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GIRAFFE multiple integral field units at VLT: A unique tool to recover velocity fields of distant galaxies★

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Abstract. The GIRAFFE spectrograph is unique in providing the integral field spectroscopy of fifteen distant galaxies at the same time. It has been successfully implemented at the second VLT unit within the FLAMES facility. We present GIRAFFE observations acquired during the Guaranteed Time Observation of the Paris Observatory, using total exposure times ranging from 6 to 12 h. The reduced 3D cube of each galaxy has been deconvolved using our new package DisGal3D. This software has been written using the only assumption that UV light traces the emission line regions. The comparison between GIRAFFE spectra and HST imagery allows us to recover details on velocity fields as small as 0.3−0.4 arcsec. It has been successfully tested using Fabry Perot observations of nearby galaxies purposely redshifted to large distances. We present here preliminary results for three distant galaxies at $0.45 < z < 0.65$, whose velocity fields have been derived with exquisite spectral ($R = 10\,000$) and spatial resolutions. Observed velocity fields range from disturbed fields expected in major merger events to those of regular spiral with minor perturbations. For the latter, one could accurately derive the dynamical major axis and the maximal rotational velocity. We conclude that dynamical properties of a large number of distant galaxies can be routinely derived at VLT. This opens a new avenue towards the understanding of the galaxy formation and evolution during the last 8 Gyr.

Key words. galaxy formation – velocity field – star formation rate – 3D spectroscopy

1. Introduction

Studies of galaxies at intermediate redshift ($0.4 < z < 1.2$) have revealed large changes of galaxy properties during the last 8 Gyr, which follow the strong declines of the cosmic star formation density (Lilly et al. 1996; Flores et al. 1999) and of the merging rate (Le Fèvre et al. 2000). Indeed, galaxies at intermediate redshift have complex morphologies and colors differents from those of the Hubble sequence and they show metal abundances lower than those of present day galaxies (Hammer et al. 2004). Major contributors for this evolution have been identified to be luminous IR galaxies (LIRGs) and luminous compact galaxies (Flores et al. 1999; Hammer et al. 2001). Besides the numerous studies of their photometric and chemical properties, very little is known about the dynamical properties of galaxies beyond $z = 0.1$.

The Tully-Fisher relation is hard to reproduce in simulations (Steinmetz & Navarro 1999), and it is of prime importance to study its evolution until $z = 1$. Significant changes of the slope of the Tully-Fisher relation are expected in the distant Universe ($z \sim 1$, Ferreras & Silk 2001) and this would be the best observable to explore the star formation process in disk galaxies. The TF relation at high redshift has been investigated by several studies using slit spectroscopy (Simard & Pritchet 1998; Bershady et al. 1999; Vogt et al. 2000; Barden et al. 2003; Böhm et al. 2004). Most of them have revealed a brightening of the rest frame *B*-band, but its magnitude (from 0.2 to 1.1 mag) as well as the constraints on the TF slope (see Fig. 10 in Ferreras & Silk) are far from being predictive up to now. Kinematics studies using 3D spectroscopy appear to be a pre-requisite to sample the whole Velocity Field (hereafter VF) of individual galaxies to distinguish between interacting and non-interacting galaxies (Mendes de Oliveira et al. 2003), and to limit uncertainties related to the major axis determination. Such effects have been already tested for nearby spirals by comparing Fabry-Perot (hereafter FP) observations with long-slit spectroscopies. The latter can easily provide under or over estimates of the maximum velocity by factors reaching 50% (Amram et al. 1995). Could slit spectroscopy be appropriate for distant galaxies which are actively forming stars (up to rates larger than 100 $M_\odot$/yr) and where the frequency of interactions is very common? It seems that our present knowledge of the dynamics of distant galaxies is very poor, maybe comparable

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to that provided from long slit spectroscopy of local galaxies in the beginning of the last century (Wolf 1914). During the last 20 years, 2D velocity fields obtained from scanning FP interferometers (and more recently also from integral field and side by side long slit spectroscopy) have proved to be powerful kinematic tools to investigate the properties of nearby galaxies (Veilleux et al. 2001; Kosugi et al. 1995; Swinbank et al. 2003; Mendes de Oliveira et al. 2003; Garrido et al. 2004; Ostlin et al. 2001).

To observe VF of distant galaxies, the integral mode IFU of FLAMES/GIRAFFE at VLT seems particularly well suited. Compared to available integral field instruments (e.g. GEMINI/GMOS, Swinbank et al. 2003), the FLAMES/GIRAFFE instrument and its IFU mode provide 3D spectroscopy of fifteen distant galaxies at the same time on a 20 arcmin FoV, thus this instrument optimizes the long exposure time needed to observe faint objects. Moreover, with IFUs, spectra are directly observed within each pixel and no further analysis is needed in contrary of FP data.

In this paper, we present the preliminary analysis of three (among 50) distant galaxies up to $z = 0.7$ which have been observed with GIRAFFE/IFU (Sect. 2). In Sect. 3 we present our new package **DisGal3D** which has been purposely developed to derive galaxy VF using the combination of GIRAFFE/IFU spectroscopy and HST/F606W imagery. A major purpose of this paper is to derive the accuracy of our method determining the maximal velocity as well as distinguishing disturbed VF from those, more regular, typical of spiral galaxies. In Sect. 4 we present our first results on distant galaxies.

2. Observations

As part of Guaranteed Time Observation programs of the Paris Observatory (P.I: F. Hammer) more than 50 distant galaxies have been observed, using the ESO VLT/FLAMES facility, IFU mode ($3'' \times 2''$ array of 20 square $0.52''$ width microlenses) with setups L04 ($R = 0.55$ Å $-$ 30 km s^{-1}) and L05 ($R = 0.45$ Å $-$ 22 km s^{-1}), and integration times from 4 to 12 h (ESO runs No. 71.A-0322(A) and 72.A-0169(A)). Observational seeing during 1 h$\times n$ exposures was ranging from 0.4 to 0.8 arcsec. Data reduction has been done using the dedicated software BLDRS developed at the Geneva Observatory (`http://girbldrs.sourceforge.netweb`). Sky subtraction has been made using standard IRAF and written purpose IDL tools. The three galaxies presented here have been selected from their morphological properties, ranging from an apparently well formed disk (03.0508) to an extreme case of merging (03.1309). Table 1 summarizes observational strategy and deduced parameters of the three distant galaxies presented in this paper.

3. Analysis

VF of galaxies have been reconstructed using a dedicated IDL package named DisGal3D. DisGal3D includes a guided microscanning algorithm and a standard deconvolution method to reconstruct VF using 3D observations. It will be detailed in a forthcoming paper (Puech et al. 2004 in preparation, hereafter P04). Our method has been validated using ten FP cubes of nearby galaxies observed at the mont Megantic (Hernandez et al. 2004 in preparation) and Haute Provence Observatories (Garrido et al. 2004). Galaxies have been redshifted in order to simulate GIRAFFE IFU spatial observational conditions but no specific spectral treatment has been done. Several simulated GIRAFFE data cubes at different seeings (from 0.6 to 1) have been produced.

Our deconvolution method proceeds in a two main steps algorithm. The first one consists of interpolating the GIRAFFE data cube through a guided microscanning thanks to HST/F606W images (Chemin et al. 2003). Here is the single assumption of our method, that is, the emission line regions are traced by the UV light. Indeed both UV and [OII] are directly or indirectly associated to hot star emissions and their luminosities correlates well (Swinbank et al. 2003; Hammer & Flores 1998). Notice that [OII] line fall in the F606 filter at $z = 0.4{-}0.8$. At this stage, only the spatial sampling has been increased and the spatial resolution remains still unchanged. The second step consists of a standard Maximum Entropy deconvolution method of each spatial slice of the interpolated cube. Spatial resolution is then improved down to approximatively one/half a GIRAFFE pixel ($0.52''$). Thus, no kinematical assumption has been made, since our method is not model-dependent. We then do background subtraction, line symmetrisation and central wavelength estimation by a barycenter method (Garrido et al. 2002). Our software include classical box smoothing or a filtering process based on wavelets decomposition (P04).

Simulated deconvolved GIRAFFE cubes have been then compared to original FP observations (Fig. 1). Our analysis demonstrates that GIRAFFE VF are equivalent to smoothed FP observations. This method allows us to discriminate between disturbed and spiral like galaxies. Figure 1 shows one of the nearby galaxy used to test our software. A preliminary analysis of residuals between Figs. 1c and 1d indicates that structures with sizes $>0.3{-}0.5$ arcsec are recovered (P04). A preliminary study of deducted rotation curves shows that ΔV should be recovered within a 10% error (P04).

4. Results

To derive the VF of each galaxy we have used the well resolved [OII][3726.2, 3728.9] Å doublet emission lines. Figure 2 displays the three optical I-band images (upper panel) superimposed to the IFU bundle and the respective reconstructed isovelocities (lower panel) superimposed to high resolution HST images in rest frame UV-band. CFRS03.0508 presents a regular VF with isovelocity lines which suggest a possible warp of the E-N side of the disk, probably due to the companion at the same redshift, 60 kpc off and opposite to it. CFRS03.9003 was classified by Brinchmann et al. (1998) as a spiral galaxy. However after analysing its colormap, Zheng et al. (2004) classify it as an irregular. It is forming stars at a very high rate, $\sim 75\ M_\odot$/yr (Flores et al. 2004). At $z = 0.619$, CFRS03.9003 present a symetric VF with a peculiar pattern of the isovelocity lines. For the two above galaxies we have been able to derive their rotation curves using the ADHOCw package (`http://www-obs.cnrs-mrs.fr/adhoc/adhoc.html`,

Table 1. Observational and deduced parameters of the three distant galaxies.

CFRS	z	I	M_B	f_λ^a	$(f_\lambda/A)^a$	$T_{\rm int}$	S/N^b	Morph[c]	VF[d]	D.P.A[e]	O.P.A.[f]	i^f	$V^e_{\rm max}$
03.0508	0.464	21.9	−20.01	31.0	11.2	6hr	446	Sp	Sp	119±5	143±2	39±3	70
03.1309	0.617	20.6	−21.76	14.9	8.0	12hr	182	Merger	Merger	N.A.	N.A.	N.A.	N.A.
03.9003	0.619	20.8	−21.51	21.3	1.5	12hr	310	Sp/Ir	Warp Sp	296±5	326±2	52±3	190

[a] [OII] integrated from VLT/FORS spectroscopy and [OII] per arcsec^2. Fluxes in units of $\times10^{-16}$ ergs/s/cm^2/Å and $\times10^{-16}$ ergs/s/cm^2/Å/arcsec^2 using HST images to measure the surface of object.
[b] Total *S/N* from reconstructed spectrum using the 20 IFU channel spectra.
[c] From HST images (Brinchman et al. 1998; Zheng et al. 2004).
[d] Dynamical morphology from reconstructed velocity field.
[e] Principal axis and maximum velocity deducted using ADHOCw package (`http://www-obs.cnrs-mrs.fr/adhoc/adhoc.html`).
[f] Optical principal axis and inclination deducted from HST I-band images.

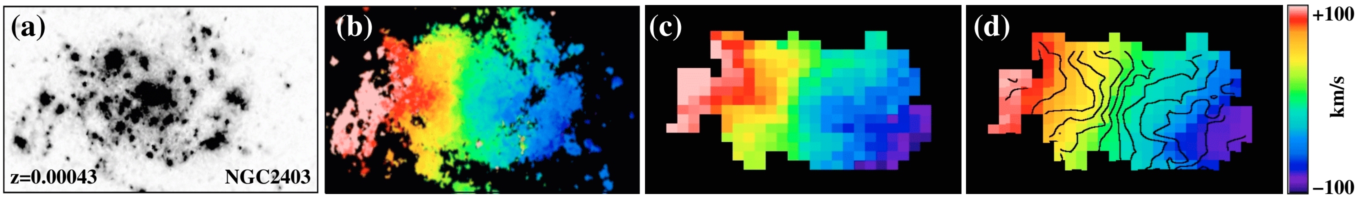

Fig. 1. Example of performed DisGal3D tests with nearby galaxies (here NGC 2403, observed with FanTOmM R = 27 000, Hernandez et al. 2004 and Gach et al. 2003). **a)** Hα map used during the deconvolution process (see text). **b)** VF obtained by FP observation at the mont Megantic Observatory (1.6 arcsec/pix). **c)** Same VF obtained with the galaxy redshifted to $z \sim 0.22$ (0.1 arcsec/pix corresponding to the HST/WFPC2 sampling). **d)** Deconvolved VF obtained by DisGal3D after convolution of the redshifted galaxy by a 0.6 arcsec seeing (see text). Superimposed isovelocities are those from **c)**.

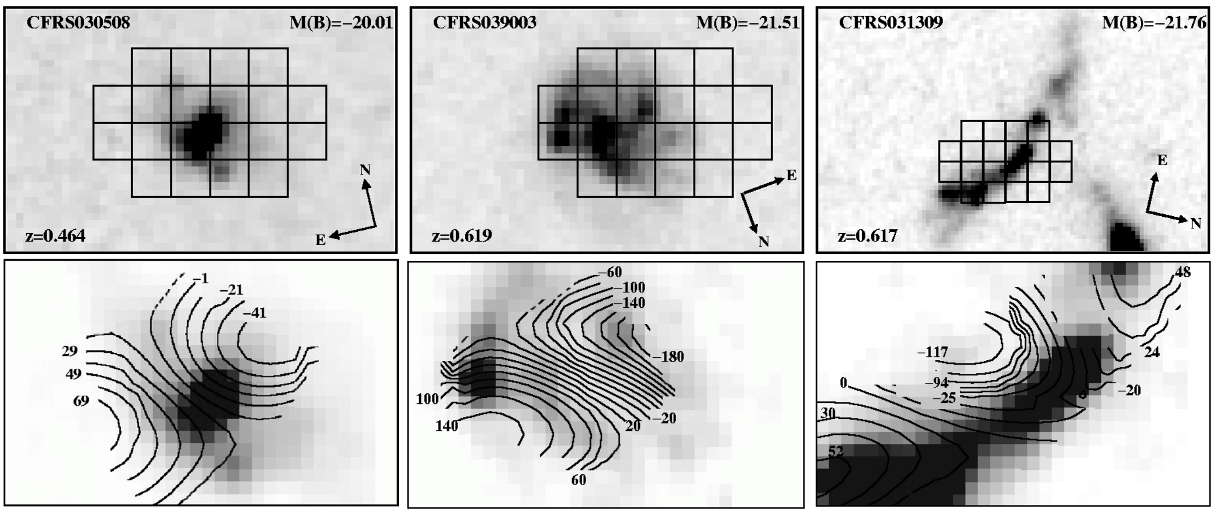

Fig. 2. *Up*: positions of the 3 × 2 arcsec^2 IFU bundle on sky, superimposed to HST I-band images. *Down*: 3 × 2 arcsec isovelocities of observed galaxies derived with DisGal3D. Each velocity field has been previously cleaned spatially by a sky level thresholding and spectrally by a *S/N* line thresholding. All features identified as possible extrapolation/deconvolution artifacts are removed before computing isovelocites within ADHOCw. Photometry in background is HST V-band, used during the deconvolution process (see text). The dynamical axis is much better defined than the optical axis, which is color dependent and may be affected by many irregularities.

see Table 1 and Fig. 3). To derive a rotation curve from a VF, one needs to correct from projection effects on the plane of the sky. The simplest way to do it is to first estimate the kinematical parameters i (inclination angle of the galaxy), PA (Position Angle of the dynamical major axis), ($X_{\rm C}$, $Y_{\rm C}$) (dynamical center) and $V_{\rm sys}$ (systemic velocity). Afterwards, these parameters are visually optimized within ADHOCw until the rotation curve reaches a sufficient degree of symmetry (at least in the rise of the curve if asymmetries occur in the VF). In our case, estimates are based on photometric PA, center and inclination (outer isophot determined by Sextractor). The most spectacular galaxy is a giant merger, CFRS031309 at z = 0.617 (Flores et al. 2004). The VF is extremely irregular and somewhat chaotic as revealed by sharp variations of the velocity along

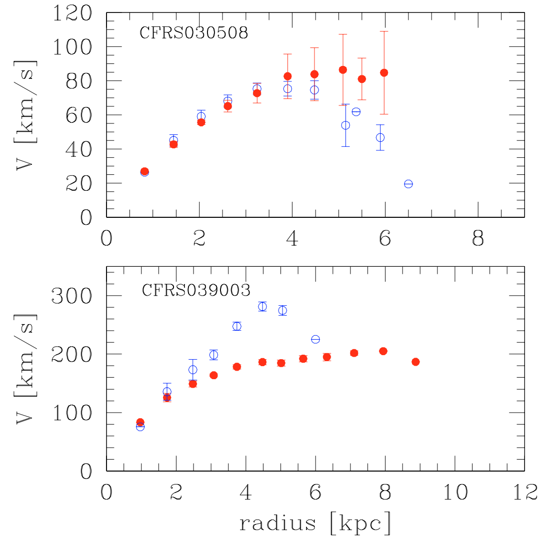

Fig. 3. Preliminary rotational velocity curves (corrected from projection effects) of CFRS03.0508 (*up*) and CFRS03.9003 (*down*) deducted using ADHOCw (preceding sides are in blue/empty circles). Both reveal a perturbed side due to possible disturbations in the VF. Each point/error bar represents the average/scatter obtained on a 1 pixel crown (∼0.1 arcsec) spreading over given angular sector centered on PA (respectively 40 and 36 degrees). In the case of CFRS03.0508, the decreasing side is likely due to an interaction with the nearby companion.

this "chain" galaxy. These can be taken as evidences for strong interactions, meaning that this system is evolving rapidly as proved also by its very high star formation rate (∼200 $M_{\odot}$/yr, Flores et al. 2004).

5. Conclusion

From a preliminary analysis of three isolated field galaxies observed with the FLAMES facility (GIRAFFE/IFU mode), we show its efficiency in producing VF of distant galaxies. Our main conclusions are:

– 3D spectroscopy with GIRAFFE IFUs is able to distinguish disturbed VF from those of regular spirals;
– maximal velocity of distant regular spirals can be estimated within $\Delta V = 10\%$, an accuracy which can be only obtained with 3D spectroscopy;
– with its 15 deployable IFUs, VLT/GIRAFFE is the best tool to establish a robust Tully Fischer relation up to $z = 1.2$, which is independent of galaxy interactions or of crude assumptions on the VF (major axis, inclination, barycenter).

Further tests must be done about the capability to distinguish finer dynamical details such as minor merger, bars and warps. This is related to the spatial accuracy of our observations and of our deconvolution techniques. We will also investigate whether (heavy) extinction can affect our results. Establishing the VF of several hundreds of distant galaxies is now within the capabilities of the VLT and this is a new tool to investigate how the Hubble sequence was formed. A preliminary public release of DisGal3D will be soon available.

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