A Kiloparsec–Scale Hyper–Starburst in a Quasar Host Less than 1 Gigayear after the Big Bang

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The host galaxy of the quasar SDSS J114816.64+525150.3 (at redshift z=6.42, when the Universe was <1 billion years old) has an infrared luminosity of 2.2×10¹³ L☉, presumably significantly powered by a massive burst of star formation³,⁴,⁵,⁶. In local examples of extremely luminous galaxies such as Arp 220, the burst of star formation is concentrated in the relatively small central region of < 100 pc radius⁷,⁸. It is unknown on which scales stars are forming in active galaxies in the early Universe, which are likely undergoing their initial burst of star formation. We do know that at some early point structures comparable to the spheroidal bulge of the Milky Way must have formed. Here we report a spatially resolved image of [CII] emission of the host galaxy of J114816.64+525150.3 that demonstrates that its star forming gas is distributed over a radius of ~ 750 pc around the centre. The surface density of the star formation rate averaged over this region is ~1000 M☉ year⁻¹ kpc⁻². This surface density is comparable to the peak in Arp 220, though ~2 orders of magnitudes larger in area. This vigorous star forming event will likely give rise to a massive spheroidal component in this system.

The forbidden ²P₃/₂ →²P₁/₂ fine–structure line of ionized Carbon ([CII]) at 158 microns provides effective cooling in regions where atomic transitions cannot be excited, and therefore helps gas clouds to contract and form stars. [CII] emission is thus known to be a fundamental diagnostic tool of the starforming interstellar medium⁹,¹⁰. Given the very bright continuum emission of the central accreting black hole of quasars in optical and near–infrared wavebands, standard star formation tracers (such as hydrogen recombination lines) cannot be used to study star formation in these systems. The [CII]
line is however much brighter than the underlying far–infrared (FIR) continuum, thus making it a prime choice to characterize star formation in quasar host galaxies.

We used the IRAM Plateau de Bure interferometer to resolve the [CII] emission from the z=6.42 host galaxy of J114816.64+525150.3 (one of the most distant quasars known\textsuperscript{11,12}; hereafter: J1148+5251) with a linear resolution of $\sim 1.5$ kpc. J1148+5251 is one of only two sources for which the detection of [CII] emission is reported at high redshift to date\textsuperscript{5,13}. A large reservoir of molecular gas ($2 \times 10^{10} M_\odot$), the prerequisite for star formation, has been characterized in this system through redshifted rotational transition lines of carbon monoxide (CO)$\textsuperscript{3,4,14}$. At a redshift of $z=6.42$ the age of the Universe was just $\sim 870$ million years (or 1/16th of its present age) and 1" on the sky corresponds to 5.6 kpc\textsuperscript{15,16}.

The distribution of the [CII] emission is shown in the middle panel of Figure 1. Gaussian fitting to the spatially resolved [CII] emission gives an intrinsic source size of 0.27"±0.05" (1.5±0.3 kpc). The [CII] emission is embedded within the molecular gas reservoir traced by CO$\textsuperscript{14}$, however the [CII] emission is offset to the north from the optical quasar and the CO peak by $\sim 0.1$" ($\sim 600$ pc). Given the good agreement between the position of the optical quasar and the simultaneous 158 micron continuum observations (Fig. 1, left) we do not attribute this offset to inaccurate astrometry. The significance of the [CII] detection is high enough that it shows spatially resolved velocity structure (red and blue contours in the right panel of Figure 1).

The (rest–frame) FIR continuum emission underlying the [CII] line is detected at 10 sigma significance in the integrated frequency spectrum (Fig. 2). If the FIR continuum was due to the (unresolved) optical quasar, a 10 sigma point source is expected at the optical position. However, from Figure 1 (left) we only find $\sim 50\%$ of the flux to be coincident with the optical quasar position. This implies that the sensitivity of our observations is not high enough to image the remaining FIR flux that is presumably due to the more extended emission from star formation. This would imply that at most 50\% of the FIR emission can be attributed to heating by the central black hole, i.e. the FIR emission is significantly powered by star formation (in good agreement with the molecular gas$\textsuperscript{3,4}$, dense gas$\textsuperscript{17}$, radio continuum$\textsuperscript{6}$ and dust properties$\textsuperscript{1,2}$ of this source).

In the following we thus assume a FIR luminosity due to star formation of $\sim 1.1 \times 10^{13} L_\odot$, i.e., a star formation rate of $\sim 1700 M_\odot$ yr$^{-1}$ (assuming a standard initial stellar mass function$\textsuperscript{1,18}$). The low significance of the resolved FIR emission is the reason why it cannot be used to constrain the size of the starburst region.

The compactness of the [CII] emission implies that massive star formation is concentrated in the central region with radius 750 pc of the system, even though molecular material is available on larger scales (but our [CII] observations cannot rule out star formation at lower surface densities over the entire molecular gas reservoir). Given the star formation rate derived above, we find an extreme average star formation rate surface density of $\sim 1000 M_\odot$ yr$^{-1}$ kpc$^{-2}$ ($\sim 7 \times 10^{12}$ $L_\odot$ pc$^{-2}$) over this central 750 pc radius region. Similarly high starburst surface densities are also found in the centre of local ULIRGs such as Arp 220 (where each nucleus of size $\sim 100$ pc has $L_{\text{FIR}}=3 \times 10^{11} L_\odot$), albeit on spatial scales that are by two orders of magnitudes smaller$\textsuperscript{7,8}$. For comparison, the Galactic young starforming cluster associated with Orion KL also exhibits such high densities in its central region$\textsuperscript{20}$ ($L_{\text{FIR}}=1.2 \times 10^{5} L_\odot$, area: $\sim 1$ arcmin$^2$, 0.013 pc$^2$, resulting in $\sim 10^{13}$ $L_\odot$ kpc$^{-2}$), however over an area that is 8 orders of magnitudes smaller than in J1148+5251.
In the context of other galaxies in the early universe, this kpc-scale ‘hyper’- starburst has a star formation rate surface density that is one order of magnitude higher than what is found in massive starforming z~2.5 submillimeter galaxies\textsuperscript{21}. It is however consistent with recent theoretical descriptions of (dust opacity) Eddington limited star formation of a radiation pressure–supported starburst on kpc scales\textsuperscript{19}. The high star formation rate surface density is also compatible with other theories describing ‘maximum starbursts’\textsuperscript{22}: stars can form at a rate limited by \[\text{SFR}=\epsilon \times \frac{M_{\text{gas}}}{t_{\text{dyn}}}\], where \(\epsilon\) is the star formation efficiency, \(M_{\text{gas}}\) is the gas within radius \(r\) and \(t_{\text{dyn}}\) is the dynamical (or free–fall) time, given by \[\sqrt{\frac{r^3}{2GM}}\]. For \(r=750\) pc, \(M \sim M_{\text{gas}} \sim 10^{10} M_{\odot}\) a star formation efficiency of \(\epsilon \sim 0.4\) is required to explain star formation rate densities that we observe in the case of J1148+5251. Such high efficiencies may be expected given the high dense gas fractions found in local ULIRGs\textsuperscript{23}. In this calculation, we assume that the stellar initial mass function in this object is not significantly different from what is known locally. Such a high star formation efficiency could be expected if J1148+5251 were to undergo a major merger, where the gas is funneled to the central 1.5 kpc on rapid timescales. We note however that our observations do not provide clear evidence for a merging system and that other mechanisms may be responsible for fueling the ongoing starburst\textsuperscript{24}. We also note that the star formation rate surface density of \(\sim 1000 M_{\odot} \text{ yr}^{-1} \text{kpc}^{-2}\) is a value averaged over the central \(\sim\text{kpc}\), i.e. this value could be significantly higher on smaller scales, which in turn may violate the theoretical descriptions of ‘maximum starbursts’.

Our observations provide direct evidence for strong, kpc–scale star formation episodes at the end of Cosmic Reionization that enable the growth of stellar bulges in quasar host galaxies. Such ‘hyper starbursts’ appear to have an order of magnitude higher star formation rate surface densities on kpc scales than previously studied systems at high redshift\textsuperscript{21}. The observations presented here are currently the best means by which to quantify star formation rates and their surface densities in quasars at the earliest cosmic epochs. They thus demonstrate that [CII] observations will play a key role in studies of resolved star formation regions in the first Gyr of the Universe using the upcoming Atacama Large Millimeter/submillimeter Array (ALMA)\textsuperscript{25}.

References:

1. Bertoldi, F., Carilli, C.L., Cox, P., Fan, X., Strauss, M.A., Beelen, A., Omont, A., Zylka, R., Dust and Molecular Emission from High-redshift Quasars, Astron. Astrophy. 406, 55-58 (2003)
2. Beelen, A., Cox, P., Benford, D.J., Dowell, C.D, Kovacs, A., Bertoldi, F., Omont, A., Carilli, C.L. 350 micron Dust Emission from High-Redshift Quasars, Astroph. J. 642, 694-701 (2006)
3. Walter, F., et al. Molecular gas in the host galaxy of a quasar at redshift z = 6.42, Nature 424, 406-408 (2003)
4. Bertoldi, F., et al. High-excitation CO in a quasar host galaxy at z =6.42, Astron. Astrophy. Letter 409, 47-50 (2003)
5. Maiolino, R., et al., First detection of [CII]158 \(\mu\)m at high redshift: vigorous star formation in the early universe, Astron. Astrophy. Letters 440, 51-54 (2005)
6. Carilli, C., et al., Radio Continuum Imaging of Far-Infrared-Luminous QSOs at
1. Fan, X., et al., A Survey of $z > 5.7$ Quasars in the Sloan Digital Sky Survey. II. Discovery of Three Additional Quasars at $z > 6$, *Astron. J.* **125**, 1649-1659 (2003)

2. Spergel, D.N., et al., Three-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Implications for Cosmology, *Astroph. J. Suppl.* **170**, 377-408 (2007)

3. Wright, E.L., A Cosmology Calculator for the World Wide Web, *Publ. Astron. Soc. Pac.* **118**, 1711-1715 (2006)

4. Thompson, T., Quataert, E., Murray, N., Radiation Pressure-supported Starburst Disks and Active Galactic Nucleus Fueling, *Astroph. J.* **630**, 167-185 (2005)

5. Elmegreen, B.G., Galactic Bulge Formation as a Maximum Intensity Starburst, *Astroph. J.* **517**, 103-107 (1999)

6. Gao, Y., Solomon, P.M., HCN Survey of Normal Spiral, Infrared–Luminous, and Ultraluminous Galaxies, *Astroph. J. Suppl.* **152**, 63-80 (2004)

7. Dekel, A., Birnboim, Y., Engel, G., Freundlich, J., Goerdt, T., Mumcuoglu, M., Neistein, E., Pichon, C., Teyssier, R., Zinger, E., The Main Mode of Galaxy Formation: Early Massive Galaxies by Cold Streams in Hot Haloes, *Nature*, under review (2008)
25. Walter, F., Carilli, C., Detecting the most distant \((z>7)\) objects with ALMA, *Astroph. \& Space Science* **313**, 313-316 (2008)

26. White, R.L., Becker, R.H., Fan, X., Strauss, M.A., Hubble Space Telescope Advanced Camera for Surveys Observations of the \(z = 6.42\) Quasar SDSS J1148+5251: A Leak in the Gunn-Peterson Trough, *Astron. J.* **129**, 2102-2107 (2005)

27. Solomon, P.M. & Vanden Bout, P.A., Molecular Gas at High Redshift, *Ann. Rev. Astron. Astroph.* **43**, 677-725 (2005)

28. Malhotra, S., et al. Infrared Space Observatory Measurements of \([\text{C II}]\) Line Variations in Galaxies, *Astroph. J.* **491**, 27-30 (1997)

29. Luhman, M.L, Satyapal, S., Fiuscher, J. Wolfire, M.G., Cox, P., Lord, S.D., Smith, H.A., Stacey, G.J., Unger, S.J. Infrared Space Observatory Measurements of a \([\text{C II}]\) 158 Micron Line Deficit in Ultraluminous Infrared Galaxies, *Astroph. J. Letters* **504**, 11-15 (1998)

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Figure 1: [CII] observations of the z=6.42 quasar J1148+5251 obtained with the IRAM Plateau de Bure interferometer. Observations were obtained in the most extended antenna configuration during three tracks in early 2007 and 2008 ($\nu_{\text{obs}}=256.17$ GHz, $\nu_{\text{rest}}=1900.54$ GHz), resulting in a resolution of $0.31'' \times 0.23''$ (1.7 kpc $\times$ 1.3 kpc; the beam-size is shown in light blue colour in the middle panel). The resolved CO emission from VLA observations is displayed as colour scale in all three panels. The cross indicates the absolute position (uncertainty: $0.03''$) of the (unresolved) optical quasar as derived from Hubble Space Telescope observations.

Left: Contours represent the far–infrared continuum emission obtained from the line–free channels of the [CII] observations integrated over a 445 km s$^{-1}$ bandwidth (contour levels are $-0.9$ (grey), $0.9$ and $1.8$ mJy (black); rms noise: $0.45$ mJy). There is good agreement between the optical quasar and the peak of the continuum emission, as well as the peak of the molecular gas emission traced by CO, demonstrating that our astrometry is accurate on scales of $< 0.1''$.

Middle: Contours show the [CII] emission over a velocity range of $-293$ to $+293$ km s$^{-1}$ (contours are plotted in steps of $0.72$ mJy; rms noise: $0.36$ mJy). The (rest–frame) beam–averaged peak brightness temperature of the [CII] emission is $9.4 \pm 0.9$ K (from the peak flux of $7.0 \pm 0.36$ mJy at a resolution of $0.31'' \times 0.23''$), which is similar to the CO brightness temperature ($8.3$ K)\textsuperscript{14}. If the intrinsic temperature of the gas were similar to that of the dust (30–50 K), this would imply that we have not fully resolved the CO or the [CII] emission.

Right: Contours of blue– and red–shifted emission (averaged over velocities from $75$–$175$ km s$^{-1}$ on either side) are plotted as blue and red contours at $3.2$ and $4.8$ mJy, respectively (rms noise: $0.63$ mJy). The dynamical mass of $\sim 10^{10} M_\odot$ within the central 1.5 kpc deduced from these observations (assuming $v_{\text{rot}} \sim 250$ km s$^{-1}$) is in agreement with earlier estimates on larger spatial scales\textsuperscript{14}. 
Figure 2: Spatially integrated [CII] spectrum of the $z=6.42$ quasar J1148+5251. The [CII] line is detected at high significance (bandwidth covered: 1 GHz, or 1100 km s$^{-1}$) and is present on top of a $4.5\pm0.62$ mJy continuum (consistent with an earlier estimate$^1$ of $5.0\pm0.6$ mJy). Gaussian fitting to the line gives a [CII] peak flux of $12.7\pm1.05$ mJy, a full width at half maximum (FWHM) velocity of $287\pm28$ km s$^{-1}$ and a central velocity of $3\pm12$ km s$^{-1}$ relative to the CO redshift$^4$ of $z=6.419$ ($\nu_{\text{obs}}=256.17$ GHz). This leads to a [CII] flux of $3.9\pm0.3$ Jy km s$^{-1}$ (consistent with earlier, unresolved observations$^5$ of $4.1\pm0.5$ Jy km s$^{-1}$), which corresponds to a [CII] luminosity$^27$ of $L_{\text{[CII]}}=1.90\pm0.16\times10^{10}$ K km s$^{-1}$ pc$^{-2}$ or $L_{\text{[CII]}}=4.18\pm0.35\times10^9 L_{\odot}$ (adopting a luminosity distance of $D_{\text{L}}=64$ Gpc$^{16}$), yielding $L_{\text{[CII]}}/L_{\text{FIR}}=1.9\times10^{-4}$. This ratio is by an order of magnitude smaller than what is found in local starforming galaxies (a finding consistent with local ultra-luminous infrared galaxies, ULIRGs$^{5,28,29}$). The line–free channels of the [CII] observations are used to construct a continuum image of J1148+5251 at 158 microns (rest wavelength) as shown in Fig. 1 (left).