

DETECTION OF H α EMISSION FROM $z > 3.5$ GALAXIES WITH AKARI-FUHYU NIR SPECTROSCOPY

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ABSTRACT

This paper presents H α emission line detections for four galaxies at $z > 3.5$ made with AKARI as part of the FUHYU mission program. These are the highest-redshift H α detections to date in star-forming galaxies. AKARI's unique near-infrared spectroscopic capability has made these detections possible. For two of these galaxies, this represents the first evidence of their redshifts and confirms their physical association with a companion radio galaxy. The star formation rates (SFRs) estimated from the H α lines under-predict the SFRs estimated from their far-infrared luminosities by a factor of $\sim 2 - 3$. We have also detected broad H α components in the two radio galaxies which indicate the presence of quasars.

Key words: galaxies: evolution; galaxies: starburst; galaxies: active; infrared: galaxies; submillimeter: galaxies; conferences: proceedings

1. INTRODUCTION

The AKARI “Follow-Up Hayai-Yasui-Umai” mission program (FUHYU, Pearson et al., 2010) used the AKARI InfraRed Camera (IRC, Onaka et al., 2007) to make extensive infrared observations of well-studied fields in order to maximise the legacy value of the AKARI data. The mission program carried out imaging during the first two phases of the AKARI mission (Serjeant et al., 2009; Pearson et al., 2010; Negrello et al., 2009), and spectroscopy during the third (warm) phase. For the galaxies discussed in this paper, the science objective was to measure rest-frame optical emission lines of radio and star-forming galaxies at very high redshifts. AKARI had the ability to obtain spectra at wavelengths in the near-infrared in the range of

2.5 μm to 5.0 μm , a region not previously available in the spectroscopy of other infrared space missions such as the Spitzer Space Telescope (and a region which has low sensitivity from the ground), which gives the unique possibility of detecting H α for galaxies at redshifts in the range $3.0 < z < 6.5$.

Spectroscopy was carried out using the IRC *NG* grism over a $1' \times 1'$ point source aperture. The grism covered 291 pixels with a dispersion of 0.0097 μm per pixel. The imaging field of view was approximately $10' \times 10'$ (412×512 pixels) with a pixel scale of 1.46". The PSF FWHM was about 6.7" in spectroscopic mode. We selected the Astronomical Observing Template (AOT) *IRCZ4* for spectroscopy, in the configuration *b;Np*. One pointing consists of ~ 10 minutes

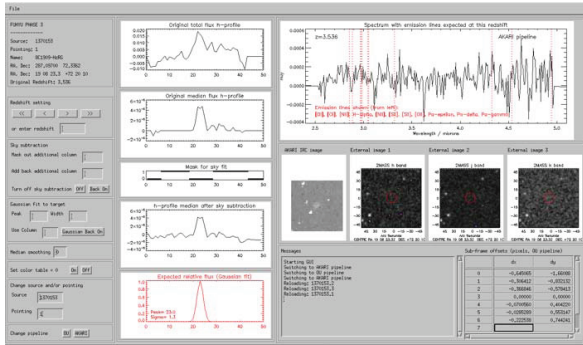


Fig. 1. Layout of the IDL graphic user interface.

exposure time, containing 5 initial dark frames, 4 exposure frames, an $N3$ reference image followed by at least 4 more NG frames, and finally a further 5 dark frames. We carried out 10 pointings per source where possible.

In total we obtained 552 pointings over 72 sources. Here we concentrate on the first identifications of emission lines in our sample of submillimeter and radio galaxies. Observations were made of four high-redshift radio galaxies (HzRGs) and three submillimeter sources ostensibly associated with one of them. These sources were mapped by the Submillimeter Common-User Bolometer Array (SCUBA) instrument on the James Clerk Maxwell Telescope (JCMT) (Stevens et al., 2003), and this study found a significant likelihood that the submillimeter sources observed were associated with the nearby radio source, based on their higher-than-expected number densities and in many cases their alignment with the radio jets. The targets discussed in this paper are listed in Table 1. This paper assumes the parameter values of the current concordance cosmology: $H_0=72.0 \text{ km s}^{-1}\text{Mpc}^{-1}$, $\Omega_M=0.3$ and $\Omega_\Lambda=0.7$.

2. DATA REDUCTION

The IRC data reduction pipeline for the warm phase (Onaka et al., 2009) was originally used to analyse our data. However, we found it necessary to make corrections for spacecraft jitter between sub-frames and for sky subtraction, and then wrote our own pipeline using Interactive Data Language (IDL) to reduce the raw spectroscopic data. Our pipeline includes dark subtraction, saturation masking, wavelength calibration and spectral response calibration using the calibration data from the IRC pipeline. We wrote our own routines to handle sky subtraction (we fitted a sixth-order polyno-

mial in the dispersion direction to remove a banding pattern across the frame, and a second-order polynomial in the image direction), de-glitching, and to estimate the offsets between sub-frames caused by spacecraft jitter during each pointing using the simultaneous imaging data. Our pipeline included IDL routines for zerofootprint drizzling and for noise-weighted source extraction which had previously been written for the SCUBA Half Degree Extragalactic Survey (SHADES, Serjeant et al., 2008). We also wrote an IDL graphic user interface (GUI) routine (see Fig. 1) to visualise various elements of the reduction process on an interactive basis. The results were then stacked by coadding the noise-weighted pointings for each target. Further details of the pipeline will be given in Sedgwick et al. (in preparation).

At the redshifts of the targets considered in this paper, the $H\alpha$ hydrogen recombination line falls within our $2.5 \mu\text{m} - 5.0 \mu\text{m}$ observed wavelength range. Other possible emission lines in our observed wavelength range proved to be undetectable.

3. RESULTS

8C1909+722 and companions. The redshift for the high- z radio galaxy (HzRG) 8C1909 was reported as $z = 3.5356$ in De Breuck et al. (2001) which showed a strong, fairly broad Ly- α emission line with FWHM = $1,200 \text{ km s}^{-1}$. The SCUBA survey detected three submillimeter galaxies (SMM1-3) close to this radio galaxy (Stevens et al., 2003). Spectroscopic redshifts were not previously known for these submillimeter galaxies. We have found that the spectrum for the radio galaxy 8C1909+722 has a broad $H\alpha$ emission line at the correct wavelength for its redshift, as shown in Fig. 2. The submillimeter galaxy SMM1 shows considerable structure, both in the submillimeter (see Stevens et al., 2003) and in our AKARI infrared image at $3 \mu\text{m}$. The brightest peak in our $3 \mu\text{m}$ image did not show an $H\alpha$ emission line, but an $H\alpha$ line was found about $3''$ away from the second peak (later found to be aligned with a strong peak at $850 \mu\text{m}$). The emission line confirms that the redshift of SMM1 is the same as that of the radio galaxy. The spectrum for the submillimeter galaxy SMM2 also showed an $H\alpha$ emission line (Fig. 2) at the same redshift ($z = 3.536$), confirming that this galaxy is also associated with the radio galaxy. The third submillimeter galaxy, SMM3, did not show a convincing $H\alpha$ emission line. Unlike SMM1 and SMM2,

TABLE 1.

The Radio and Submillimeter Sources Discussed in this Paper. Flux Data is from Stevens et al. (2003).

Object	RA h m s	Dec d m s	Redshift	850 μ Flux mJy	No. of Pointings	Exposure mins
8C1909+722 HzRG	19 08 23.3	+72 20 10.4	3.536	34.9	10	100
8C1909+722 SMM1	19 08 27.4	+72 19 28.0		23.0	10	100
8C1909+722 SMM2	19 08 29.3	+72 20 49.6		8.7	10	100
8C1909+722 SMM3	19 08 16.1	+72 20 24.0		4.3	13	130
8C1435+635 HzRG	14 36 37.4	+63 19 13.1	4.261	6.0	10	100
4C60.07 HzRG	05 12 54.8	+60 30 51.7	3.788	23.8	10	100
4C41.17 HzRG	06 50 52.1	+41 30 30.8	3.792	12.0	7	70

this galaxy is not aligned with the jets from the radio galaxy. Stevens et al. (2003) had proposed that these galaxies had formed as a single galaxy cluster, on the basis of their higher-than-expected number density and the alignment of SMM1 and SMM2 with the radio jets. We have confirmed that this association is correct in the case of these two submillimeter sources.

Spectrum of the other three HzRGs. For the radio galaxy 4C60.07, a redshift of $z = 3.788$ was known from the Ly- α emission line reported in Roettgering et al. (1997) with FWHM = 2875 km s $^{-1}$. A detailed SMA, Spitzer and VLA study by Ivison et al. (2008) suggested an early-stage merger between the host galaxy of an AGN (the HzRG) and a companion starburst/AGN, and that a second submillimeter source was comprised of cold dust gas and probably a short-lived tidal structure caused by the merger. Our stacked spectrum for this radio source has a broad H α emission line at the expected wavelength (Fig. 2, bottom). This spectrum comes from a point about 3'' away from the 3 μ m peak and is aligned with the second peak in the 870 μ m flux in Ivison et al. (2008). Emission lines were not detected from the other two HzRGs, 8C1435+635 and 4C41.17.

Star formation rates. For star-forming regions, a relationship has been found between the H α luminosity and total star formation rate (SFR) (Kennicutt, 1998) which gives the results for SMM1 and SMM2 shown in Table 2. The levels of star-formation rate found in the two submillimeter galaxies are $\sim 1,650$ and 1,180 M_{\odot} yr $^{-1}$ respectively. No adjustment has been made for extinction by dust.

We can obtain an alternative measure of the star formation rate using an estimate of the 60 μ m luminosity (Kennicutt 1998) which we have estimated from the 850 μ m luminosity (see Table 2). The results of this calcu-

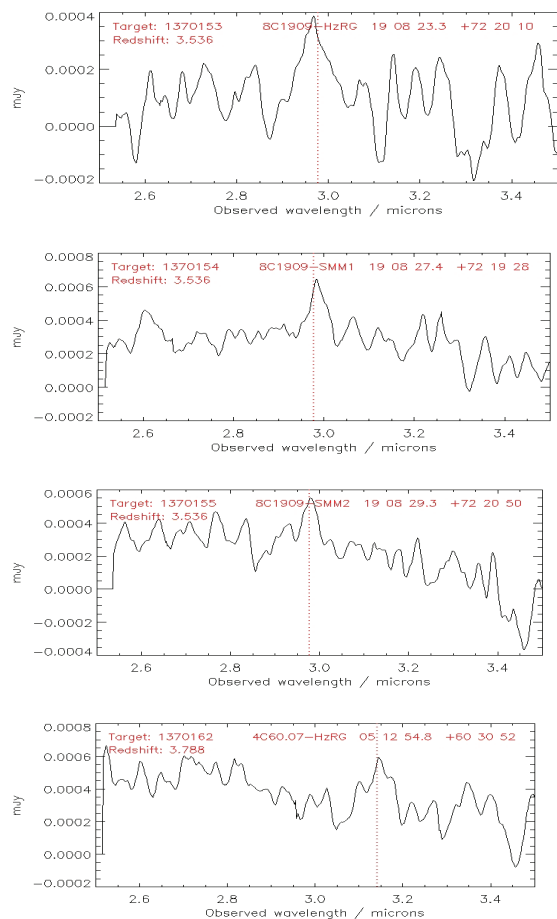


Fig. 2. Stacked spectra for the four sources in which H α line has been detected at the expected redshifts of the radio galaxies. From top: 8C1909+722HzRG, SMM1, SMM2 and 4C60.07. The dashed red vertical lines show the H α emission line at the expected redshifts.

TABLE 2.

Estimates of Star Formation Rates Based on $H\alpha$ Emission Luminosities, and Deconvolved FWHM Based on the Width of the Lines. The FIR Luminosities and SFRs are Based on the $850 \mu\text{m}$ Flux Assuming an M82 SED.

Source	Flux($H\alpha$) $10^{-18} \text{ W m}^{-2}$	L($H\alpha$) 10^{37} W	SFR($H\alpha$) $M_{\odot} \text{ yr}^{-1}$	L(FIR) $10^{13} L_{\odot}$	SFR(L_{FIR}) $M_{\odot} \text{ yr}^{-1}$	FWHM($H\alpha$) km s^{-1}
8C1909+722 HzRG	6.5	7.0		5.1	9,300	7,000
8C1909+722 SMM1	1.9	2.1	1,650	3.4	6100	unresolved
8C1909+722 SMM2	1.4	1.5	1,180	1.3	2300	unresolved
4C60.07 HzRG	2.9	3.8		3.4	6,300	7,700

lation assuming an M82 SED are also shown in Table 2. Compared to these, the star formation rates estimated from $H\alpha$ show a decrement by a factor of $\sim 2 - 3$, most likely caused by dust obscuration. This can be compared with a $\text{SFR}(L_{\text{FIR}})/\text{SFR}(H\alpha)$ of ~ 10 found in a previous study of submillimeter to radio galaxies in the redshift range to $z = 1.408$ to 2.692 using K-band spectroscopy (Swinbank et al., 2004). The total FIR luminosity also shows that these four galaxies are HyperLuminous InfraRed Galaxies ($L_{\text{FIR}} > 10^{13} L_{\odot}$).

The deconvolved FWHM of the $H\alpha$ lines is also shown in Table 2 and is $7,000 \text{ km s}^{-1}$ and $7,700 \text{ km s}^{-1}$ for 8C1909+722 and 4C60.07 respectively, a level which shows that dust-shrouded quasars are present.

4. CONCLUSIONS

Our detection of $H\alpha$ emission lines from two submillimeter galaxies in the region of 8C1909+722 provides evidence of their association with the radio galaxy. The extent of the system is $\sim 1.5'$ ($\sim 700 \text{ kpc}$), suggesting that this may be a present-day cluster of galaxies. We found $\text{SFR}(L_{\text{FIR}})/\text{SFR}(H\alpha)$ of $\sim 2 - 3$.

For the two radio galaxies with $H\alpha$ detections, the width of the emission lines shows they are quasars. Ivison et al. (2008) suggested that the peak of 4C60.07 was a gas-rich starburst/AGN; our discovery that it is a quasar supports the argument that binary AGNs at close separations may be due to the triggering or enhancement of AGN activity during mergers.

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