X-shooter Science Verification Proposal

Title:Detailed Study of the UV–Optical Spectrum in a Lensed Sub-mm Galaxy

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Abstract:

During a sub-mm survey of massive clusters using APEX/LABOCA we have recently discovered the brightest sub-mm galaxy known. With 106 mJy at 870μm this is a factor 3× brighter than any other high-z star-forming galaxy and even brighter than the lensed QSOs (the Cloverleaf and APM08729). The brightness of this source is due to gravitational amplification by a foreground cluster. The source we detected actually represent an elongated image of the background galaxy, with an amplification factor of $\sim 32\times$, so that intrinsically this is a fairly "normal" star-forming galaxy with an unlensed sub-mm flux of ~3mJy and hence a far-IR luminosity of $\sim 1\times 10^{12} L_\odot$ (i.e. a high-z ULIRG). Critically the lens amplification results in a similar increase in the linear resolution of any observations of the source, by a factor of $\sim 10\times$. We have a spectroscopic redshift in hand (z =2.326). Given the uniqueness of this source, we propose to obtain an Xshooter spectrum to probe the rest-frame UV–optical emission line properties. This will allow us to study the chemical abundances (through the R_{23} index), the Lyα/Hα emission line flux ratio, redenning corrected star-formation rate and search for AGN signatures. This target is the first high-z ULIRG offering the opportunity for detailed follow-up on sub-kpc scales, similarly to the local example of Arp220 but seen at $z \sim 2$.

Scientific Case:

In the last decade UV/optical surveys have suggested that the star formation activity in the Universe peaked ~8 Gyrs ago at z ~ 1 (Lilly et al. 1996, Madau et al. 1996). However, surveys in the mid- and far-infrared show that up to half of the extra-galactic background light is radiated in the infrared, peaking near 200μm. Much of this background appears to be produced by obscured star-formation in dusty, but intrinsically luminous, infrared (IR) galaxies (LIRGs, $L_{FIR} \geq 10^{11} L_\odot$) which are expected to lie at moderate and high redshifts, z ~ 1 (Dole et al. 2004; Papovich et al. 2004). Crucially, surveys at longer wavelengths, particularly in the sub-mm/mm, have suggested that far-IR luminous galaxies may even dominate the star-formation at z > 1 (Blain et al. 1999). Due to the dust, these galaxies are typically faint in the restframe UV, and so their importance is understated by UV/optical surveys. Thus, understanding the evolution of star-formation rate density with redshift requires characterisation and interpretation of galaxies selected from both optical/UV **and** infrared and sub-mm wavelengths (e.g. Lagache et al. 2005). This proposal is concerned with characterising the rest-frame UV–optical emission lines from the brightest sub-mm galaxy so far found, on sub-kpc scales.

This proposal: We recently discovered the brightest high-redshift sub-millimeter source known, with an 870-μm flux of 106±3mJy based on APEX/LABOCA observations (Fig. 1). This is 3× brighter than any other high-redshift sub-millimeter galaxy, and even brighter than the brightest sub-millimeter QSOs (APM08279 or the Cloverleaf). The brightness of this source is due to gravitational amplification by the foreground cluster MACS2135 (Fig. 2). On 19th May, we obtained a redshift measurement using Zpectrometer on GBT, derived as z = 2.32 through the detection of the CO(1-0) line (Fig. 3). Using our lensing model for the cluster MACS2135, we identify the submillimeter source as a pair of images of a background galaxy, which straddle the z = 2.32 radial critical curve (Fig.2, in blue), with a third fainter image identified on the opposite side of the cluster center. This source is amplified by a factor of 32× (or 4 magnitudes), so that intrinsically this is a fairly "normal" star-forming SMG with an unlensed sub-millimeter flux of ~3mJy and so a likely far-infrared luminosity of 3×10^{12} L$\odot$, comparable to the local ULIRG Arp 220. We have identified this radial arc throughout the optical, near-infrared and mid-infrared wavelengths, from archival ACS/F606W, UKIRT/K band and Spitzer/IRAC images of the same field of view. The overall SED shows a strong increasing flux with wavelength.

[1]This proposal is submitted for a larger group including teams from the Green Bank Telescope (GBT) and the Plateau de Bureau Interferometer (PdBI)

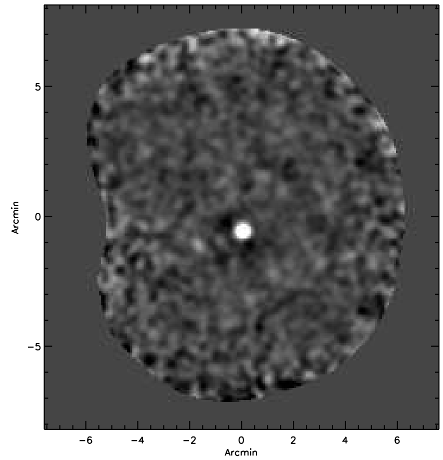

Fig. 1. APEX/LABOCA 870μm image of the cluster MACS2135-0102 showing the 106 mJy detection of the lensed galaxy which is detected at $>30\,\sigma$ in just 2 hours.

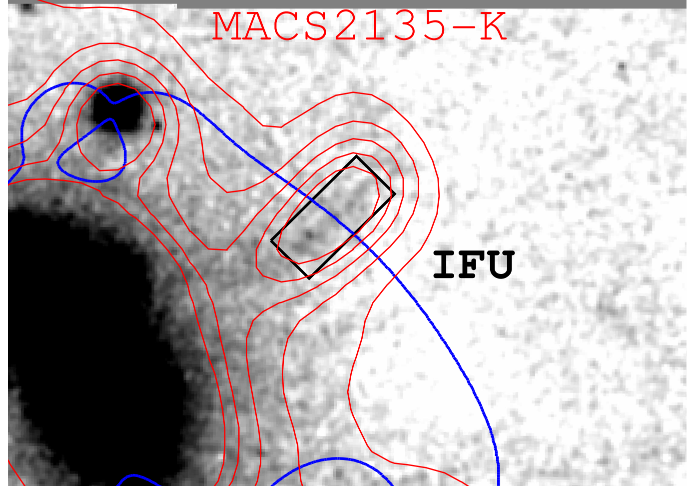

Fig. 2. Close-up of UKIRT/UFTI shallow (10 mins) K band image showing the near-infrared counterimage of the SMM lensed galaxy which forms a radial arc. The object straddles the radial critical curve at $z = 2.326$ (blue line), as derived from our lensing mass model. We overlaid in red the contours from the IRAC-3.6μm image.

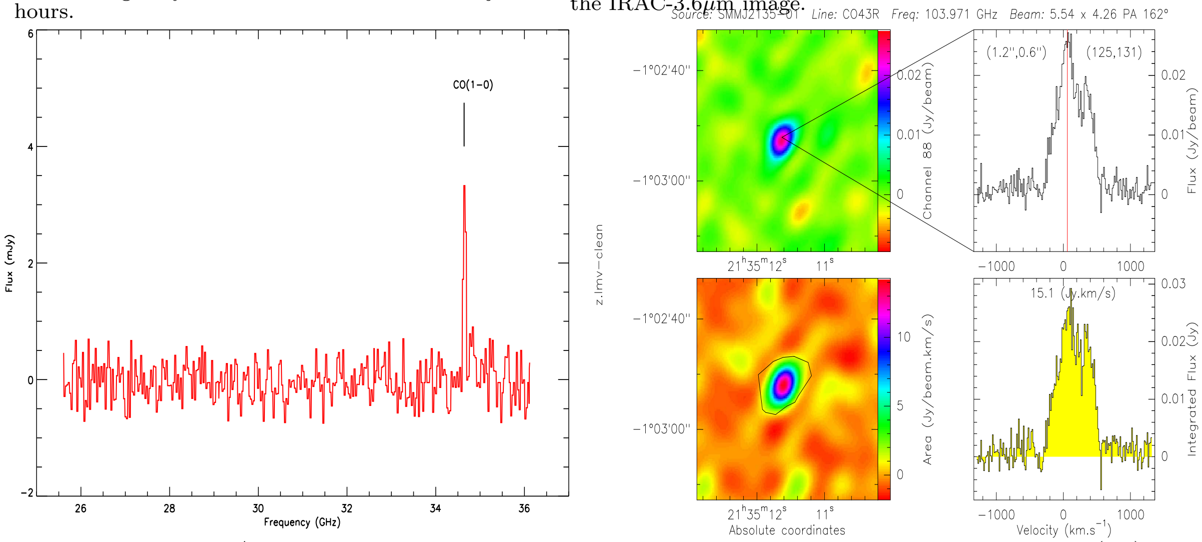

Fig. 3: *Left:* GBT/Zpectrometer spectrum of the galaxy taken on 19 May showing a strong detection of CO(1-0) and used to derive a redshift of z=2.3259$\pm$0.0002. The peak flux is 3.4 mJy and the line width is FWHM=450 km s^{-1}. *Right:* Subsequent PdBI observations around the redshifted CO(3-2) taken on 21st May through a PdBI DDT observation. The velocity structure in the CO emission is double horned and clearly non-gaussian, preliminarily suggesting disk-like dynamics.

We propose to follow-up this unique object with Xshooter in order to obtain the overall optical to near-infrared spectrum, with the following science goals:

- SFR and global chemical abundances from HII regions emission lines: The sub-millimeter flux of this source is equivalent to an observed (magnified by $\times$32 due to lensing) star formation rate of $\sim$16000 M$\odot$/yr, after conversion to a bolometric luminosity assuming the typical dust temperature of SMGs (e.g. Coppin et al. 2006, Kovacs et al. 2006). Even assuming a typical 10$\times$ decrement (e.g. Swinbank et al. 2004), the Hα flux will be $> 5\times10^{-15}$ ergs/s/cm^2. The Hα flux and the Hα/Hβ Balmer decrement will provide us with more precise measurements of the star-formation rate and reddening, respectively. Thanks to the magnification, we expect the $[OII]$,Hβ and $[OIII]$ line fluxes to range between $\sim 5\times10^{-16}$ and $\sim 1\times10^{-15}$ ergs/s/cm^2, and therefore to be easily detected in the near-infrared. This will enable to measure the global metallicity and chemical abundances from the widely-used R23 method (Zaritsky et al. 1994). The metallicity degeneracy in the R23 relation can be broken through the measurement of additional lines such as $[NII]$ and $[SII]$ located close to the Hα line. We even expect to detect the faint $[OIII]$ line at rest-frame 4636 Å, expected to have a flux ratio $[OIII]_{4636}/[OIII]_{5007} = 0.02$ (Hu et al. 2009), and which would enable a metallicity measurement through the direct method.

- Rest-frame UV and optical spectra comparisons: In the case of Lyman-α in emission in the optical spectrum, we will compare the Lyman-α and Hα fluxes (and derived SFR) and use the shape of the line to estimate the effect of galactic outflows, known to affect the Lyman-α line shape and make it appear redshifted.

- Resolved dynamics and metallicity. Critically the magnification by the foreground lens results in an increase in the linear resolution of all observations of this source, by a factor of $\sim$10$\times$. Hence, under 0.8-arcsec seeing we reach an effective resolution of 0.08-arcsec in the source, or 600 parsecs.

As the source is extended by $\sim 3 \times 0.8$ arcsec, it perfectly matches the 0.9"-width slit of Xshooter, or the IFU mode (Fig. 2). In both cases, by measuring HII emission line fluxes across the image , we will directly probe the resolved dynamics with > 5 individual resolution elements in the source plane in a $z \sim 2$ galaxy. The high signal-to-noise expected in each line would enable to obtain a pixel-to-pixel map of the metallicity and reddening (through the Balmer line ratio) at 600 pc resolution. In the case of Lyman-α in emission, we will measure the relative velocities between Lyman-α and Hα across the galaxy on the same scales, to search for evidence of outflows. This was done before using the combination of VIMOS and SINFONI observations at $z = 5$ (Swinbank et al. 2007).

- Searches for possible AGN signatures: together with the usual strong starburst lines (Balmer series, $[OII]$, $[OIII]$, $[NII]$,$[SII]$) we will search for fainter lines in the rest-frame UV and optical spectrum, such as CIV (1549 Å), [OI] (6300 Å) and HeII (5876 Å). This will allow us to determine the possible AGN contribution in the overall spectrum, providing a more reliable star-formation rate measurement. Since the galaxy is spatially extended, we will also be able to resolve out the AGN contribution.

Targets and observing mode

Target	RA	DEC	V mag	K mag	Mode (slit/IFU)	Remarks
MACSJ2135-0102	21 35 11.55	-01 02 52.7	23.0	18.5	IFU or 0.9"-width slit	Seeing < 0.8"

Time Justification:

With expected emission line fluxes of ($0.5 - 5 \times 10^{-15}$ ergs/s/cm^2) in the near-infrared, the main goals of this proposal should be straightforward with X-shooter. Based on X-shooter ETC estimates assuming an extended object of 3×0.8" , constant surface brightness and an exposure time of 1 hour (long slit mode) or 2 hours (IFU mode), we will detect the Halpha, $[OIII]_{5007}$, Hbeta, and $[OII]_{3727}$ with SNR=10-100, and even the much fainter lines such as $[OIII]_{4363}$ which is only usually detected in local galaxies where high s/n can be reached. The spatially resolved physical properties are best achieved with X-shooter using the Integral Field Unit mode. However, since this object is extended by 3 arcsec along a specific direction, the main goals of this proposal (including the spatially resolved physical properties) can also be achieved with a 0.9"-width long slit oriented at a position angle 135 degrees (North increasing East).

In summary: we request 2 hours observations with X-shooter in IFU mode, or alternatively 1 hour in long-slit mode, to measure the line fluxes, line velocities and widths in an rest-frame optical/near-infrared spectrum of a highly magnified $z = 2.3$ submillimeter galaxy.