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# First results from SPIFFI, II: The luminous infrared galaxy NGC 6240 and the luminous sub-millimeter galaxy SMMJ 14011+0252

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**Abstract.** This is the second of two papers (I: Horrobin et al. 2003) on the first scientific results from the SPIFFI integral field spectrometer at the VLT. Here we discuss the observations and properties of the prototypical luminous infrared galaxy NGC 6240 and the luminous sub-millimeter galaxy SMMJ 14011+0252. Taking full advantage of the excellent seeing conditions of 0.27", our integral field spectroscopy data allow us for the first time to study in detail the stellar and gas dynamics in NGC 6240 on scales of 125 pc, and to establish a galactic shock as the origin of the strong emission from molecular hydrogen. Our observations of SMMJ 14011+0252 provide us with deep, spatially resolved near infrared spectra of the SCUBA selected luminous submillimeter galaxy at a redshift of z=2.565, revealing a remarkably old, massive and metal-rich starburst galaxy for the early epoch at which it is observed.

**Key words:** galaxies: individual (NGC6240, SMMJ 14011+0252) – techniques: spectroscopic



## 1. A galactic shock in the merger NGC 6240

The infrared luminous galaxy NGC6240 (D=97 Mpc, $L_{IR} = 6 \times 10^{11} L_\odot$) is in many ways a prototype for the class of gas rich, infrared (ultra-) luminous mergers that dominate the upper end of the local luminosity function of IRAS galaxies (Sanders & Mirabel 1996). The NGC6240 system has two rapidly rotating, massive bulges/nuclei at a projected separation of 1.6″(750 pc, upper left panel in Fig.1), each of which contains a powerful starburst and a luminous, highly absorbed, X-ray active AGN (Tecza et al. 2000, Komossa et al. 2003, Lutz et al. 2003). As such, NGC6240 is probably a local template for the population of dust and gas rich, merger/AGN systems at high redshift that likely contribute about half of the energy density at z≈2.5 (see the section on SMMJ14011+0252). NGC6240 is also the most luminous local source of ro-vibrationally excited $H_2$ quadrupole line emission. About $2 \times 10^9$ $L_\odot$, or 0.3% of the infrared luminosity, emerges in $H_2$ infrared line emission, and the origin and excitation of this spectacular line emission has been the subject of many studies. The K-band spectrum is full of vibrationally excited $H_2$ lines with excitation potentials up to about 20,000 K above the ground state (right panel, Fig.2).

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We observed NGC6240 with SPIFFI in K-band in excellent seeing with the 0.1″/pixel scale, resulting in a data cube with 0.27″ FWHM resolution. The spectra cover the wavelength range from 1.95 - 2.45 $\mu$m with a spectral resolving power of approximately 4000. The total exposure time on-source is 20 minutes. Sky-subtraction was carried out by nodding the telescope. Fig.1 compares the distribution of the stellar light (top left) with that of the ionized gas (top right) and vibrationally excited molecular hydrogen (middle panels). Most of the starburst activity (as traced by Br$\gamma$) occurs in the two nuclei on scales of 200 pc, although there appears to be one extra-nuclear Br$\gamma$ source in the gas bridge between the two nuclei, suggestive of star formation there. The vibrationally excited $H_2$ is very different and follows

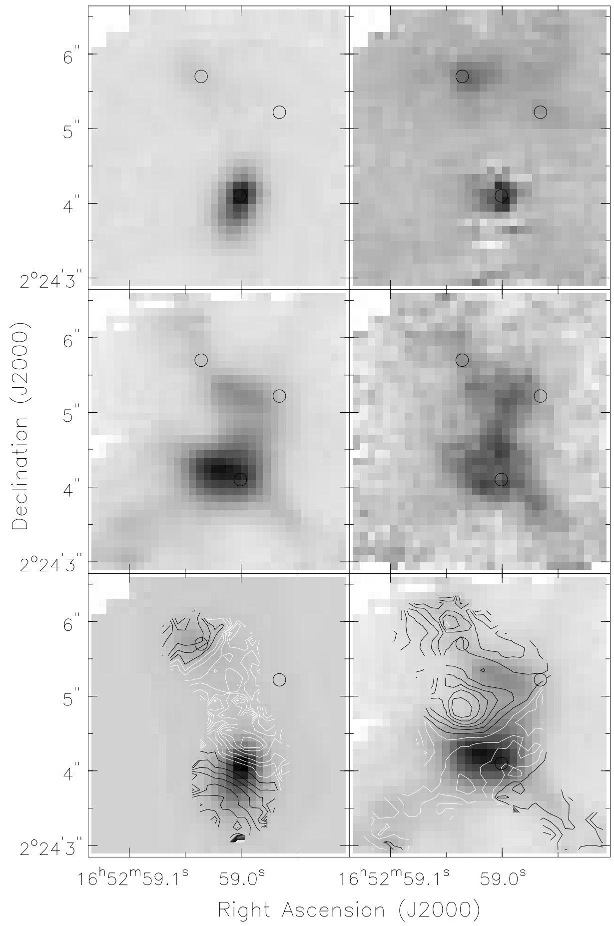


**Fig. 1.** SPIFFI images, stellar and $H_2$ kinematics of the infrared luminous merger NGC6240. Top panels: Stellar light (upper left, from CO 0-2 absorption flux), Br$\gamma$ flux (upper right), $H_2$ v=1-0 S(1) (middle left) and v=2-1 S(1) (middle right) distributions, as observed with SPIFFI with 0.1″/pixel and 0.27″ FWHM resolution. In all images the position of the two nuclei and an extra-nuclear Br$\gamma$ source are marked. Bottom left: stellar velocity field (contours) superposed on K-band image. The contour lines are in steps of 50 km/s, redwards (black contours) and bluewards (white contours) of the systemic velocity at 7300 km/s. Bottom right: $H_2$ v=1-0 S(1) velocity contours (same units as for stars) on $H_2$ image.

a complex spatial and dynamical pattern (lower right panel of Fig.1) with several extended streamers, as already found in earlier, lower resolution studies (e.g., van der Werf et al. 1993). The high resolution SPIFFI data now permit us to follow the $H_2$ distribution, excitation and kinematics on $\leq 10^2$ pc scales. The two middle panels show that the v=2-1 and v=1-0 emission lines exhibit very similar large-scale distributions. The only difference occurs in the most prominent $H_2$ peak, where the higher excitation v=2-1 S(1) line is located closer to but still off the southern nucleus. The $H_2$ kinematics are extremely complex (lower right panel in Fig.1) and very different from the relatively simple counter-rotation pattern of the stars (lower left, Fig.1). The gas bridging the two nuclei is redshifted relative to the northern and southern nucleus and exhibits a very steep velocity gradient of 500 km/s over 0.7″ as it curves around toward the southern nucleus. There it appears to crash into the nuclear regions approximately at right angles relative to the stellar rotation pattern and with a velocity of 150 to 200 km/s relative to the stars. From the bright $H_2$ peak just NE of the southern nucleus, two gas streamers emerge and envelop the southern galaxy. This kinematic pattern resembles the gas bridges found in simulations of gas rich mergers after the first peri-approach. We may be observing the two galaxies after the first "hang out" phase in the process of falling back in for the second peri-approach. In the process they are strongly interacting with and shock exciting the tidally swept out gas bridge between the nuclei.

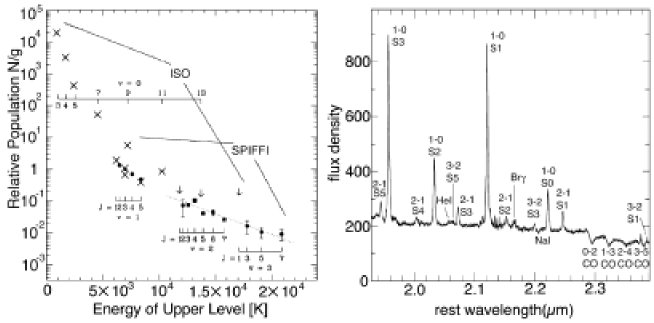


**Fig. 2.** K-band spectrum (right, 0.5″ aperture near southern nucleus) and level diagram (left) of $H_2$ rotationally excited (grey: from ISO SWS, Lutz et al. 2003) and ro-vibrationally excited states (black: SPIFFI). A constant temperature distribution is a straight line in this diagram, with a slope inversely proportional to temperature. The NGC6240 data indicate the presence of a wide range of excitation temperatures up to about 3300K (dotted black line fitting the v=2 and v=3 data). The offset between v=0 and v>0 data may be due to extinction, or due to an additional component of somewhat cooler material. The distribution can be fit by a combination of J- and C-shock models, or by a bow-shock model (Rosenthal et al. 2000).

The right panel of Fig.2 shows an excitation diagram of the $H_2$ emission, where we have combined the SPIFFI data with ISO SWS measurements of the rotational line emission (Lutz et al. 2003). The $H_2$ level populations follow a smooth distribution with local excitation temperature steadily increasing with level energy (the slope of the local level distribution is inversely proportional to excitation temperature). The highest excitation lines we observe require an excitation temperature of about 3300 K. The observed level distribution is very similar to that observed in the Orion-KL star formation shock (Rosenthal et al. 2000). With the possible exception of the region very near the southern nucleus, the $H_2$ spatial distribution, kinematics and level populations thus strongly favor a galactic shock model as the origin of the spectacular $H_2$ emission. The high temperature and turbulence also explains why little star formation has yet occurred in the dense molecular gas bridge between the two nuclei. The cooling time of that gas is $\leq 10^7$ years, comparable to the time to the second peri-approach of the two nuclei. At this point NGC6240 will probably experience an even stronger star formation episode that will turn the system into a true ultra-luminous galaxy.

## 2. A portrait of the luminous sub-millimeter galaxy SMMJ 14011+0252

The strength of the extragalactic mid- and far-IR/submillimeter background indicates that about half of the cosmic energy density (excluding the microwave background) comes from distant, dusty starbursts and AGN (Puget et al. 1996). Surveys with ISOCAM at 15$\mu$m, SCUBA at 850$\mu$m, and MAMBO at 1200$\mu$m suggest that this background is dominated by luminous and ultra-luminous infrared galaxies (LIRGs/ULIRGs: $L_{IR} \approx 10^{11.5..13}$ $L_{\odot}$) at $z \geq 1$ (e.g. Genzel & Cesarsky 2000, Blain et al. 2002, Elbaz et al. 2002). Little is known yet about the physical properties of this important submillimeter galaxy population since they are very faint in the rest wavelength UV/visible range. Half a dozen SCUBA sources presently have mm-confirmed spectroscopic redshifts near $z \approx 2.5$ (Frayer et al. 1998, 1999, Genzel et al. 2003, Downes & Solomon 2003, Neri et al. 2003), close to the redshift of the peak of cosmic star formation and QSO activity (Chapman et al. 2003). The submillimeter population may trace the formation of massive/luminous AGN/starburst systems that may evolve into massive local early type galaxies and bulges.

One of the brightest SCUBA galaxies is the source SMMJ14011+0252 at z=2.565, which is gravitationally lensed by the foreground z=0.25 cluster Abell 1835 (Fig.3, Ivison et al. 2001). HST imaging shows that the system consists of several sub-components (J1 (c, se, n), J2) spread over about 3″ (top right panel of Fig.3, 24 kpc without correction for lensing). We observed SMMJ14011+0252 with SPIFFI in J, H and K-bands with the 0.25″ pixel scale for a total of 8 hours on-source integration (Tecza et al. 2004). Individual exposure times in the three bands were 10, 5, and 10 minutes, respectively. Sky-subtraction was carried out by nodding the telescope to a nearby blank field, thus spending another total of 8 hours on the sky. The effective resolution in the different data sets is between 0.5″ and 0.75″. The lower right panel of Fig.3 shows the line free K-band continuum distribution. In comparison to the HST image (Ivison et al. 2001, appropriately smoothed to the same resolution as the SPIFFI data), the rest-frame optical ($\approx$R-band) distribution is dominated by the extended J1 complex, with a significant extension to the NNE. The continuum subtracted H$\alpha$ distribution (bottom left panel) is very different from either of the continuum maps. The H$\alpha$ emission comes from an $4'' \times 1.6''$ feature elongated along p.a. 10-15°, approximately centered on J1c but peaking on either side of the continuum peak.

Figure 4 shows the near-IR spectra obtained with SPIFFI and integrated over the central J1 complex. Our flux scales were determined using the UKIRT faint standard G5 star FS135. These data were obtained and reduced in the same way as the SMMJ14011+0252 data, with the additional step of dividing out a solar spectrum. Although FS135 was not observed on every night, counts on SMMJ14011+0252 were consistent enough from night to night that conditions must have been essentially photometric throughout. As already found by Ivison et al. (2001), the rest-frame optical/UV emission line spectrum is dominated by a starburst (HII region)

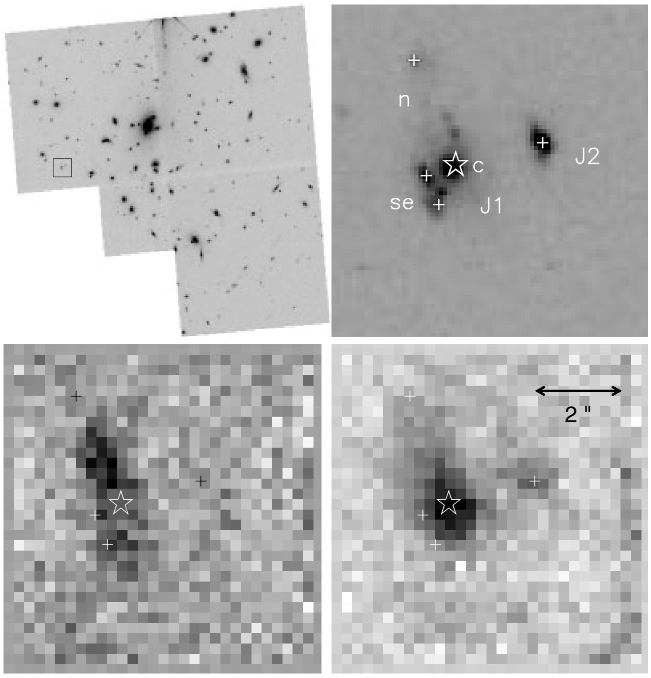


**Fig. 3.** The SCUBA galaxy SMMJ14011+0252 (z=2.565). Top left: R-band HST WFPC2 image of the z=0.25 cluster Abell 1835, which gravitationally lenses the background submm galaxy SMMJ14011+0252 by about a factor of 4 to 6. Top right: HST R-band image of the central few arcseconds of the source with a log-scale color stretch (white square in left panel, from Ivison, priv.comm.). The various components of the J1/J2 system are marked by crosses. Bottom right: Line free K-band continuum image obtained with SPIFFI. The star marks the position of the CO mm line and continuum emission (Downes & Solomon 2003). Bottom left: Continuum subtracted SPIFFI H$\alpha$ map. The SPIFFI images have a resolution of about 0.65x0.5″.

spectrum without much evidence for AGN activity. The H$\alpha$ and [NII] line profiles exhibit blue wings with velocities of several hundred km/s and a [NII]/H$\alpha$ line ratio of about 1 (indicated by the grey line in the lower spectrum of Fig. 4). These values are characteristic of shock-heated superwinds seen at low redshift (Lehnert & Heckman 1996). The J/H/K spectral energy distribution exhibits a break between the J and H bands that can be well fit by an A-star continuum model at redshift $z \approx 2.5$ (thick grey line, age a few $10^2$ Myrs). We interpret this emission as coming mainly from J1c and its extended surroundings, and conclude that J1c is a post-starburst stellar component at the same redshift as the young starburst and possibly part of the central bulge/disk of the submm source. The position of the powerful submm starburst, as marked by the mm CO line and continuum emission (Downes & Solomon 2003) is consistent with the location of the K-band peak. The H$\alpha$ line emission has a remarkably narrow profile ($\approx$130 km/s) and exhibits a systematic velocity gradient mainly in east-west direction, perpendicular to its spatial elongation. J2 also shows H$\alpha$ emission, which is about 170 km/s offset from the systemic velocity of J1.

We can place the optical starburst features on the classical diagnostic diagrams. All diagnostic ratios ([OIII]/H$\beta$ vs [NII]/H$\alpha$, or [OI]/H$\alpha$ or [SII]/H$\alpha$) put the system firmly

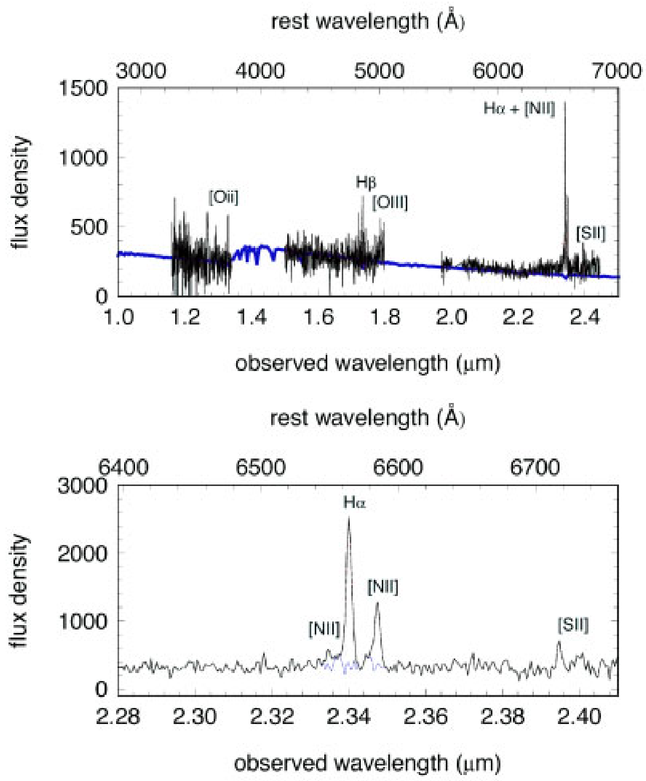


**Fig. 4.** SPIFFI spectra of the central 2.5″ centered on J1c. The J/H/K spectrum (top) shows a typical starburst emission line spectrum, plus a continuum with a spectral break between J and H that can be well fit by a few $10^2$ Myr starburst (A-star spectrum) at redshift 2.5 (thick grey curve). The zoom into the region around H$\alpha$ emission (bottom) shows the narrow line widths, with a blueshifted residual wing that is probably due to a superwind (grey curve).

in the region of low excitation, low extinction (E(B-V)$\approx$0.2 implied by the Balmer decrement) but high H$\alpha$ equivalent width, local starbursts. The density sensitive [SII] line ratio also indicates a very typical electron density of about $10^2$ cm$^{-3}$. Perhaps most importantly we deduce a super-solar oxygen abundance (12+log(O/H)$\approx$9) from the reddening corrected, classical (I([OIII]) +I([OII]))/I(H$\beta$) ratio, using the fits of Kobulnicky et al. (1999) to the appropriate relation of McGaugh (1991). In addition, and somewhat surprisingly, the relatively strong [NII] emission relative to [OII] indicates that SMMJ14011+0252 has a relatively large nitrogen enrichment. These results are very significant since they pertain, in contrast to high-redshift QSO emission line regions, to large regions in the galaxy and imply that star formation has been proceeding in this system for a considerable period of time.

The morphology of the H$\alpha$ emission, its kinematics, the likely identification of J1c with a post-starburst component at the same redshift and the similar but not identical redshifts of J1 and J2 all can be explained in a simple lensing model where J1 and J2 are two physically associated background galaxies located behind the central cD of Abell 1835 that are magnified by about a factor of 4 to 6. The corresponding demagnified images of J1 are fairly circular and point to a central dusty starburst (the submm source) surrounded by a low inclination and low extinction star forming disk (H$\alpha$ and optical continuum) of diameter about 8 kpc. Assuming a magnification of 5, the current star formation rate can be estimated from the galaxy's (sub)millimeter photometery (Ivison et al. 2000, Smail et al. 2002), which implies a far infrared luminosity (8 - 1000 $\mu$m) of about 2x$10^{12}$ $L_\odot$, corresponding to a current star formation rate of $\approx$ 150 $M_\odot$/yr. Assuming that this burst has been proceeding for the last 100 Myr, the minimum age derived from the continuum break, the inferred stellar mass formed in this burst is about 1.4x$10^{10}$ $M_\odot$. For comparison the present (molecular) gas mass is about 2x$10^{10}$ $M_\odot$ and the virial mass of the J1/J2 system is about 6x$10^{10}$ $M_\odot$. While these numbers are obviously quite uncertain, they imply that SMMJ14011+0252 is a massive ($\approx$m*) system forming in a major starburst event at z$\approx$2.5, possibly triggered by the interaction of the J1/J2 components. Its luminosity is similar to those of very luminous local starbursts, such as the ULIRG mergers. Our conclusion is very much strengthened by the high metallicity of SMMJ14011+0252. The only low-z systems with such high a metallicity are massive ($\geq$m*) early type galaxies. As our knowledge about the high-z submillimeter population increases, the evidence becomes firmer that these systems indeed must be precursors of massive local bulges and ellipticals. This is perhaps in contrast to the Lyman break population whose evolutionary endpoint seems less clear.

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