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A vigorous starburst in the SCUBA galaxy N2 850.4

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ABSTRACT

We present optical and near-infrared (near-IR) spectroscopy of a $z = 2.38$ hyperluminous IR galaxy, covering the rest-frame wavelength range from 1000–5000 Å. It appears to comprise two components separated by less than 1 arcsec on the sky ($\lesssim$8 kpc); one component (B) is blue, the other (P) is red in rest-frame ultraviolet(UV)–optical colours. The combined system has a rest-frame luminosity of $\sim 8L^*_V$ and its rest-frame optical spectrum is characteristic of a Seyfert active galactic nucleus. However, its rest-frame UV spectrum exhibits striking features associated with young stars, including P-Cygni lines from stellar winds and blueshifted interstellar absorption lines indicative of a galactic outflow. Redshifts are derived from stellar photospheric lines in the UV and from narrow emission lines in the rest-frame optical, and these are compared to those measured for the molecular gas recently detected with the Institut de Radioastronomie Millimetrique (IRAM) interferometer. The offsets indicate that the far-IR emission is most likely associated with the near-IR source P, which hosts the Seyfert nucleus, while the UV-bright component B is blueshifted by 400 km s^{-1}. This suggests that the two components are probably merging and the resulting gravitational interactions have triggered the hyperluminous activity. Modelling of the UV spectral features implies that the starburst within the UV component of this system has been going on for at least ~10 Myr. Assuming that the bolometrically-dominant obscured component has a similar lifetime, we estimate that it has so far formed a total stellar mass of $\sim 10^{11}$ M$_\odot$. If this star formation continues at its present level for substantially longer, or if this activity is repeated, then the present-day descendant of N2 850.4 will be a very luminous galaxy.

Key words: galaxies: evolution – galaxies: formation – galaxies: individual: ELAIS N2 850.4 – galaxies: individual: SMM J16358+4057 – galaxies: starburst – cosmology: observations.

1 INTRODUCTION

Surveys with the Submillimetre Common User Bolometer Array (SCUBA) and Max-Planck Millimeter Bolometer (MAMBO) cameras have identified a population of ultraluminous and hyperluminous galaxies, $L_{\rm bol} \geqslant 10^{12}$ and $\geqslant 10^{13}$ L$_\odot$ respectively, at high redshifts, $z > 1$ (Cowie, Barger & Kneib 2002; Dannerbauer et al. 2002; Scott et al. 2002; Smail et al. 2002; Webb et al. 2002). Unfortunately, the modest spatial resolution of submillimetre (submm) instruments, combined with the relative faintness of these galaxies in optical wavebands, has meant that detailed investigation of their properties has been limited to a handful of cases (Ivison et al. 1998, 2000, 2001; Soucail et al. 1999; Gear et al. 2000; Chapman et al. 2002a; Ledlow et al. 2002; Dunlop et al. 2003; Smail et al. 2003). However, sensitive high-resolution radio maps provide a powerful tool for localizing the submm emission, assuming that the tight correlation between far-infrared (FIR) and radio emission in dusty galaxies continues to high redshifts. In this way, it has proved possible to identify counterparts to large samples of radio-identified submm galaxies (Barger, Cowie & Richards 2000; Chapman et al. 2001; Ivison et al. 2002, I02) and hence to begin to make progress on determining the redshifts of significant samples of SCUBA galaxies (Chapman et al. 2003a).

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To gauge the contribution of submm galaxies to the formation of the stellar populations in galaxies at $z \sim 0$ we need to determine whether their immense FIR luminosities originate from dust-reprocessed star formation or active galactic nuclei (AGNs) activity and also what the lifetime of this activity is. Signatures of AGN activity have been found in a few well-studied examples (e.g. Ivison et al. 1998; Ledlow et al. 2002) and it is generally supposed that most systems will comprise a mix of starburst- and AGN-powered emission, although the latter may be weak (Almaini et al. 2003; Alexander et al. 2002, 2003). Having concluded that star formation provides a significant fraction of the bolometric luminosity from typical SCUBA galaxies, the critical issue for understanding their contribution to the stellar density at $z = 0$ is to measure the duration of the starburst activity. The star formation rates in representative SCUBA galaxies are very high, of the order of 10^3 $M_\odot$ yr^{-1}, but if this activity occurs in a compact nuclear burst then the activity could in principle only last ∼1 Myr, and thus produce only a modest mass of stars, sufficient for a typical bulge. Alternatively, if the burst is more prolonged (or repeated) then much larger stellar masses could form, providing a clear link between the SCUBA galaxies and the most massive local stellar systems at $z = 0$. Obtaining a robust lower limit on the lifetime of a massive starburst in a SCUBA galaxy would provide an essential confirmation of the role of intense, obscured star formation in the evolution of luminous elliptical galaxies.

Another important consequence of timing the intense activity in SCUBA galaxies is the expectation that their activity may be self-regulating, through the intervention of powerful winds and outflows. These outflows will have a profound effect on both their internal processes (by removing the gas reservoir needed to fuel star formation and AGN activity) and the formation and evolution of galaxies in their immediate surroundings. Evidence of the striking effects of starburst- and AGN-driven winds from active galaxies at low and high redshifts is growing (Heckman, Armus & Miley 1990; Vernet & Cimatti 2001; Strickland et al. 2002; Pettini et al. 2002; Ledlow et al. 2002). As the most luminous galaxies in the high-redshift Universe, SCUBA sources may provide a unique laboratory for the study of the influence of feedback on galaxy formation and the properties of the intergalactic medium (Adelberger et al. 2003).

In this paper we present spectroscopic observations of a radio-identified, submm-selected galaxy, ELAIS N2 850.4 at $z = 2.38$ (Scott et al. 2002; Fox et al. 2002; I02; Chapman et al. 2003a), which displays the spectral signatures of a massive, vigorous starburst. Similar features are visible in several other galaxies in the Chapman et al. (2003a) sample, although these are typically fainter galaxies and the features are therefore noisier. Thus, by virtue of its unusual optical brightness, N2 850.4 presents the clearest example to date of an ultraviolet (UV) detected starburst in a SCUBA galaxy. In the following we adopt an $\Omega_o = 1$, $\Omega_\Lambda = 0$, $H_o = 50$ km s^{-1} Mpc^{-1} cosmology. If we used a flat cosmology with $\Omega_\Lambda = 0.7$ and $H_o = 65$ km s^{-1} Mpc^{-1}, then the implied luminosities will rise by 20 per cent and the linear scale will increase by 10 per cent. We present our observations in the next section. We describe our analysis and results in Section 3, discuss these in Section 4 and give our conclusions in Section 5.

2 OBSERVATIONS AND REDUCTION

N2 850.4 was identified as a relatively bright submm source at 16 36 50.0, +40 57 33 (J2000), with an 850-μm flux of 8.2 ± 1.7 mJy and a 450-μm limit of <34 mJy (3-σ), in the survey of the ELAIS-field by Scott et al. (2002). Fox et al. (2002) provide constraints on the photometric properties of possible counterparts lying within the large submm error circle of this source, including 3-σ upper limits from the *Infrared Space Observatory* (*ISO*) on the 7- and 15-μm emission of <1 and <2 mJy, respectively. Using a deep 1.4-arcsec resolution 1.4-GHz map of the field from the Very Large Array (VLA), I02 identified a compact radio source with a 1.4-GHz flux of 221 ± 17 μJy, at 16 36 50.425, +40 57 34.46 (J2000), within 5 arcsec of the submm centroid.[1] A relatively bright optical/near-infrared (near-IR) counterpart to this radio/submm source was also identified by I02 in their *VRIK* imaging at 16 36 50.461, +40 57 34.25 (J2000) in the *R* band and 16 36 50.402, +40 57 34.19 (J2000) in *K*; both positions are tied to the radio reference frame with a precision of ±0.3 arcsec. I02 list a magnitude of $K = 18.43 \pm 0.02$ for N2 850.4 and blue optical colours $(R–I) = 0.45 \pm 0.03$, $(V–R) = 0.12 \pm 0.03$, but a relatively red optical–near-IR colour $(I–K) = 3.40 \pm 0.03$.[2] We illustrate the morphology of N2 850.4 as well as its wider environment, using the images from I02, in Fig. 1. I02 classify the system as a probable pair of galaxies, with a blue optical source and a redder near-IR galaxy, on the basis of small offset in the centroid in the two wavebands, ∼0.2 arcsec. This offset is visible as the red extension to the north-east of the galaxy in Fig. 1. We limit the maximum possible separation of the two components to $\lesssim 1$ arcsec and measure the FWHM of the galaxy as 0.64 arcsec in *V* and 0.71 arcsec in *K*, corrected for seeing. In the following we denote the blue optical source as component 'B' and the redder feature as component 'P'.

Spectroscopic observations of N2 850.4 were obtained with the Low Resolution and Imaging Spectrograph (LRIS) on the

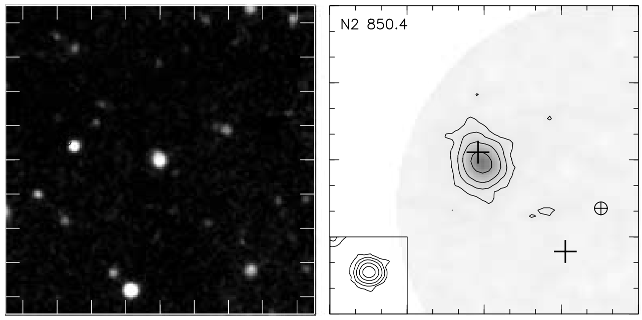


Figure 1. A 45 × 45 arcsec^2 true colour *VRK* image of N2 850.4 (left) showing the red emission extending out to the north of the optical source. Note the presence of an extremely red object 11 arcsec to the west of N2 850.4 with $K \sim 19.5$ and $I–K \sim 4.2$. An expanded view, 12 × 12 arcsec^2 (47 kpc at $z = 2.38$, $h_0 = 0.5$, $q_0 = 0.5$), shows the morphology of the galaxy (right) from the composite $V + R + K$ image. The crosses show the positions of the two radio sources in the vicinity of the submm source, whose centroid is shown by the cross-in-circle. We only show the grey-scale image within the 8-arcsec radius error-circle of the submm source. The contours are logarithmically spaced and the image has been smoothed with a 0.4-arcsec FWHM Gaussian to suppress pixel-to-pixel noise. To demonstrate the reality of the extension to N2 850.4 we show as an inset a similar contour plot of a star 20 arcsec south of the source, which shows a more strongly peaked and circular morphology. This figure can be seen in colour in the on-line version of this article on *Synergy*.

[1] A possible 3-σ radio source lies 2.1 arcsec from the nominal submm position (Fig. 1), but based on probabilistic arguments I02 claim that this is less likely to be the correct ID. The results presented here for the remarkable properties of N2 850.4 argue strongly against this association.

[2] The galactic extinction in this field is $E(B–V) = 0.006$ based on Schlegel, Finkbeiner & Davis (1998) and so we apply no correction.

Keck-I telescope[3] as part of a spectroscopic survey of radio-identified SCUBA galaxies (Chapman et al. 2003a). A total of 3.6 ks of integration was obtained on the night of 2002 March 19 using a slit mask with 1 arcsec wide slitlets and the 400 l mm^{-1} grism on the blue arm, with the 600 l mm^{-1} grating for the red arm. This set-up provides a combination of wavelength coverage down to the atmospheric cut-off in the blue and reasonably high resolution in the red to facilitate sky subtraction. The position angle (PA) of the mask was 80° and objects were nodded along the slits by 2 arcsec between subexposures to improve flat-fielding and to allow the construction of a fringe frame from the science images. The observations were reduced in a standard manner using IRAF tasks.

The LRIS spectrum shown in Fig. 2(a) includes a series of strong emission lines which indicate a redshift of $z \simeq 2.4$, a blue continuum $F_\lambda \propto \lambda^{-2.1}$ and detectable emission down to 1000 Å in the rest frame. The identifications of some of the stronger emission and absorption features are marked, including Lyα, OVI λ1035, NV λ1240, O I λ1302 (probably blended with Si III λ1304 and SiII λ1295), Si IV λ1396 (merged with O IV] λ1405) and C IV λ1549.

The N V λ1240, Si IV λ1396 and C IV λ1549 lines show classic P-Cygni profiles, with blueshifted absorption troughs with widths of 3000–4000 km s^{-1}, which are illustrated in more detail in the inset panel in Fig. 2(a). Several of these lines have associated broad, redshifted emission features. The detailed morphologies of these emission lines (and also Lyα) suggest the presence of two components to the emission: one narrow and blue, the other broader, redshifted and spatially offset by 0.2 arcsec along the slit to the north-east. We therefore fit the emission lines corresponding to Lyα, N V λ1240, Si IV λ1396+O IV] λ1405 and C IV λ1549, with two Gaussian components (Table 1).

In addition to the strong absorption features from stellar winds we identify interstellar absorption lines from Si II λ1260 and CII λ1335 at $z = 2.379 \pm 0.002$ and $z = 2.373 \pm 0.002$, respectively. We also see weak emission features associated with fine-structure lines of Si II at 1265 and 1309 Å (Table 1). Finally, there are a number of weak, narrow photospheric absorption lines of S V λ1502, CIII λ1427 and Si III λ1417 visible in the spectrum, with rest-frame equivalent widths 0.5–1 Å; we use these below to estimate the systemic redshift of the stars dominating the UV emission.

To investigate the spectral properties of N2 850.4 in the rest-frame optical we also obtained a *JH*-band spectrum of this galaxy on the night of 2002 May 18, using the near-IR spectrograph, Cooled Infrared Spectrograph and Camera (CISCO), and the OH atmospheric suppression unit (OHS) on the Subaru telescope[4] (Iwamuro et al. 2001). A total of 7 ks of data were acquired in 0.4–0.6 arcsec seeing as a series of 1-ks exposures. We employed a 1-arcsec wide slit at a PA of 0° and nodded the source along the slit by 10 arcsec between exposures. Atmospheric transmission corrections came from Smithsonian Astrophysical Observatory (SAO) standard stars and wavelength calibration was obtained from the OH lines measured in observations without the OHS. Checks of the instrument stability suggest that this calibration is good to <7 Å. The data were reduced in a standard manner, including flat-fielding, sky subtraction, correction of bad pixels and residual sky subtraction. The final *JH* spectrum is shown in Fig. 2(b), where we identify several strong lines, including [O II] λ3727, Hβ and [O III] λ5007. The details of the emission line measurements from the CISCO/OHS spectrum are given in Table 1. There are two velocity components in the Hβ and most strikingly in the [O III] λ5007 lines; we list the double Gaussian fits to both lines in Table 1. The limits on the [O II] λ4959 emission corresponding to the [O III] λ5007 components are consistent with the standard flux ratio of these lines. Note that the lower redshift component of the [O III] λ5007 line is extended along the slit to the north by $\lesssim$1.5 arcsec and to the south by ~0.5 arcsec (see the inset in Fig. 2b). A spectrum of the extended emission shows not only [O III] λ5007, but also [O II] λ3727; narrow Hβ and [O III] λ4959 components suggest *in situ* ionization of the gas. In all cases the flux or equivalent width quoted in Table 1 is for the emission from the core of the galaxy.

3 ANALYSIS AND RESULTS

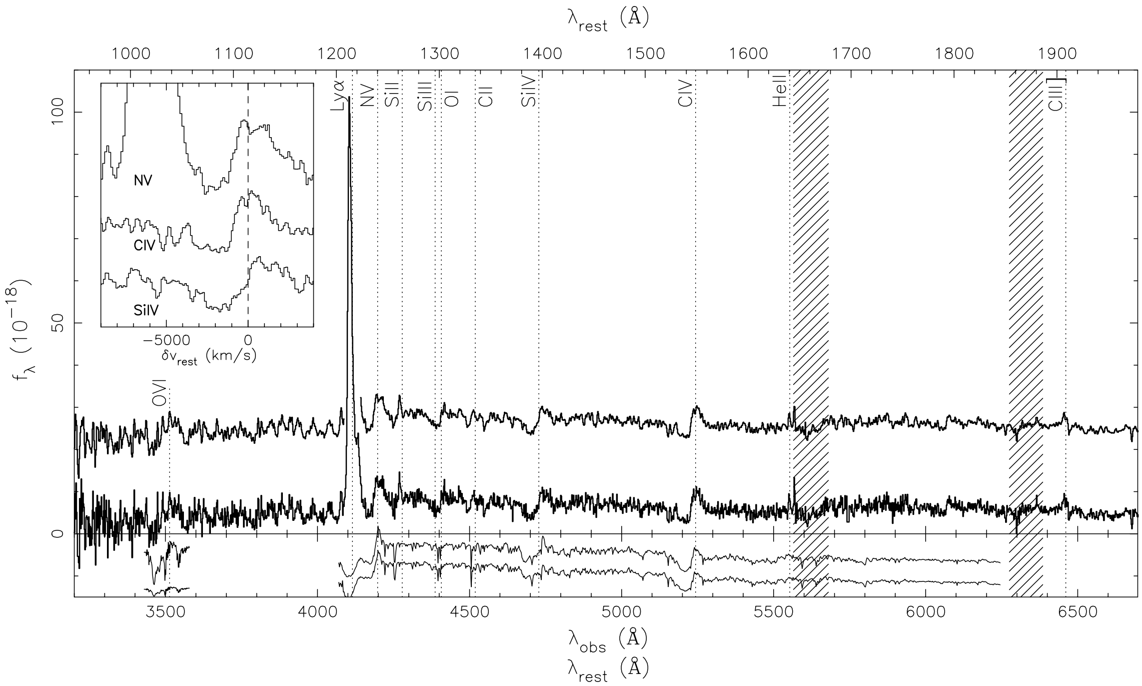
As Table 1 demonstrates, there are a bewildering range of different spatial and velocity components in the spectra of N2 850.4, with redshifts spanning $z = 2.373$–2.401. To bring some coherence to the picture we suggest a number of groupings for these components in Table 2. We also add two further redshift estimates. The first comes from cross-correlating the weak photospheric lines in the UV spectrum with template models from Starburst99 (after masking all the interstellar and wind features). This provides our best estimate of the systemic redshift of the young UV stellar population, $z = 2.380$, which is very close to the redshift of the narrow Lyα component. The second measurement comes from recent observations of CO(3–2) molecular emission using the Institut de Radioastronomie Millimetrique (IRAM) Plateau de Bure (PdB) interferometer (Genzel R. et al., in preparation), which yields $z = 2.384$ for the systemic redshift of the large mass of molecular gas in this galaxy, and should provide the most reliable estimate of the redshift of the luminous submm source.

The redshift of $z = 2.384$ for N2 850.4 is higher than that inferred by I02 from the radio/submm spectral index of the source (see also Fox et al. 2002), $z = 1.3^{+0.6}_{-0.4}$ based on the Carilli & Yun (2000) calibration. It is just within the 1-σ bound of the Rengarajan & Takeuchi (2001) version of the indicator, which yields $z = 1.8^{+0.6}_{-0.4}$. This suggests either an additional contribution from an AGN to the radio emission, or that the dust emission from N2 850.4 is characterized by a particularly hot dust temperature (Blain 1999; Blain, Barnard & Chapman 2003; Chapman et al. 2003b). Using a hotter range of dusty galaxy spectral energy distributions (SEDs), Aretxaga et al. (2002) estimate $z = 2.9^{+1.2}_{-0.9}$ for N2 850.4 from its 1.4-GHz, 1.3-mm and 850-μm detections and a 450-μm upper limit. The allowed redshift range is relatively broad, but does include the true redshift. It is interesting to consider the influence of a short duration for the star formation on the radio emission from N2 850.4; if the starburst is extremely young, then no supernovae will yet have occurred, perhaps suppressing its radio emission, and reducing its estimated redshift using the Carilli–Yun indicator.

One further complication in relating the UV and FIR properties of N2 850.4 is our lack of knowledge about the *exact* location of the sites of emission in the two wavebands. The precision of the relative optical–radio astrometry from I02 is ±0.3 arcsec, similar to the offset (to the north) of the radio source relative to the optical counterpart (Fig. 1), which is therefore not significant. As discussed by Ivison et al. (2001), the complex mix of emission and dust absorption in SCUBA galaxies could result in our sampling very different regions of these systems at different wavelengths; see Goldader et al.

[3] The W. M. Keck Observatory is a scientific partnership between the University of California, the California Institute of Technology and the National Aeronautics and Space Administration, and was made possible by the generous financial support of the W. M. Keck Foundation.

[4] Based on data collected at Subaru Telescope, which is operated by the National Astronomical Observatory of Japan.



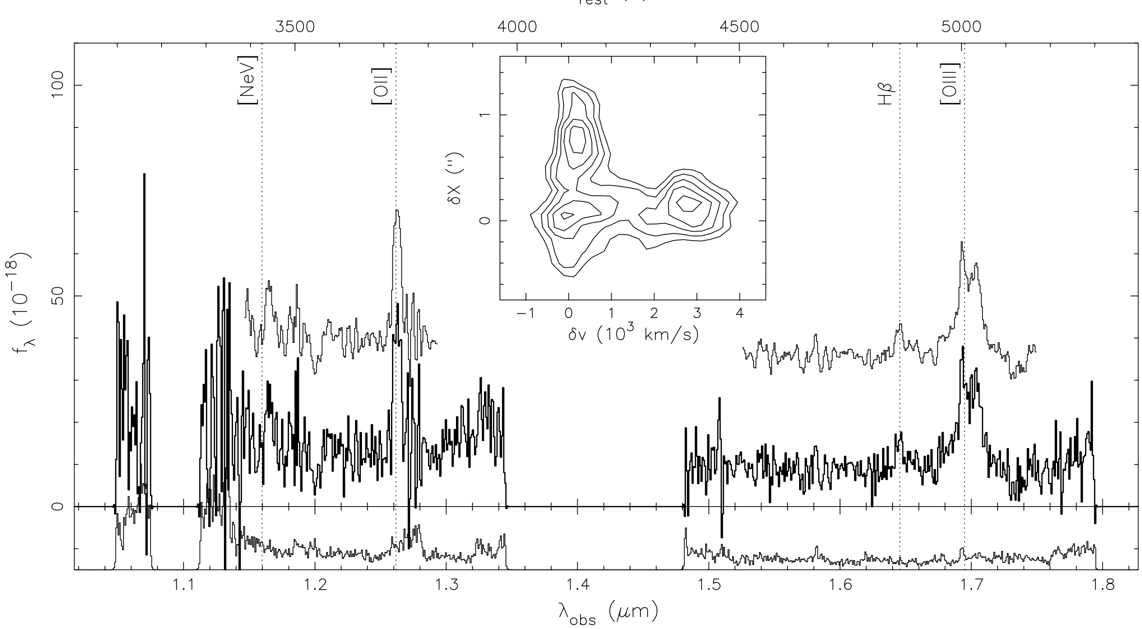


Figure 2. (a) The upper panel is the LRIS spectrum of N2 850.4 in the rest-frame UV. The middle spectrum in this panel shows the raw data and the upper spectrum is smoothed to the instrumental resolution. We mark the expected wavelengths of strong emission or absorption features based on a redshift of the galaxy of $z = 2.384$ from the observed wavelength of the CO(3–2) emission (Genzel R. et al., in preparation). The hashed areas show regions of the spectrum which are affected by strong sky emission or the dichroic in the spectrograph. The two lower spectra in this panel show the UV spectra predicted by the Starburst99 model assuming 3-Myr-old burst (upper) and 10-Myr continuous (lower) star formation models, both with a Salpeter IMF (these have been corrected to the redshift of the photospheric absorption lines to allow easy comparison with the blueshifted features in the UV). These models illustrate the strength of the P-Cygni features expected for stellar population dominated by young, massive stars. The inset shows more details of the P-Cygni absorption features seen in the LRIS spectrum. (b) The lower figure shows the Subaru CISCO/OHS *JH*-band spectrum of N2 850.4 covering the rest-frame optical. Again we identify the strongest emission lines in the spectrum and note that [O II] λ3727 provides 10 per cent of the emission in the *J* band and [O III] λ5007 contributes 25 per cent of the *H*-band flux. The upper trace is smoothed to the instrumental resolution and the lower trace illustrates the sky noise as a function of wavelength. The inset panel shows a position–velocity plot around the [O III] λ5007 line, demonstrating the spatial and velocity extent of this emission line.

(2002), who reach a similar conclusion based on UV observations of local ultraluminous infrared galaxies (ULIRGs). Indeed, colour differences within N2 850.4 (see Fig. 1; I02) suggest that dust obscuration in this galaxy may be highly structured. Alternatively, the colour differences may originate from spatially distinct components within the system (I02).

The proposed groupings of the various velocity components in N2 850.4 (Table 2) are motivated by the likely origin of the different

Table 1. Properties of rest-frame optical and UV emission lines of N2 850.4.

Line	λ_{rest} (Å)	λ_{obs} (Å)	z	Width (km s^{-1})	Flux (erg s cm^{-2})	Comment
Lyα	1215	4111.4	2.382	900	6.9×10^{-16}	Narrow component
		4126.7	2.395	2600	1.2×10^{-15}	Broad component
N V	1239	4199.1	2.386	500	2.8×10^{-17}	Narrow component
		4214.1	2.398	2500	1.9×10^{-16}	Broad component
Si II	1265	4269.6	2.376	560	4.0×10^{-17}	
OI	1302	4423.0	2.394	700	1.7×10^{-17}	Blended with Si III λ1295 and Si II λ1304
Si II	1309	4416.3	2.373	300	1.2×10^{-17}	
Si IV+O IV]	1404	4742.5	2.378	400	4.7×10^{-17}	Narrow component
		4761.9	2.392	800	6.9×10^{-17}	Broad component
C IV	1549	5241.0	2.383	500	1.7×10^{-17}	Narrow component
		5256.6	2.394	1600	1.3×10^{-16}	Broad component
HeII	1640	5542.0	2.378	$\leqslant$300	2.0×10^{-17}	
CIII]	1909	6461.6	2.385	850	3.7×10^{-17}	
[Ne V]	3426	11642	2.400	<1500	7.4×10^{-17}	
[O II]	3727	12624	2.387	<1500	2.4×10^{-16}	
Hβ	4861	16447	2.383	<1500	2.6×10^{-17}	Narrow component
		16495	2.393	4000	5.8×10^{-17}	Broad component
[O III]	5007	16924	2.380	<1500	2.1×10^{-16}	Spatially extended
		17030	2.401	1900	2.8×10^{-16}	Red component

Table 2. Suggested groupings of different redshift components and probable origins in N2 850.4.

Lines	z	Δv (km s^{-1})	Component	Comment
CO emission	2.384±0.001	0		Genzel R. et al., in preparation
Narrow optical emission	2.384±0.003	0	P - Systemic	[O II], Hβ, [O III]
UV photospheric absorption	2.380±0.002	−350	B - Systemic	
UV interstellar absorption	2.376±0.003	−700	B - Outflow	Si II, CII
Narrow UV emission	2.382±0.003	−150	B - Outflow	Lyα, N V, Si IV+O IV, C IV
Broad UV emission	2.395±0.003	1000	P - Outflow	Lyα, N V, Si IV+O IV, C IV
Broad optical emission	2.401±0.001	1500	P - Outflow	[Ne V], broad Hβ, broad [O III]

spectral features and their spatial distribution. We identify two key components. The first dominates the UV luminosity of the system and contributes narrow UV emission lines and weak photospheric absorption features at a redshift $z \simeq 2.381$; this we equate with component B. The second component produces a number of narrow rest-frame optical emission lines in the OHS spectrum at a redshift close to that measured for the molecular gas, $z \simeq 2.384$ (400 ± 200 km s^{-1} offset from the UV source), and most likely arises in the near-IR component, P. We therefore associate the near-IR emission with the source of the extremely luminous, dust-reprocessed FIR emission.

Having isolated the features from the two putative components of N2 850.4, we can study their spectral properties in more detail. We use the rest-frame optical emission line properties to classify N2 850.4 spectrally. Several properties suggests that N2 850.4/P harbours an AGN; the redshifted, broad emission lines in the rest-frame optical (and UV) and the apparent detection of the high ionization [Ne V] λ3426 line, indicating hard radiation from an AGN. The flux ratio of [O III] λ5007 to Hβ is ~5.8 (including flux from both broad and narrow [O III] and Hβ lines), which suggests a Seyfert-2 classification, while the presence of broad Hβ would instead argue for the AGN component lying in the Seyfert-1 class. Hence, N2 850.4/P appears to be a transition object with characteristics of both Seyfert 1 and 2, although the very broad [O III] λ5007 line means that it does not fit easily into any of the existing transition classes (Osterbrock 1981).

AGN features are most obvious in the rest-frame optical spectrum, but they also appear in the rest-frame UV (where they are spatially offset from the UV continuum emission). In particular, the strength and breadth of the Lyα, N V λ1239, Si IV λ1397 and C IV λ1549 emission lines require a broad AGN contribution. These features suggest only a modest AGN contribution to the rest-frame UV emission, for example the C III] λ1909 line is weaker than the C IV λ1549 line. Indeed, the most striking features in the UV spectrum are the broad, blueshifted absorption troughs in the blue wings of the N V λ1239, Si IV λ1397 and C IV λ1549 lines (see the inset in Fig. 2a). In principle, these features could be generated by any source of outflowing gas with the correct physical conditions; however, a stellar origin is indicated by the close agreement between the strengths and kinematics of the lines and the predictions for a population of hot stars in models from the Starburst99 library (Leitherer et al. 1999). Fitting these models either to the whole spectral range 1230–1630 Å or just to spectral windows centred on the main P-Cygni lines yields similar results; the UV spectral features are reproduced only by a stellar population dominated by massive, young O and B stars. We show two examples of acceptable Starburst99 models in Fig. 2(a): a 3-Myr-old starburst with a Salpeter initial mass function (IMF) up to 100 M$_{\odot}$ and $E(B{-}V)$

= 0.13 ± 0.02 based on the parametrized dust model from Calzetti et al. (2000); and a model with continuous star formation, an age of 10 Myr, and the same IMF and extinction law. The broad agreement between the strengths and velocity widths of N V λ1239, Si IV λ1397 and C IV λ1549 troughs is excellent. Note that the strength of the Si IV λ1400 wind feature supports the younger estimate, but the modest signal-to-noise of the spectrum precludes a stronger conclusion. We conclude that the rest-frame UV emission from N2 850.4/B is dominated by light from a young, intense starburst, which is probably of the order of 10 Myr old.

The three groups of spectral features associated with N2 850.4/B show similar behaviour to that seen in Lyman-break galaxies (Shapley et al. 2003), with the redshift of the UV photospheric absorption lying approximately midway between the narrow Lyα redshift and the interstellar lines. Quantitatively, if we adopt a systemic velocity of the UV-bright starburst of $z = 2.381$ from the photospheric absorption lines, then the redshifts for the two strong interstellar absorption lines visible in Fig. 2(a), Si II λ1260 and C II λ1335 at $z = 2.376$, suggest blueshifts of the order of 400 ± 300 km s^{-1} and comparable linewidths. If this material actually originated in the more obscured component of this system, then the relative velocity of the material is closer to −800 km s^{-1}. In either case, the blueshift is an unambiguous signature of the presence of outflowing material, probably resulting from a galactic wind driven by the vigorous starburst activity (e.g. Heckman et al. 1998; Pettini et al. 2002). The large velocity offsets seen in the high excitation rest-frame optical lines indicate that material is also outflowing on a smaller scale around the AGN.

In summary, we propose that N2 850.4 comprises two related, but independent, components, a highly obscured, gas-rich galaxy with a Seyfert nucleus, N2 850.4/P, and a young, modestly obscured UV-bright starburst companion, N2 850.4/B. These two components are offset spatially by $\lesssim$1 arcsec and kinematically by ∼400 km s^{-1}.

4 DISCUSSION

To quantify the extent of the star formation activity in N2 850.4 we look at its FIR and optical luminosities. At $z = 2.4$, N2 850.4 is a hyperluminous galaxy with a bolometric luminosity of (3 ± 2) × 10^{13} L$_\odot$, based on its submm flux and a dust temperature of $T_{\rm d} = 58$ K derived from the FIR–radio correlation (Chapman et al. 2003a). If this emission arises purely from massive star formation, then the luminosity corresponds to a star formation rate of ∼6 × 10^3 M$_\odot$ yr^{-1} for stars more massive than 1 M$_\odot$ (extrapolating down to 0.1 M$_\odot$ the rate would rise by a factor of 3.2). However, a significant AGN contribution to the radio emission would lower the derived dust temperature, and thus both the bolometric luminosity and the implied star formation rate. For example, if we adopt an extreme model where 75 per cent of the radio emission is generated directly by the AGN, then the best-fitting dust temperature drops to $T_{\rm d} = 31$ K and the bolometric luminosity declines by a factor of ∼10.

To improve the precision of the luminosity and dust temperature measurements we require mid-IR and FIR photometry from the *Space Infrared Telescope Facility* (*SIRTF*). Using our current best-fitting SED we predict fluxes for N2 850.4 in the *SIRTF* bands at 24, 70 and 160 μm of 3.3, 25 and 110 mJy respectively. These fluxes are factors of 2–8 times greater than the expected confusion limits in these bands and hence the source should be easily detectable in the *SIRTF* wide-area infrared extragalactic (SWIRE) survey of this region. These observations should provide a conclusive measurement of the temperature of the dust in the galaxy and a test of the form of the FIR–radio correlation at high-z.

Several of the properties of N2 850.4 outlined in the previous sections are reminiscent of other well-studied SCUBA galaxies, many of which contain a partially-obscured and relatively modest luminosity AGN (Ivison et al. 1998; Soucail et al. 1999; Ledlow et al. 2002; Smail et al. 2003; Chapman et al. 2003a; Alexander et al. 2003). What is remarkable about N2 850.4 are the strong signatures of vigorous ongoing star formation, especially the P-Cygni absorption troughs. This combination of features is not unknown in galaxies at $z \sim 0$; a local analogue of the spectrum of N2 850.4 is provided by the Seyfert-2 galaxy NGC 7130 (González Delgado et al. 1998; Contini et al. 2002).

The *Hubble Space Telescope* Goddard High Resolution Spectrograph (GHRS) spectrum of NGC 7130 (figure 8 in González Delgado et al. 1998) is strikingly similar to that of N2 850.4. Both galaxies show weak emission lines of N V, S IV and C IV, all with strong P-Cygni absorption troughs. González Delgado et al. interpret these spectral features as the result of a nuclear starburst with an age of 3–4 Myr. NGC 7130 also shows two components of [O III] λ5007 with very different widths. The narrower line is blueshifted with respect to the broader component that results from emission in outflowing gas driven by an AGN or starburst. In N2 850.4 we see a much larger velocity shift between the two components. The narrower, blue component is spatially extended along our slit and exhibits a small velocity shear of the order of 160 km s^{-1} on an arcsec scale. The most significant difference between NGC 7130 and N2 850.4 is their luminosities; at 3 × 10^{11} L$_\odot$ NGC 7130 is two orders of magnitude less luminous than N2 850.4.

N2 850.4 is also astonishingly bright in the rest-frame optical waveband. The observed K-band magnitude of $K = 18.43$ (I02) implies a rest-frame V-band absolute magnitude of $M_V \simeq -24.8$. However, its red (I–K) colour (I02) may reflect a strong contribution from the Hα line to the K-band flux. Assuming that 50 per cent of the K-band light comes from the Hα line (similar to the emission line contribution in the H band), this would reduce the absolute magnitude to $M_V \sim -24.0$, but still indicating a very luminous galaxy.

In view of the extreme luminosity of N2 850.4 we should consider the possibility that strong gravitational lensing artificially boosts its apparent brightness, as seen in several extremely luminous high-z sources, including some SCUBA galaxies (e.g. Graham & Liu 1995; Williams & Lewis 1996; Ibata et al. 1999; Downes & Solomon 2003; Chapman et al. 2002b; Dunlop et al. 2003). The apparent offset between the optical and near-IR emission from N2 850.4 could be due to the offset between the source and a foreground galaxy lens. The spectral properties of N2 850.4 suggest that if a lens is present, then it contributes neither much light to the optical spectrum shortward of ∼6000 Å nor any emission lines in the optical/near-IR windows. The most obvious class of lens is thus an early-type galaxy at $z \sim 0.5$–1. However, only a sub-L^* lens would not exceed the K-band magnitude, implying an Einstein radius of only ∼0.1 arcsec in the absence of any local large-scale structure. For significant strong lensing amplification ($\gg$10 ×), we would expect the lens and source to be aligned at the ∼0.1 arcsec level, similar to the observed offset in the centroids in the optical and near-IR wavebands (I02). However, the detection of spatially-extended optical and near-IR line emission argues against significant lens amplification, which would imprint a strong amplification gradient on this emission. We do not believe that N2 850.4 is strongly affected by gravitational lensing. However, a definitive conclusion must await either higher-resolution imaging, or preferably, spatially-resolved two-dimensional spectroscopy.

The distinct optical and near-IR components in the system are separated by less than 8 kpc in projection and the apparent velocity offset between their rest-frame UV photospheric and narrow optical emission line redshifts is ~400 km s^{-1}. If the two components are bound/merging, then the total mass of the system must be around 1×10^{12} M$_\odot$, which is comparable to previous dynamical mass estimates for SCUBA galaxies based on CO linewidths (e.g. Frayer et al. 1998, 1999; Genzel et al. 2003; Downes & Solomon 2003). While the velocity offset is uncertain, it is consistent with the identification of N2 850.4 as a massive galaxy undergoing an interaction with a companion.

Assuming a velocity dispersion for N2 850.4 comparable to the velocity offset between the optical and near-IR components, ~400 km s^{-1}, then the crossing time for the galaxy is ~10 Myr, similar (given the large uncertainties) to the estimated age of the starburst and supporting the interpretation of the UV starburst as an instantaneous event triggered by the interaction. This suggests that the same time-scale should be applied to the obscured activity which is powering the FIR emission.

The near-IR luminosity of N2 850.4 implies a very bright absolute magnitude $M_V < -24$ (assuming it is not strongly lensed), which corresponds to a 3×10^9 M$_\odot$ starburst for a Salpeter IMF from 1–100 M$_\odot$ for continuous star formation in the 10-Myr Starburst99 model with no dust reddening. Assuming a constant star formation rate over the lifetime of the burst then suggests that the galaxy must have been forming stars at a rate of $\sim 3 \times 10^2$ M$_\odot$ yr^{-1}. Although there is a large uncertainty in this estimate, it is far below the star formation rate determined from the FIR luminosity. The predicted bolometric luminosity of the optical component from the Starburst99 model is $\sim 10^{12}$ L$_\odot$, again roughly 10 per cent of that estimated from the 850-μm and radio flux. Any reddening to the population dominating the rest-frame optical emission would clearly increase this estimate. Using the extinction inferred from the rest-frame UV spectrum gives $A_V \sim 0.4$, or a correction of 50 per cent. Alternatively, using the empirical relationships derived by Meurer, Heckman & Calzetti (1999) between the spectral slope at 1600 Å and the ratio of FIR to 1600 Å luminosities for local lower-luminosity starbursts, we estimate a similar factor of 10 shortfall between the predicted bolometric luminosity of N2 850.4 based on its rest-frame UV flux and that inferred from submm and radio observations.

The order of magnitude difference in the bolometric luminosity estimated from the young stellar population in the UV and that detected in the submm waveband is consistent with these arising in distinct components. This supports our earlier proposal that N2 850.4 consists of a lightly-obscured young stellar population providing ~10 per cent of the bolometric luminosity (B), and a highly-obscured starburst/AGN (P) which produces the bulk of the remainder. Hence, in the following we assume that the starburst activity seen in the UV and the submm have separate origins. However, we caution that the only way to confirm this hypothesis is to obtain higher-resolution observations of N2 850.4 at both wavelengths.

Turning to the UV starburst in N2 850.4/B, we can use the size of the starburst and the star formation rate to estimate the star formation density in this component. As the rest-frame UV emission from the galaxy is dominated by light from very young stars, we estimate the physical size of the starburst from the V-band (rest frame 1600 Å) extent of the galaxy: 0.64 arcsec, or 5.0 kpc. Interestingly, the large extent of the starburst region is also supported by the apparently modest wind velocity given the strength of the UV starburst. Using the analytical wind model of Shu, Mo & Mao (2003), a star formation rate of 300 M$_\odot$ yr^{-1} and a wind velocity of ~350 km s^{-1} we predict that the starburst region should be ~10 kpc in diameter. Moreover, this same model predicts that the wind should have substantial mass-loading, $\dot{M} \sim 10^3$ M$_\odot$ yr^{-1}.

Using the estimated size of the starburst and adopting the extinction-corrected star formation rate determined from the UV flux above, this yields a star formation density of ~25 M$_\odot$ kpc^{-2} yr^{-1}, with an uncertainty of a factor of at least 2. This is similar to the claimed limiting intensity for the star formation density in local UV starbursts derived by Meurer et al. (1997), 45 M$_\odot$ kpc^{-2} yr^{-1}. If the UV component of N2 850.4 is forming stars at a maximal rate, then this suggests that the same physical mechanisms which occur at low redshift to limit starbursts are also operating in this luminous system at $z = 2.38$. This should give some encouragement that feedback mechanisms calibrated at low redshift may be applicable at these much earlier times. Trying to apply this approach to the obscured component will require better constraints on the extent of the FIR emission in this galaxy and the contribution from an AGN to the radio and FIR emission.

Given the enormous star formation rate of the burst, is this truly a primeval galaxy undergoing its first star formation event? We believe that this is unlikely as the optical emission features we see suggest an AGN is present in the system, and this requires that a relatively massive black hole has had time to grow. Using the [O III] λ5007 luminosity of the galaxy, $L_{[\mathrm{O\,III}]} = 1.7 \times 10^{42}$ erg s^{-1}, then the correlations in Alonso-Herrero, Ward & Kotilainen (1997); Alonso-Herrero et al. (2002) suggest a black hole mass of $\gtrsim 10^8$ M$_\odot$. Assuming that black holes grow through accretion with a radiative efficiency of ~0.1 then such a massive black hole would take $\gtrsim$100 Myr to grow even at a constant accretion luminosity of the order of 10^{13} L$_\odot$ – much longer than the estimated time-scale of the current burst – suggesting that this is unlikely to be the first, significant star formation event in this galaxy. Thus, if the star formation and AGN activity in young galaxies are related, then both types of activity may be intermittent (Page et al. 2001; Almaini et al. 2003). Nevertheless, the current burst is still capable of producing very large numbers of stars; if we assume the lifetime of the obscured starburst is the same as that in the UV companion, 10 Myr, then the star formation rate implies that up to $\sim 10^{11}$ M$_\odot$ may have already been formed.

We note that N2 850.4 is the only one of $\lesssim$10 SCUBA galaxies (with UV spectroscopy sufficiently deep to identify the spectral signatures of a young starburst, $\lesssim$10 Myr) which shows obvious starburst features (Ivison et al. 2000; Chapman et al. 2003a). Assuming that all SCUBA galaxies follow the same evolutionary path, with a UV-detectable phase for 10 per cent the submm-luminous phase would then have a time-scale of the order of 100 Myr – allowing the systems to form 10^{12} M$_\odot$ of stars. In that case, we are seeing the formation of very massive galaxies. Alternatively, SCUBA galaxies may typically not appear in a UV-luminous phase such as N2 850.4, or their young starburst features may be weaker, and masked by featureless UV emission from an AGN.

5 CONCLUSIONS

Our rest-frame optical and UV spectroscopy of N2 850.4 reveal a multitude of features associated with starburst activity, including an array of interstellar absorption lines and P-Cygni wind absorption profiles, which confirm the stellar origin of the continuum emission in the rest-frame UV. We also identify the spectral signatures of large-scale gas outflows, which may be driving significant amounts of enriched material into the galaxy's halo and the surrounding intergalactic medium, and which may eventually remove enough gas to halt the starburst. The inferred luminosity of the young stellar population requires a star formation rate of $\sim$300 $M_{\odot}$ yr^{-1} in the UV-bright component. More importantly, the strength of the spectral features is consistent with a young ($\gtrsim$10 Myr old) starburst. Such obvious signs of a young starburst have not previously been observed in the SCUBA population.

However, from spectroscopic data the UV bright component, N2 850.4/B, appears to be spatially and kinematically distinct from the near-IR component of the system, N2 850.4/P, which has a similar redshift to the molecular gas reservoir recently detected by Genzel et al. (in preparation), indicating it is likely to be the source of the luminous FIR emission. The interaction between the two components probably triggered the hyperluminous FIR activity. The velocity offset between the components is $\sim$400 km s^{-1}, suggests that, if the UV bright companion is in a bound orbit, N2 850.4 is a very massive galaxy, $\sim 10^{12}$ $M_{\odot}$.

As with other well-studied SCUBA galaxies, N2 850.4 shows spectral features of a partially obscured AGN, which we locate in the FIR luminous component of this system, N2 850.4/P. Nevertheless, the modest linewidths and luminosity of the AGN suggest it is unlikely to dominate the energy output of the whole system and so we conclude that the bulk of bolometric emission from N2 850.4 is derived from reprocessed radiation from highly-obscured, young stars.

The most interesting result that can be derived from our spectra is the constraint on the minimum time-scale of the unobscured activity in this system, of the order of $\gtrsim$10 Myr. Assuming that the FIR emission was triggered at the same time, then the obscured starburst is also at least 10 Myr old. From the bolometric FIR luminosity, we can infer that approximately 10^{11} $M_{\odot}$ of stars have been formed.

However, we note that the likely time-scale for the formation of the massive black hole in the near-IR/FIR luminous system is significantly longer than $\sim$10 Myr, implying both that this is probably not the first starburst experienced by this galaxy, and that star formation activity in the SCUBA population may occur in brief, repeated bursts, triggered by a series of interactions and mergers. Although brief, these bursts are still powerful; in the current starburst this massive system could have formed an entire L^{*} galaxy's worth of stars. This underlines the possible association of SCUBA galaxies with the formation phase of the most luminous galaxies seen in the local Universe: giant ellipticals.

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