Optical and Near-Infrared Integral Field Spectroscopy of the SCUBA Galaxy N2-850.4

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ABSTRACT

We present optical and near-infrared integral field spectroscopy of the SCUBA galaxy SMM J163650.43+405734.5 (ELAIS N2 850.4) at z=2.385. We combine Lyα and Hα emission line maps and velocity structure with high resolution HST ACS and NICMOS imaging to probe the complex dynamics of this vigorous star-burst galaxy. The imaging data shows a complex morphology, consisting of at least three components separated by ~1″ (8 kpc) in projection. When combined with the Hα velocity field from UKIRT UIST IFU observations we identify two components whose redshifts are coincident with the systemic redshift, measured from previous CO observations, one of which shows signs of AGN activity. A third component is offset by 220±50 km s⁻¹ from the systemic velocity. The total star formation rate of the whole system (estimated from the narrow-line Hα and uncorrected for reddening) is 340±50 M⊙ yr⁻¹. The Lyα emission mapped by the GMOS IFU covers the complete galaxy and is offset by +270 ± 40 km s⁻¹ from the systemic velocity. This velocity offset is comparable to that seen in rest-frame UV-selected galaxies at similar redshifts and usually interpreted as a star-burst driven wind. The extended structure of the Lyα emission suggests that this wind is not a nuclear phenomenon, but is instead a galactic scale outflow. Our observations suggest that the vigorous activity in N2 850.4 is arising as a result of an interaction between at least two dynamically-distinct components, resulting in a strong starburst, a starburst-driven wind and actively-fuelled AGN activity. Whilst these observations are based on a single object, our results clearly show the power of combining optical and near-infrared integral field spectroscopy to probe the power sources, masses and metallicities of far-infrared luminous galaxies, as well as understanding the role of AGN- and star-burst driven feedback processes in these high redshift systems.

Key words: galaxies: high-redshift, sub-mm; - galaxies: evolution; - galaxies: star formation rates, AGN; - galaxies: specific: SMM J163650.43+405734.5 (N2 850.4).

1 INTRODUCTION

Recent surveys have concluded that a substantial fraction of the high redshift submillimetre (sub-mm) selected galaxy population comprises morphologically complex systems with high instantaneous star formation rates and actively fuelled AGN (Smail, Ivison & Blain 1997; Barger et al. 1999; Scott et al. 2002; Smail et al. 2002; Ivison et al. 2002; Alexander et al. 2003, 2005; Chapman et al. 2003; Webb et al. 2003; Dannebauer et al. 2004; Knudsen 2004; Swinbank et al. 2004; Chapman et al. 2005a; Pope et al. 2005). Understanding the importance of this population requires identifying their power source (e.g. to determine whether star formation- or AGN- activity dominate the luminosity output) and, perhaps more importantly, masses for these galaxies. Although they have only moderate space densities, their apparently high star formation rates mean their contribu-
Figure 1. (a) True colour $I_{814}$-band image of N2 850.4 from the HST ACS and NICMOS imaging. The image shows a complex morphology, with at least three distinct components separated by $\sim 1''$ (\~8 kpc) in projection. (b) IRTF Hα narrow-band image of N2 850.4 with the contours from the NICMOS $H_{160}$-band image overlaid. This Hα narrow-band image shows a diffuse halo of material distributed asymmetrically around the galaxy [seeing $\sim 0.7''$]. (c) The velocity field of N2 850.4 derived from UIST IFU observations of the Hα emission line overlaid on the NICMOS $H_{160}$-band image. The redshift of component A is in excellent agreement with previous CO observations (Neri et al. 2003). Components A and B are separated by $50 \pm 50$ km s$^{-1}$ whilst there is a velocity difference of $+270 \pm 50$ km s$^{-1}$ between components A and C [the 0.6'' seeing is marked by the solid bar in the top left hand corner]. (d) HST ACS $I_{814}$-band (F814) image of N2 850.4 with the Lyα intensity from the GMOS IFU overlaid as contours (the contours mark 3, 4, 5, 6 and 7σ). We also overlay the footprint of the GMOS IFU fibers which have $> 3\sigma$ emission line detections. The solid bar in the top left hand corner of this panel represent 0.6'' seeing. The Lyα contours match the high surface brightness emission traced by the $I_{814}$-band imaging data, although there is Lyα emission to the East (labelled D) which is not seen in the $I_{814}$-band morphology. The Lyα is redshifted from the systemic by $+270 \pm 40$ km s$^{-1}$ which may be indicative of a galactic-scale outflow.

to the cosmic star formation rate could be significant (e.g. Chapman et al. 2005b). Moreover, the star formation activity suggests a priori that these galaxies should house starburst-driven superwinds – outflows which expel gas from the galaxy potential (e.g. Pettini et al. 2001; Shapley et al. 2003) and which are believed to play an important role in regulating galaxy formation, preventing the bulk of baryons cooling into stars (the “cosmic cooling crisis”, White & Rees 1978; Cen & Ostriker 1999; Balogh et al. 2001). However, to study the energetics and dynamics of these frequently complex systems (e.g. Smail et al. 2004) we must trace the distribution of the velocity and intensity of emission lines on sub-arcsecond scales. Ideally, this should be achieved in 2-D to untangle the complex morphologies of these systems and, in addition to search for signatures of lensing, which might provide a more mundane explanation of the apparently intense luminosities of these galaxies (Tecza et al. 2004).

In this paper we demonstrate the power of combining optical and near-infrared integral field spectroscopy with high resolution Hubble Space Telescope (HST) imaging to
study the dynamics, morphologies, masses and outflows of SCUBA galaxies. Using the Integral Field Units (IFUs) on GMOS (optical) and UIST (near-infrared) we have studied the SCUBA galaxy SMMJ163650.43+405734.5 (ELAIS N2 850.4; Scott et al. 2002; Ivison et al. 2002; Smail et al. 2003). In §2 we present the data reduction and results from the spectroscopic and imaging data. In §3 and §4 we present our analysis and conclusions respectively. We use a cosmology with \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_M = 0.3 \) and \( \Omega_{\Lambda} = 0.7 \) in which \( 1'' \) corresponds to 8.2 kpc at \( z = 2.4 \).

2 OBSERVATIONS AND ANALYSIS

N2 850.4 was first catalogued as a bright \((8.2 \pm 1.7\text{ mJy})\) sub-mm source by Scott et al. (2002) and identified through its radio counterpart by Ivison et al. (2002). A spectroscopic redshift of \( z = 2.38 \) for the radio counterpart was measured by Chapman et al. (2003, 2005a). N2 850.4 has a far-infrared bolometric luminosity of \( L_{\text{FIR}} = 3.1 \times 10^{13} \text{L}_{\odot} \) (Chapman et al. 2005a) which corresponds to a star formation rate of \( \sim 5400 \text{M}_{\odot}\text{yr}^{-1} \), (Kennicutt 1998); (although the far-infrared luminosity may have a contribution from a non-thermal (AGN) component). Interferometric observations of the molecular CO emission in this system by Neri et al. (2003) have tied down the systemic redshift as \( z = 2.384 \pm 0.001 \) and indicate a gas mass of \( 5.5 \times 10^{10} \text{M}_{\odot} \). The system was studied in detail by Smail et al. (2003) whose multi-wavelength longslit observations suggest that this system comprises at least two components, one of which has a Seyfert-like AGN and the other maybe a UV-bright starburst with an outflow. These observations show extended [OIII]5007 emission as well as strong UV stellar absorption features.

However, due to the multi-component nature of this system and the way in which longslit observations mix spatial and spectral resolution, the observations of this galaxy have been difficult to interpret (Smail et al. 2003). By targeting N2 850.4 with an IFU we are able to decouple the spatial and spectral resolution and cleanly probe the dynamics and power sources of this hyper-luminous SCUBA galaxy.

2.1 HST Optical and Near-Infrared Imaging

HST Advanced Camera for Surveys (ACS) observations were obtained from the HST public archive\(^{\dagger}\) (Program ID \#9761). The data consist of dithered exposures with the F814W filter, taken in LOWSKY conditions using the default four point ACS-WFC-DITHER-BOX configuration. This pattern ensures optimal half-pixel sampling along both coordinates. The total integration time was 4.8 ks. We reduced the data using the latest version of the MULTIDRIZZLE software (Koekemoer et al. 2002) using the default parameters with PIMFRAC=1 and SCALE=1. The resulting image has 0.05'' pixels and is free from artifacts (Fig. 1).

The NICMOS data were obtained in Cycle 12, and the target was observed using the NIC2 camera in the F160W filter for a total of 2.3 ks (Program ID \#9856). We employed the standard four point spiral dither pattern, LOWSKY conditions and used the MULTICAM readmode. Each exposure was corrected for a pedestal offset, and then mosaiced using the CALMICB task in IRAF. Unfortunately the observation was effected by the South Atlantic Anomaly (SAA), and extra processing steps were required\(^{\ddagger}\). The final images appear very flat and have very low cosmic ray contamination. Absolute astrometry of the NICMOS images is accurate to only \( \lesssim 2'' \), so we cross-correlated the full image against the high resolution ACS data to align the near-infrared image with the optical image. Both are aligned to the FK5 coordinate system of our deep radio map of this field (Ivison et al. 2002) which has an absolute astrometry precision of 0.3''. A complete discussion of the optical and near-infrared observations and data-reduction is given in Borys et al. (2005).

We degrade the HST ACS data to the same resolution as the NICMOS observations and make a true colour (\( I_{814} - H_{160} \)) image of N2 850.4. An inspection of this imaging data (Fig. 1) reveals a complex system made up of several components. In particular, the brightest features have similar colours and an apparent geometry which is reminiscent of a triply-imaged, strongly lensed system. Could the immense luminosity of N2 850.4 be due to strong lensing (e.g. Chapman et al. 2002)\(^{\ddagger}\)? Our IFU observations of this system provide a powerful tool for testing this suggestion, since the redshifts and spectral features should be the same for all three components if they are all images of a single background galaxy.

2.2 IRTF Narrow-band Imaging

Narrow-band imaging of N2 850.4 was carried out using the 3-m NASA Infra-Red Telescope Facility\(^{\ddagger}\) (IRTF) Telescope between 2003 April 28 and May 02. The observations were made in generally photometric conditions and \( \sim 0.7'' \) seeing. We used the NSFCAM camera (Shure et al. 1993) which employs a 256 \times 256 InSb detector at 0.15'' pixel\(^{-1}\) to give a 38'' field of view (which probes roughly 300 kpc at \( z \sim 2.4 \)). The continuously variable tunable narrow-band filter (CVF) in NSFCAM provides an \( R = 90 \) passband which was tuned to target the H\a emission at the systemic galaxy redshift measured \( (z = 2.384) \) from CO and UV spectrum of Neri et al. (2003) and Smail et al. (2003) respectively. Shorter, matched broad-band imaging were interspersed between the narrow-band exposures to provide continuum subtraction. The total narrow-band integration time was 19.8 ks and the total broad band integration time was 2.2 ks. These observations, their reduction and analysis are discussed in detail in Swinbank et al. (2004).

\( ^{\dagger} \) For a full description, see http://www.stsci.edu/hst/nicmos/tools/post_SAA_tools.html

\( ^{\ddagger} \) The Infrared Telescope Facility is operated by the University of Hawaii under Cooperative Agreement no. NCC 5-538 with the National Aeronautics and Space Administration, Office of Space Science, Planetary Astronomy Program.
2.3 Spectroscopic Imaging

2.3.1 UIST Near-Infrared Integral Field Spectroscopy

Observations of N2 850.4 were made in queue mode with the UKIRT Image-Spectrometer (UIST) IFU between 2003 March 27 and April 04 in <0.6″ seeing and photometric conditions\(^5\). The UIST IFU uses an image slicer and reimaging mirrors to reformat a square array of 14-slices of the sky, (each 0.24″×0.12″) into a pseudo-longslit. The resulting field of view is 3.4″×6.0″ (Ramsay Howat et al. 2004).

We used the HK grism which has a spectral resolution of λ/Δλ = 1000 and covers a wavelength range of 1.4-2.4μm. Observations were carried out in the standard ABBA configuration in which we chopped away to sky by 12″ to achieve good sky subtraction. Individual exposures were 240s seconds and each observing block was 7.2 ks which was repeated four times, thus the total integration time was 28.8 ks.

To reduce the data we used the relevant ORAC-DR pipeline (Cavanagh et al. 2003) which sky-subtracts, extracts, wavelength calibrates, flatfields, and forms the datacube. To accurately align and mosaic the four datacubes we created white light (wavelength collapsed) images around the redshifted Hα emission line from each observing block and used the peak intensity to centroid the object in the IFU datacube. We then spatially aligned and co-added the four individual data-cubes (weighted by Hα signal-to-noise) using MOSAIC in KAPPA.

To search for velocity structure we attempt to identify Hα emission on a pixel-by-pixel basis by averaging over a 0.48″×0.48″ region (4×2 pixels), increasing to 0.6″×0.72″ (5×3 pixels) if no emission line could initially be identified. At z = 2.385, Hαλ6562.8 emission falls at 2.221μm, which is away from any strong OH emission or absorption. We attempt to fit a single Gaussian to the Hα emission line, but also attempt to identify an [NII]λ6583 emission line, only accepting the fit if the χ² is significantly better than without the [NII] line. We checked the wavelength calibration of each IFU pixel by fitting a nearby sky line with a Gaussian profile. The errors in the velocity field are calculated building two independent data-cubes, each of 14.4 ks and recomputing the velocity field in an identical manner to that described above. Using the same fitting techniques as above we estimate that the average velocity error to be ≃ 50 km s\(^{-1}\). Spectra from the three components identified in the UIST IFU observations are shown in Fig. 2.

To confirm the velocity gradients seen in the UIST IFU data (Fig. 1) we also obtained a 4.8 ks exposure around the Hα emission lines with the Keck near-infrared longslit spectrograph. We aligned the slit along components A and B in Fig. 1 and derive the same velocity offsets between components as in our the IFU data (the spectra and line fluxes are shown and discussed in Swinbank et al. 2004).

2.3.2 GMOS Optical Integral Field Spectroscopy

N2 850.4 was observed with the GMOS-IFU on Gemini North on 2002 June 12 during Science Demonstration Programmes ID: GN-2002A-DD-4. Obtained at the Gemini Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: the National Science Foundation (United States), the Particle Physics and Astronomy Research Council (United Kingdom), the National Research Council (Canada), CONICYT (Chile), the Australian Research Council (Australia), CNPq (Brazil) and CONICET (Argentina).

\(^5\) The United Kingdom Infrared Telescope is operated by the Joint Astronomy Centre on behalf of the UK Particle Physics and Astronomy Research Council.

Figure 2. Top: Near-infrared spectrum of component A around the Hα emission line. This component is at the same redshift as the systemic redshift (z = 2.384) as measured from the molecular CO emission by Neri et al. (2003). Middle: Near-infrared spectrum of component B from which shows a +50 ±50 km s\(^{-1}\) velocity shift from the systemic. This component also has a broad Hα regions offset by +800±150 km s\(^{-1}\) which indicates AGN activity. The FWHM of the broad line is 2300 ± 250 km s\(^{-1}\). Lower: Near-infrared spectrum of component C which shows a 220 ± 50 km s\(^{-1}\) velocity offset from the systemic. Component C also displays a broad line component (FWHM = 1800 ± 300 km s\(^{-1}\)) which is at a similar redshift to the broad line seen in component B and may arise due to the same scattering seen in [OIII]λ5007 seen by Smail et al. (2003). The top panel has been binned by a factor of two in the spectral direction to enhance the contrast of the Hα emission. The dotted line shows the wavelength for Hα expected at the systemic redshift of 2.384 (Neri et al. 2003; Smail et al. 2003).

due to the same scattering seen in [OIII]λ5007 seen by Smail et al. (2003). The top panel has been binned by a factor of two in the spectral direction to enhance the contrast of the Hα emission. The dotted line shows the wavelength for Hα expected at the systemic redshift of 2.384 (Neri et al. 2003; Smail et al. 2003).
that the extracted spectra included the blue edge of the CCD (where the Lyα emission falls) and then used to extract and wavelength calibrate the spectra of each IFU element. The variations in fibre-to-fibre response were removed using the continuum around the expected range of Lyα emission. To check the wavelength calibration around 4100Å we wavelength calibrated the CuAr arc observations and fit the arc lines between 4000 and 4200Å with Gaussian profiles. We measure the rms offset between the observed arc line centroids and the arc line list to be less than 0.02Å (which corresponds to less than 8 km s\(^{-1}\) in the rest frame of the galaxy). This gives us confidence that any velocity structures or offsets in the HST IFU data are real and not simply an artifact of the observations. To search for velocity structure the spectra were averaged over a 3 × 3 pixel (0.6′′ × 0.6′′) spatial region, except where the signal was too low to give a significant detection of the line, in which case the smoothing area was increased to 4 × 4 pixels. In regions where this averaging process still failed to give an adequate \(\chi^2\) (i.e. the inclusion of an emission line component does not improve the fit), no fit was made. In order to detect and fit the line we required a minimum S/N of 3 and checked every fit by eye. In the inner regions of the galaxy all of the Gaussian profile fits are accepted, while in the outer regions we reject fits if the line centroid is greater than 3000 km s\(^{-1}\) away from the systemic, or the best fit Gaussian profile has a width greater than FWHM\(\pm 320\) km s\(^{-1}\). This indicates star-formation rather than AGN activity, although there is also evidence for a broad-line Hα component which is at the same redshift as the broad line seen in component B (Fig. 2). This broad line may arise as part of the same scattered emission seen in the [OIII]5007 emission in Smail et al. (2003). To attempt to identify which component hosts the AGN activity, we construct a (wavelength collapsed) white light image from the datacube between 2.23µm and 2.25µm (i.e. the broad-line Hα emission) and compare this with the white light image generated by collapsing the datacube between 2.215µm and 2.225µm (which includes the narrow-line Hα emission). Unfortunately these two images look very similar and it is not possible to identify which component hosts the AGN.

The velocity offsets and spectral differences seen among the various morphological components immediately rules out the possibility that all are gravitational lensed images of a single background source. Instead, it appears that N2-850.4 is a multi-component and complex merger. Assuming the velocity offsets arises due to merging components in the potential well, we estimate a dynamical mass of \(\geq 2 \times 10^{11} \text{ M}_\odot\).

The velocity offsets from the Hα emission can be compared directly to the dynamics from the CO(4–3) and CO(7–6) observations from Neri et al. (2003) (see also Greve et al. 2005). It appears that the broad CO(4–3) emission arises from two components (a bright component at \(z=2.383\), and a fainter component at slightly higher redshift (at \(z=2.388\) which is located \(\geq 0.3''\) to the NE of the first component). Narrow CO(7–6) emission is also detected at the same position and redshift as the lower redshift CO(4–3) emission. Assuming the CO(7–6) and the lower redshift CO(4–3) emission arise from warm, dense gas associated with A and/or B and the higher redshift CO(4–3) emission arises from component C, the velocity and spatial offsets are in excellent agreement with our IFU observations. Furthermore, this suggests that A/B and C all host gas reservoirs, with B being the most massive. The implied molecular gas mass from the CO observations is \(\sim 5.5 \times 10^{10} \text{ M}_\odot\), thus the dynamical mass (\(\sim 2 \times 10^{11} \text{ M}_\odot\)) for N2 850.4 is approximately four times

### 3 ANALYSIS

To spatially align the imaging and spectroscopy observations we begin by constructing a Hα image from the UIST IFU and align this with the IRFT Hα and continuum images (which are also aligned to the NICMOS and ACS images using stars in the field of view). Furthermore, to tie these to the GMOS data, we construct a Lyα and continuum image from the GMOS IFU and align these with the galaxy in an observed V-band image from Ivison et al. (2002). This V-band image is then aligned to the near-infrared imaging and results accurate alignment between the GMOS, UIST, IRFT and HST observations. We estimate that the uncertainty in the astrometry between any two frame to be \(\leq 0.2''\). Having combined the HST \(H_\alpha\) and \(H\alpha_{314}\)-band NICMOS and ACS imaging with the velocity structure of the Hα emission, we find at least three dynamically distinct components (labelled A, B, and C in Fig. 1) and we show the near-infrared spectra around the Hα emission from these components in Fig. 2. The redshift of components A and B are in excellent agreement with previous CO(4–3) observations which measured the systemic redshift to be \(2.384 \pm 0.001\) (Neri et al. 2003; Greve et al. 2005). The other component, labelled C is dynamically distinct from the systemic redshift. Component B has an [NII]/Hα emission line ratio of 0.37 \(\pm 0.05\), which is indicative of star-formation, although the presence of an underlying (2300 \(\pm 250\) km s\(^{-1}\)) Hα broad line region suggests AGN activity or scattered light from an AGN. The velocity offset of the narrow line Hα from the systemic galaxy is \(+50 \pm 50\) km s\(^{-1}\) and has a width of 360 \(\pm 25\) km s\(^{-1}\) whilst the broad line Hα is redshifted by \(+800 \pm 150\) km s\(^{-1}\) (all line widths are deconvolved for the instrumental resolution).

Turning to the Lyα emission line map from the GMOS IFU observations (Fig. 1), we find an an extended, diffuse Lyα halo. Whilst the Lyα seems to roughly follow the \(I_{314}\)-band morphology, we also identify Lyα emission lying outside the optical extent of the galaxy (labelled D in Fig. 1). The spatial extent of the Lyα is \(\sim 16\) kpc, however, most interestingly the velocity of the emission line is placed +270 \(\pm 40\) km s\(^{-1}\) redward of the systemic velocity of this system. We detect no significant velocity structure in the Lyα emission across the system (see Table 1).

Using a deep, 1.44′ resolution 1.4-GHz map of the field from the VLA, Ivison et al. (2002) identified a compact radio source with a centroid which corresponds exactly to the location of component B in Fig. 1. This gives us confidence that this component is responsible for the far-infrared activity. The third component (labelled C) is offset from A/B by \(+220 \pm 50\) km s\(^{-1}\) and has an upper limit of [NII]/Hα< 0.05 and a width of 320 \(\pm 30\) km s\(^{-1}\). This indicates star-formation and has an upper limit of [NII]/Hα< 0.05 and a width of 320 \(\pm 30\) km s\(^{-1}\). This indicates star-formation rather than AGN activity, although there is also evidence for a broad-line Hα component which is at the same redshift as the broad line seen in component B (Fig. 2).
greater than gas mass estimate suggesting that this system has a high baryonic fraction in the central regions.

Using the Hα emission line as a star-formation rate indicator we can calculate the star formation rate in each of the three components. For solar abundances and adopting a Salpeter IMF, the conversion between Hα flux and star formation rate is

\[ \text{SFR}(\text{M}_\odot \text{yr}^{-1}) = 7.9 \times 10^{-30} L(\text{H}\alpha) \, \text{W m}^{-2} \]  

(Kennicutt 1998). This calibration assumes that all of the ionising photons are reprocessed into nebular lines (i.e. they are neither absorbed by dust before they can ionise the gas, nor do they escape the galaxy). Using the narrow-line Hα emission line fluxes with this calibration we find that the star formation rates of components A, B and C (uncorrected for reddenning) are \( \lesssim 30, 150 \pm 30 \) and \( 140 \pm 30 \text{M}_\odot \text{yr}^{-1} \) respectively. The total star formation rate is a factor of 10 less than the star formation rate implied from the far-infrared luminosity, and implies approximately three magnitudes of dust extinction (e.g. Smail et al. 2004).

4 DISCUSSION & CONCLUSIONS

The colours and morphology of N2 850.4 from our HST ACS and NICMOS imaging resemble that of a strongly lensed galaxy, however the lens interpretation is quickly ruled out from the Hα emission maps which show that this system is made up of at least three dynamically distinct components separated by \( \sim 1" \) (8 kpc) in projection and up to \( 220 \pm 50 \text{km s}^{-1} \) in velocity. The ground- and space-based imaging data also shows a diffuse and asymmetric halo of material surrounding the galaxy. The Hα redshift of components A/B in Fig. 1 are in excellent agreement with previous CO and rest-frame UV longslit observations which have measured the systemic redshift to be 2.384 (Neri et al. 2003; Smail et al. 2003; Greve et al. 2005). The presence of an underlying broad (\( \sim 2000 \text{km s}^{-1} \)) emission line (offset by \( \sim +800 \text{km s}^{-1} \)) in components B and C suggests AGN activity. Comparable narrow-line Hα to broad-line velocity offsets are frequently seen in local Seyfert nuclei (e.g. Ostenbrook & Shuder 1987; Corbin et al. 1996; Storchi-Bergmann et al. 2003) as well as high-redshift radio galaxies (e.g. Simpson et al. 1999). The third component detected in narrow-line Hα emission is redshifted from the systemic by \( 220 \pm 50 \text{km s}^{-1} \). Combined with the high resolution imaging, the complex morphology and dynamics of this system suggests a massive merger event which has presumably triggered a strong, obscured star-burst and AGN activity.

The GMOS IFU observations show that N2 850.4 has an extended halo of Lyα emission. The Lyα halo has a spatial extent of \( \sim 16 \text{kpc} \) and is redshifted relative to the systemic velocity by \( +270 \pm 40 \text{km s}^{-1} \). It is interesting to compare the Lyα emission from N2 850.4 with the giant sub-mm detected Lyα haloes LAB1 and LAB2 in the SAA22 field (Steidel et al. 2000; Chapman et al. 2001, 2004; Bower et al. 2004; Wilman et al. 2005). From our observations, N2 850.4 has a slightly lower integrated Lyα luminosity (\( \sim 3 \times 10^{43} \text{erg s}^{-1} \)) compared to LAB1 and LAB2 (\( 1 \times 10^{43} \text{erg s}^{-1} \) and \( 9 \times 10^{43} \text{erg s}^{-1} \) respectively), but is much more compact (LAB1 and LAB2 have areas of over 100arcsec\(^2\) (5000 kpc\(^2\)), however the limiting surface brightness of the GMOS observations are \( \sim 5 \times 10^{-16} \text{erg s}^{-1} \text{cm}^{-2} \text{arcsec}^{-2} \) significantly less than the surface brightness limit of LAB1 and LAB2 narrow-band imaging observations), and it is therefore possible that N2 850.4 is surrounded by a large-scale diffuse emission halo below the sensitivity limit of the GMOS IFU observations. Nevertheless, the Lyα emission from N2 850.4 is much more peaked than LAB1 and therefore this halo may represent a different evolutionary phase. Unfortunately, due to the very different surface brightnesses of the systems and the large pixel scale of the SAURON IFU (which has 1.0\(^\prime\) fibrres), it is very difficult to directly compare the dynamics of the two systems (Bower et al. 2004). In terms of the wider environment, it is interesting to note that a second sub-mm detected galaxy has recently been detected in the same structure as N2 850.4 (at a distance of 2.5 Mpc; Chapman et al. 2005a).

The observed velocity offset between Hα and Lyα emission is comparable to those seen in the spectra of rest-frame UV selected galaxies at \( z \gtrsim 2 \) (e.g. Teplitz et al. 2000; Pettini et al. 2001; Shapley et al. 2003) where they have been attributed to galactic scale outflows produced by the collective effects of heating and outflows from supernovae. In this scenario, the Lyα appears redshifted due to resonant scattering of photons from the inner surface of a receding shell of material. Such flows have been termed “superwinds” by analogy to the wind seen in the spectra of local ultra-luminous infrared galaxies and local star-burst galaxies (e.g. Martin 2005, Keel 2005). If such winds can escape from the potential well, they can carry metals to large distances from the galaxy and deposit large amounts of energy in the intergalactic medium. These winds thus have important consequences for the metal enrichment of the Universe (Aguirre et al. 2001) and galaxy formation models (Benson et al. 2003). The key issue, however, is whether the wind material is localised within individual HII regions (in which case, it may not escape the galaxy potential), or whether the expelled shell already envelops the complete galaxy. The latter interpretation is supported by Adelberger et al.’s (2003) observation of a small scale anti-correlation between galaxies and Lyα absorption in QSO spectra (although as those authors quote, the statistical significance of this result is modest). If it can be demonstrated that the superwind had already escaped from the galaxy disk, then it may have enough energy to escape the gravitational potential to distribute its energy metals widely across the Universe.

To distinguishing between these scenarios, we must examine the spatial variation of the velocity offset between Hα and Lyα. Our data show no correlation between the emission wavelength of Lyα and the velocity variations clearly seen in Hα. This argues that the Lyα emission originates outside the individual components. If we were seeing the inner surface of a shell located well outside the galaxy we would expect a negligible velocity shear and indeed our observations place a limit on the shear of \( \lesssim 100 \text{km s}^{-1} \).

We can also investigate how closely the morphology of the Lyα emission traces the star-forming regions of the galaxy. While the Lyα intensity map generally traces the \( IS1 \)-band morphology, the diffuse extension labelled \( D \) in Fig. 1, has no counterpart in the \( IS1 \)-band image. This component may be a dense knot in an outflowing shell and would be compatible with a model in which scattered Lyα photons are observed from the outflowing shell.

The data presented here support that idea that we are seeing wind material that has already escaped from the
galaxy. It is interesting to compare the velocity offset in Lyα with the escape velocity of the galaxy. Using the dynamical mass estimate ($\sim 2 \times 10^{11} M_\odot$) enclosed in a radius of $\sim 8$ kpc we estimate escape velocity to be $\gtrsim 500$ km s$^{-1}$ (assuming a central concentration of $c = 7$ for $z = 2.4$); (Navarro, Frenk & White 1997). Whilst this escape velocity exceeds that of the outflowing material, the fate of the outflow will depend on its present location (or equivalently, its initial velocity). For example, if the outflow originated in the galaxy with an initial speed of $\sim 270$ km s$^{-1}$, then it will surely rain back down on the galaxy. However, if, as we have argued, the shell is currently located outside the galaxy (i.e. $\gtrsim 10$ kpc), then the escape velocity will be a factor of $\sim 2$ less, in which case the outflow will probably escape the gravitational potential and distribute the gas much more widely in the environment. We also note that the UV-bright starburst in N2 850.4 is still relatively young ($\sim 10$ Myr; Smail et al. 2003) and therefore this material may still be accelerating into the inter-galactic medium. Future observations of a larger sample of these galaxies (at various evolutionary stages) may yield further information about the origin of the outflows and the size of the regions which they affect around them (Geach et al. 2005).

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