshift of the proposed sample corresponds to an age of only $\sim 10^{9.1}\,$yr after the Big Bang. As the sample is selected from relatively shallow, large area survey these are naturally very high luminosity objects: their mean bolometric luminosity is estimated in Section 5 to be $10^{47.1\pm0.3}\,\mathrm{erg\,s^{-1}}$. Given the standard Eddington luminosity relationship

$$L_{\mathrm{Edd}} = 1.3\times10^{47}\,\frac{M_{\mathrm{BH}}}{10^{9}\mathrm{M}_{\odot}}\,\mathrm{erg\,s^{-1}} \qquad (1)$$

this implies that the black holes powering these quasars must have masses greater than $\sim 10^{9}\,\mathrm{M}_{\odot}$. One of the key science questions in high-redshift quasar studies is: how these quasars managed to accumulate such *high black hole masses* by this early age of the universe, what the duty cycles of their very high luminosities are and what is the impact of this energy on the interstellar and iter- and intra-galactic medium that surround them.

Furthermore, at the present day and in the nearby Universe there are well established relationships between masses of black holes and many of the properties of their host bulges, galaxies and halos (e.g., Kormendy & Gebhardt 2001). The black hole remnants of the quasars that we are studying at these high redshift correspond to some of the most massive elliptical galaxies in the present universe. For example, using the relationship by Bennert et al. (2011):

$$\log_{10}\left(\frac{M_{\mathrm{BH}}}{\mathrm{M}_{\odot}}\right) = (-4.0\pm0.1) + (1.12\pm0.2)\log_{10}\left(\frac{M_{\mathrm{host},\star}}{\mathrm{M}_{\odot}}\right), \qquad (2)$$

the types of black holes proposed to be studied here correspond to $M_{\mathrm{host},\star} \sim 10^{13}\mathrm{M}_{\odot}$ at the present time. Although there are uncertainties on how this relationship evolves at high redshifts, it is clear that:

(i) A host galaxy of just 10% (estimated from redshift scaling in Bennert et al. 2011) of the expected present day stellar mass would have to have had an average star-formation rate of $\Psi \sim 10^{3}\mathrm{M}_{\odot}\,\mathrm{yr}^{-1}$ over the age of universe up until then to make its stars
(ii) It would still need to create or accrete another $\sim 10^{12}\,\mathrm{M}_{\odot}$ stars over next $\sim 10^{10}\,$yr

Clearly then quasars at high redshift must be associated with star formation in some way. The key questions is what triggers this star formation, when does this triggering occur, and what is the physics of interaction between the quasar, the star formation, the molecular gas and inflow of pristine gas into the nucleus of the galaxy.

In agreement with these simple arguments, existing observations already indicate that high-redshift quasars are often associated with vigorous, dust enshrouded, circum-nuclear star-bursts. Evidence for this comes from:

(i) Dust-continuum photometry, e.g., by Carilli et al. (2001), Priddey et al. (2003) and Leipski et al. (2010), showing large far-infrared luminosities and colour temperatures that suggest star-formation rather than the quasar itself as the source of the energy for the emission
(ii) Molecular gas imaging, e.g., by Wang et al. (2011), showing large reservoirs of dense molecular gas
(iii) Existing [C II] integrated measurements (cited above) which are too large to be due to the quasar alone and resolved [C II] measurements by Walter et al. (2009) showing that [C II] luminosity is primarily due to a circum-nuclear star burst

The [C II] line is of particular interest for these studies because:

(i) It is one of the most luminous lines in the IR/sub-mm/mm parts of the spectrum, usually containing 0.1-1% of far-infrared luminosity
(ii) It is an important coolant of the interstellar medium, contributing significantly to its overall energy balance
(iii) The low ionisation potential means that this atomic species is present in a wide range of physical conditions of the interstellar medium
(iv) In contrast to low-order CO lines it is usually not optically thick, allowing simple interpretation of the observations
(v) Short wavelength allows high resolution imaging on even modest baselines

Recent studies at $z \sim 2$ by, for example, Stacey et al. (2010) have shown that the line is a good tracer of star-formation even at high redshift.

4 SCIENCE GOALS OF THESE OBSERVATIONS

The science goals of these observations are to:

(i) Measure in a statistically significant way the current star-formation rate in hosts of quasars at $z \sim 5.1$
(ii) Constrain the contribution to [C II] luminosity from X-ray dissociation regions
(iii) Constrain the dynamical masses of nuclear regions of quasar hosts by measuring the dispersion of sub-mm lines

The goals will be achieved by measuring, through this proposal, the integrated [C II] luminosity, far-infrared intensity and possibly the CO $J = 16 \rightarrow 15$ luminosity of the sample of 24 quasars selected uniformly with well-defined criteria from the SDSS.

These observations would also define an high-quality sample for follow-up at lower frequencies (for lower CO transitions, tracing the moderately dens molecular gas), for higher resolution ALMA imaging (to constrain the spatial distribution of [C II]) and near-infrared to measure in more detail the properties of the quasars themselves.

5 SAMPLE SELECTION

The sample to be observed was selected from the “Catalog of Quasar Properties from SDSS DR7” (dated May 2011) by Shen et al. (2011). The following selection criteria were applied:

(i) Redshift range $4.456 < z < 5.908$. This redshift range places the [C II] at sky frequencies $275\,\mathrm{GHz} < \nu < 319\,\mathrm{GHz}$ which is an atmospheric window with greater than 80% transmission when there is 1 mm precipitable water vapour along line of sight (see Figure 1)

(ii) Uniformly selected target, i.e., `UNIFORM_TARGET` column value which is true

(iii) Declination below 22 degrees. Low declination sources are selected to make observing with ALMA as efficient as possible. The particular value used was adjusted to give 24 sources in the sample

This results in a sample of 24 quasars (Table 1) with a mean redshift 5.1, standard deviation of 0.1 and total range of 0.33. Shen et al. (2011) computes estimated bolometric luminosities for quasars in the catalogue but these are not given for the very highest redshift quasars that make up the present sample as the relevant lines are redshifted out of SDSS spectra. An approximate lower limit bolometric luminosity can however be estimated by considering quasars in this catalogue at slightly lower redshift (so they have measured bolometric luminosities) but with similar other properties. Considering, for example, all quasars at redshift above 4 which do have an estimated luminosity in the catalogue, their mean bolometric luminosity is $10^{47.1\pm0.3}\,\mathrm{erg\,s^{-1}}$ or $10^{13.5\pm0.3}\,\mathrm{L_\odot}$ (the uncertainties represent sample dispersion, not necessarily measurement or estimation error) . For comparison *K*-corrected *i*-band absolute magnitude of sample proposed here is 0.2 magnitudes more luminous than the quasars used in this luminosity estimate.

Assuming the standard cosmology a representative luminosity distance for the proposed sample is $D_\mathrm{L} \sim 5 \times 10^4\,\mathrm{Mpc}$ and a representative angular size distance is $D_\mathrm{A} \sim 1.3 \times 10^3\,\mathrm{Mpc}$[1].

6 EXPECTED FLUXES

[C II] emission due to star formation/photon dissociation regions. Recent study by De Looze et al. (2011) estimates the relationship between star-formation rate Ψ and the [C II] luminosity as:

$$\frac{\Psi}{100\,\mathrm{M_\odot\,yr^{-1}}} = \left(\frac{L_{[\mathrm{C\,II}]}}{10^{9.1}\,\mathrm{L_\odot}}\right)^{0.983} \tag{3}$$

At the distance of the proposed sample, [C II] emission due to star formation rate of $100\,\mathrm{M_\odot\,yr^{-1}}$ therefore corresponds to line flux of $1.7 \times 10^{-20}\,\mathrm{W\,s^{-1}}$ or approximately $1.7\,\mathrm{Jy\,km\,s^{-1}}$ at 310 GHz, which a line flux which should be measured to good signal to noise by proposed observations.

The actual star-formation rate associated by host quasar galaxies is subject of this study so can not be predicted with great certainty. However existing [C II], CO and continuum measurements suggest that it is $300 - 1000\,\mathrm{M_\odot\,yr^{-1}}$ in at least a substantial fraction of host of high-redshift quasars and will therefore be observed easily with the proposed observation. Correspondingly, meaningful upper limits can be set on star formation in hosts that are quiescent.

Name	z	$i_{z=2}$ (mag)
SDSS J001115.23+144601.8	4.9672	-29.64
SDSS J082454.02+130217.0	5.1877	-28.10
SDSS J084627.84+080051.7	5.0301	-28.18
SDSS J085430.37+205650.8	5.1786	-28.65
SDSS J090245.76+085115.8	5.2258	-28.05
SDSS J095707.67+061059.5	5.1854	-28.82
SDSS J100043.77+210326.6	5.0250	-27.67
SDSS J100444.30+202520.0	5.0839	-27.74
SDSS J103418.65+203300.2	4.9985	-28.08
SDSS J105445.43+163337.4	5.1866	-27.86
SDSS J112637.96+173458.5	5.1751	-27.92
SDSS J113246.50+120901.6	5.1670	-28.35
SDSS J115424.73+134145.7	5.0104	-27.75
SDSS J120055.61+181732.9	4.9841	-28.18
SDSS J120952.72+183147.2	5.1580	-28.20
SDSS J122237.96+195842.9	5.1886	-28.04
SDSS J123333.47+062234.2	5.2891	-28.13
SDSS J133412.56+122020.7	5.1342	-28.06
SDSS J133843.66+203242.7	4.9584	-27.71
SDSS J134819.87+181925.8	4.9606	-28.65
SDSS J142325.92+130300.6	5.0374	-28.20
SDSS J153459.75+132701.4	5.0589	-28.10
SDSS J161447.03+205902.9	5.0912	-28.06
SDSS J222845.14-075755.3	5.1417	-28.22

Table 1. Sample proposed for observation

[C II] emission due to quasar/X-ray dissociation region. Stacey et al. (2010) estimates $L_{[\mathrm{C\,II}]} = 2 \times 10^{-3} L_\mathrm{X}$ where L_X is the X-ray luminosity in the 2 to 10 k*e*V energy range. X-ray luminosity of high-luminosity quasars is approximately 1/50th of the bolometric luminosity (e.g., Hopkins et al. 2007) therefore

$$\log_{10}\left(\frac{L_{[\mathrm{C\,II}]}}{L_\mathrm{bolo,QSO}}\right) \sim -4.4. \tag{4}$$

Assuming bolometric luminosity of $L_\mathrm{bolo,QSO} = 10^{13.5}\,\mathrm{L_\odot}$, this leads to $L_{[\mathrm{C\,II}]} = 10^{9.1}\,\mathrm{L_\odot}$. At the representative distance this corresponds to line flux of $1.7 \times 10^{-20}\,\mathrm{W\,s^{-1}}$ or approximately $1.7\,\mathrm{Jy\,km\,s^{-1}}$ at 310 GHz. This is the same flux as expected due to star-formation at a rate of $100\,\mathrm{M_\odot\,yr^{-1}}$ and should likewise be measurable with good signal to noise.

Far-IR continuum. The proposed observations will measure far-infrared continuum at rest wavelengths of $\lambda \sim 160\,\mu\mathrm{m}$. This is at much longer wavelengths then the peak of FIR spectrum for dust heated by an active galactic nucleus and substantially longward of the peak for starburst heated dust. The relationship between total luminosity and intensity at these wavelengths is therefore very dependent on the temperature of emitting dust and consequently dependent on geometry of source and difficult to predict. An approximate model following McMahon et al. (1999) but adapted to the now standard cosmology and the redshift of the proposed sample is:

$$M_\mathrm{d} = \frac{S_{\nu=310\,\mathrm{Ghz}}}{1\,\mathrm{mJy}}\,10^{7.9}\,\mathrm{M_\odot} \tag{5}$$

$$L_\mathrm{FIR} \sim 2.5 \times 10^{12}\,\mathrm{L_\odot}\,\frac{S_{\nu=310\,\mathrm{Ghz}}}{1\,\mathrm{mJy}} \tag{6}$$

$$\Psi \sim \alpha 250\,\mathrm{M_\odot\,yr^{-1}}\,\frac{S_{\nu=310\,\mathrm{Ghz}}}{1\,\mathrm{mJy}} \tag{7}$$

where $S_{\nu=310\,\mathrm{Ghz}}$ is observed flux density at 310 GHz, M_d is the dust mass and α depends on the assumed initial mass function of stars and is of order unity. Therefore, under this simple and uncertain model, a star-burst forming stars at rate of $250\,\mathrm{M_\odot\,yr^{-1}}$ will give a continuum flux of about 1 mJy and be well detected with the proposed observations.

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[1] See, e.g., `http://www.astro.ucla.edu/~wright/CosmoCalc.html`

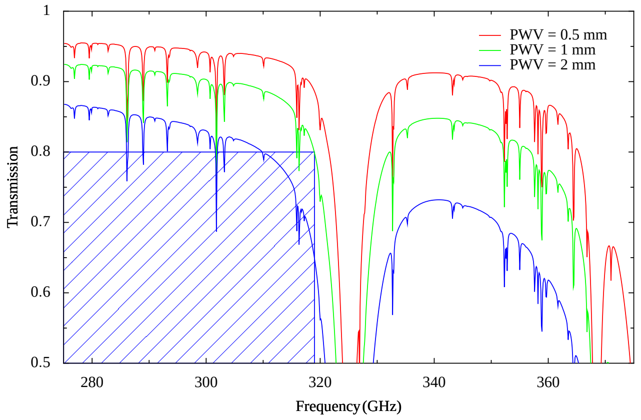

Figure 1. Model atmospheric transmission at the ALMA site for three values of line-of-sight precipitable water vapour column. The hatched range of frequencies is the range for which transmission is greater than 80% for 1 mm of water vapour and consequently the range of frequencies in which I am proposing observations the red-shifted [C II] line. (Transmission curves were computed using the ATM library and the `absorption` program.)

Observationally, Priddey et al. (2003) made continuum observations at 850 μm of a similar sample of quasars and detected four out 14 at flux densities of 14–3.7 mJy, i.e., much higher than the expected detection limit for the proposed observations. Also, for a sub-mm selected galaxy, Valtchanov et al. (2011) find [C II] line to continuum ratio of about 5, which is very similar to the ratio of line to continuum sensitivity for proposed observations.

CO $J = 16 \rightarrow 15$ line. The luminosity of the CO $J = 16 \rightarrow 15$ is difficult to predict. Generally, CO luminosity from at these high J numbers from photon dominated region driven by star formation is expected to be small. In the model for the CO ladder in quasar host galaxies by Wang et al. (2010), for example, the luminosity of CO lines decreases rapidly at $J = 8 \rightarrow 7$ and higher transitions. However, gas heated by X-rays can have high luminosities at high J CO lines (e.g., Meijerink et al. 2007) and the transition can be excited by shocks too. As this line is not the primary target for this survey, a detailed analysis is left for after the measurements are made.

7 REQUESTED OBSERVATIONS

7.1 Array configuration

I request observations in the compact array to ensure that no flux is resolved out in this initial study. In this configuration essentially all baselines are shorter than 120 m (Vila Vilaro et al. 2011) and therefore at our observing frequency have fringe spacings of 1.4 seconds of arc or more. At the redshift of the sample this corresponds to a length scale of about 10 kpc. This is obviously much larger than length scales associated with quasars and the interstellar medium likely to be heated by the quasar (< 1 kpc), and also of typical circum-nuclear starbursts ($\sim$ kpc) and of the existing measurement of the size [C II] emitting region in a high-redshift quasar host by Walter et al. (2009). Therefore it is unlikely to that the sources will be resolved and I assume point-source sensitivity estimates. Additionally, as the sources are unlikely to be resolved, a particularly uniform *uv*-coverage is not required and these observations are well-suited for the snapshot mode being proposed.

7.2 Spectral setup

The target sample is selected so that the [C II] line at rest frequency of $\nu = 1900.536\,\mathrm{GHz}$[2] is observable in the $275\,\mathrm{GHz} < \nu < 319\,\mathrm{GHz}$ atmospheric window. The actual redshift distribution of sources as selected leads to the range of sky frequencies of the [C II] line of 302 to 319 GHz. Because the atmospheric water vapour line limits transmission at frequencies above 319 GHz while transmission and sensitivity is very good below 302 GHz, I propose to observe the [C II] line in the 4-6 GHz IF baseband in the **upper** sideband.

With this setup, the 4-6 GHz IF baseband in the **lower** sideband will observe the CO $J = 16 \rightarrow 15$ line (rest frequency 1841.345 GHz, sky frequency difference at mean redshift is 9.7 GHz), although slightly offset from the centre of the band. The remaining two 6-8 GHz IF basebands are proposed to be used to observe the continuum emission, leading to at least 4 GHz of raw bandwidth for continuum estimation.

7.3 Integration time

The snapshot survey is proposed to target reliable detection of $L_{[\mathrm{C\,II}]} \sim 10^{9.1}\,\mathrm{L}_\odot$ which at the redshift the sample corresponds to $1.7\,\mathrm{Jy\,km\,s^{-1}}$ or about 8.5 mJy peak line flux. A good sensitivity to aim for this is then 1.4 mJy in $100\,\mathrm{km\,s^{-1}}$ which allows $6\,\sigma$ detection of peak of the line and should also constraints the line width even at the survey limit. This sensitivity is achievable with ALMA Cycle 0 in 15 minutes, and therefore the whole sample of 24 sources is observable in only 6 hours of on-source time.

The sensitivity to the CO $J = 16 \rightarrow 15$ will be somewhat better than to the [C II] line because of the lower frequency and higher atmospheric transmission.

The continuum sensitivity is estimated 0.17 mJy assuming 4 GHz of usable bandwidth (i.e., accounting for excision of line emission and baseband edges).

7.4 Calibration requirements

This is a moderate dynamic range snapshot survey so standard ALMA absolute flux calibration should be sufficient. If the ALMA Cycle 0 goal of 10% absolute flux calibration is achieved then this would be comparable to complementary data from other facilities.

Standard phase calibration should be sufficient for this project as the proposal is for compact configuration, moderate frequency, moderate dynamic range and low astrometric accuracy. Moderate spectral dynamic range also reduces the requirements for bandpass calibration.

This project is overall a low risk from aspect of calibration.

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8 PROPOSAL OUTCOME – ADDED 2011-09-08

This proposal was **not** accepted by the ALMA Time Allocation Committee and will not be observed.