The SINS Survey: Rotation Curves and Dynamical Evolution of Distant Galaxies with SINFONI

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It has become clear in recent years that about half of the stellar mass in galaxies was put in place by redshift z ~ 1, when the Universe was 40 % of its current age. However, the details of how the mass was assembled and what physical processes were involved at early stages of galaxy evolution remain unclear. Progress has been hampered by the lack of detailed spatially-resolved studies of galaxies beyond *z* ~ 1. This has now become possible with SINFONI, the adaptive optics-assisted near-infrared integral field spectrometer at the VLT. Here we report on our SINFONI observations of massive star-forming galaxies at *z* ~ 2–3. The data enabled us to investigate their morphologies and kinematics on typical spatial scales of 4–5 kpc. The most surprising outcome is that a majority of these galaxies appear to be large, rotating, and often gas-rich discs. Even more compelling evidence is provided by the exceptionally detailed SINFONI data of a *z* ~ 2 galaxy observed with adaptive optics, resulting in a spatial resolution of 1.2 kpc, and of a highly magnified *z* ~ 3 galaxy for which the gravitational lensing of a foreground galaxy cluster acts as a microscope, revealing the dynamics on scales as small as 200 pc.

Our understanding of the formation and evolution of galaxies has improved dramatically over the past two decades. This has been driven by the advent of large ground-based telescopes and space-based facilities equipped with sensitive instruments, leading to a veritable explosion of multiwavelength surveys accumulating ever larger samples of galaxies over an ever increasing range of redshifts. We now have a robust outline of the global evolution of the stellar mass and luminosity density, star-formation history, and nuclear activity over cosmic time. In parallel, theoretical models and semi-analytical simulations have matured and provide a global framework for galaxy formation in the cold dark-matter paradigm: galaxies form as baryonic gas cools at the centre of collapsing dark-matter halos while mergers of halos and galaxies lead to the hierarchical build-up of galaxy mass.

Much of our current knowledge about high-redshift galaxies, however, rests on relatively crude broad-band photometric information, rarely on integrated spectra probing their rest-frame UV emission, even less frequently their rest-frame optical light. As a result, very little is known about the dynamical and detailed physical properties of high-redshift galaxies. The description of galaxy formation in models and simulations remains uncertain because the complex physics of the baryonic processes driving the growth of galaxies lacks observational constraints.

Clearly, the next step is now to understand *how* galaxies were built up. When and how fast did galaxies of different masses assemble? What was the relative importance of mergers versus smooth infall in the accretion of mass? What were the physical processes involved and their interplay? What is the connection between bulge and disc formation? A promising way to address these issues observationally is from detailed spatially-resolved studies of individual galaxies. Until only recently, galaxies in the crucial redshift range *z* ~ 1–4 were virtually inaccessible to such studies: they are faint, their projected angular sizes are small, and important spectral diagnostic features that are emitted in the rest-frame optical are redshifted into the near-infrared bands, between 1 and 2.5 μm. SINFONI (Eisenhauer et al. 2003; Bonnet et al. 2004), mounted on Yepun (UT4) at the VLT, has now changed the situation. SINFONI consists of a cryogenic near-infrared integral field spectrometer, SPIFFI, that obtains simultaneously the entire *J*, *H*, *K*, or *H*+*K* band spectrum of each spatial pixel within the field of view. SPIFFI is coupled to a curvature-sensing adaptive-optics (AO) module, MACAO, that currently enables diffraction-limited observations with a natural guide star, and with a laser guide star when PARSEC becomes available.

The SINS survey

Given the new opportunities afforded by SINFONI, we have undertaken a large and coherent observational programme of near-infrared integral field spectroscopy of high-redshift galaxies, the 'SINS' survey. This will provide new insight on the dynamics, sizes, morphologies, masses, gas-phase metallicities and ionisation state of galaxies at early stages of their evolution. Ultimately, SINS aims at elucidating the evolution of star formation, angular momentum, mass growth/assembly, and metal enrichment as a function of cosmic time, baryonic mass, and dark-matter halo mass. The integral field capabilities of SINFONI have substantial advantages over the classical long-slit spectroscopy: measurements do not suffer from the biases and uncertainties due to the fixed orientation and possible misalignments of slits relative to the targets, and the kinematics can be directly related to morphological features and spatial variations in physical properties. This is essential for reliable structural and dynamical studies of high-redshift sources that are often complex and whose morphologies can dramatically vary depending on the wavelength of study.

Our work focuses on the crucial redshift range $z \sim 1$–4, where the peak of major mergers, QSO, and (dust-enshrouded) star-formation activity occurred, and where probably a substantial fraction of massive elliptical galaxies and bulges of spiral galaxies were assembled. In what follows, we concentrate on the dynamics and morphologies derived from the Hα line emission of galaxies at $z \sim 2$, and the [OIII]λ5007 line emission of one galaxy at $z \sim 3$.

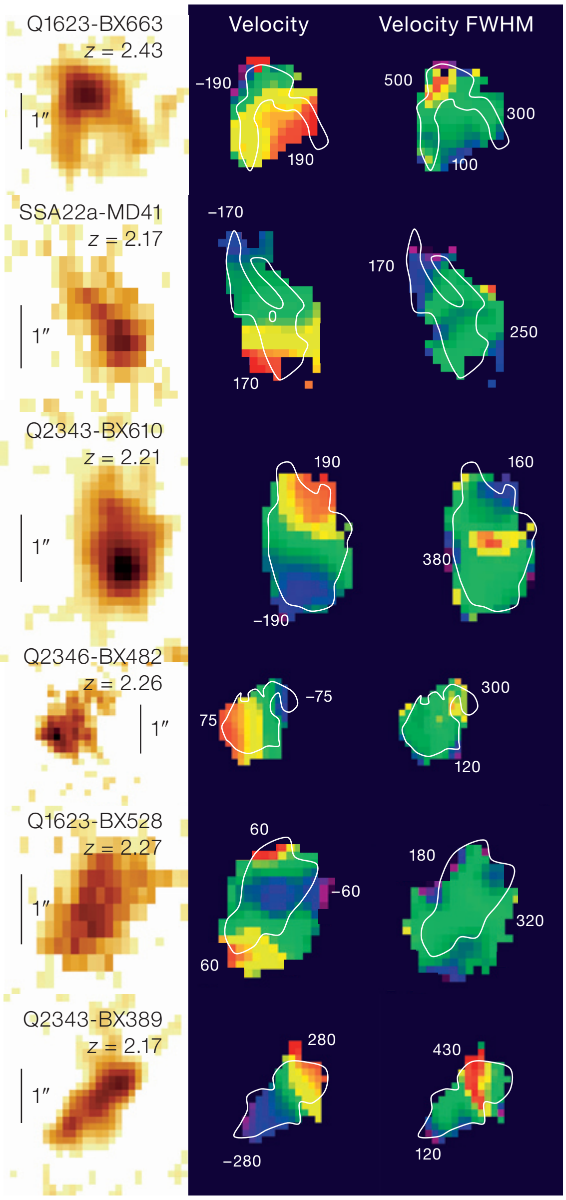


Figure 1: Two-dimensional Hα morphologies and kinematics from SINFONI of six of our $z \sim 2$ BM/BX galaxies. Each row shows the spatial distribution of the velocity-integrated emission (left), the velocity field (middle), and the FWHM velocity width (right). The angular scale of 1″, corresponding to ≈ 8.3 kpc at the redshifts of the sources, is shown for each galaxy. The velocities (relative to the systemic velocity) and velocity FWHM increase from purple to red, and the range in km s^{-1} is given for each map; the white contour outlines the Hα morphology. All velocity fields exhibit the smooth gradient expected for rotating discs, except for Q1623-BX528 where the reversal in velocities possibly indicates a counter-rotating merger (Förster Schreiber et al. 2006).

First convincing evidence for rotating discs at $z \sim 2$

Our largest sample to date consists of 14 star-forming 'BM/BX' galaxies at $z \sim 2$ (Förster Schreiber et al. 2006). BM/BX galaxies are selected on the basis of their optical (rest-frame UV) colours (e.g., Adelberger et al. 2004). We chose our targets primarily from the sample with near-infrared long-slit spectroscopy presented by Erb et al. (2006). The optical and near-infrared colours and magnitudes of the 14 objects span nearly the full range observed for the general BM/BX population. The SINFONI observations were carried out under typical seeing conditions of ~ 0.5″–0.6″, giving a spatial resolution of 4–5 kpc at the redshift of the sources.

The immediate result from the observations is that the Hα emission for the majority of the sources is spatially resolved, extending over ~ 10–20 kpc in several of them. The Hα morphology of the larger systems tends to be irregular and clumpy. The most surprising outcome, however, was the discovery in several galaxies of convincing evidence for rotation in a disc. We expected that most of the larger systems would exhibit irregular and chaotic gas kinematics, but found instead the opposite.

Figure 1 shows the Hα line maps and kinematics for the six largest BM/BX galaxies in our sample. The velocity fields appear smooth and ordered, and all but one show a monotonic variation and steepest gradient along the morphological major axis, as expected for rotating discs. Smooth kinematic structure despite a clumpy and asymmetric morphology is reminiscent of the Hα velocity fields of many local star-forming disc galaxies. Moreover, for three sources in particular, the velocity gradient along the major axis flattens at radii ~ 10 kpc, tracing the rotation curve out to the flat part that is characteristic of disc galaxies

(Figure 2). Their observed velocity dispersion peaks close to the geometric/kinematic centre, another property of rotating discs. Quantitatively, the kinematics of these three galaxies can be very well fit with dynamical models of rotating discs.

Implications for the evolution of high-redshift galaxies

Our SINFONI data provide new ways of exploring the dynamical properties and evolution of distant galaxies. In the framework of rotating discs, we derive for our BM/BX sample an average maximum circular velocity (i.e., where the rotation curve of a disc galaxy turns over) of 180 ± 90 km s^{-1}, and dynamical masses from ~ 5 × 10^9 $M_\odot$ to as large as ~ 2.5 × 10^{11} $M_\odot$. The specific angular momentum of the sample is ~ 900 km s^{-1} kpc, up to 1000–2000 km s^{-1} kpc for a few objects. Interestingly, these values are similar to the specific angular momenta of local late-type spiral galaxies.

A potentially interesting probe of the dynamical evolution of high-redshift galaxies is the ratio of the circular velocity to the local velocity dispersion, v_c/σ. Characteristic values are ~ 0.1–1 for local ellipticals and ~ 10–50 for local discs of spirals. From the kinematic modelling of our best resolved BM/BX galaxies, we infer v_c/σ ~ 2–4. This implies that their discs are dynamically hot and geometrically thick, probably very gas-rich and unstable to global star formation and fragmentation.

The properties revealed by SINFONI for several of our BM/BX sources are not unlike those seen in some simulations of the evolution of gas-rich galactic discs (e.g., Immeli et al. 2004), in which the clumpy fragmenting discs are unstable and the star-forming clumps sink towards the gravitational centre by dynamical friction against a diffuse underlying gas disc to form a central bulge on ~ 1 Gyr time-scales. This could provide a mechanism whereby some of the BM/BX objects in our sample later evolve into galaxies with a massive spheroidal component like those observed in the present-day Universe.

A z ~ 3 Lyman-break galaxy under the microscope: rotation on fine spatial scales

In another remarkable SINS target, a star-forming Lyman-break galaxy at $z = 3.2$, the small-scale dynamics revealed by our SINFONI data add strong support for disc rotation at high redshift (Nesvadba et al. 2006). For this source, the 1E0657-56 'arc and core', the linear resolution in terms of physical scale is boosted by a factor of ~ 20 due to strong gravitational lensing by the foreground galaxy cluster 1E0657-56. The angular resolution of the data is ≈ 0.5″, corresponding in the source plane to about 200 pc over the well-sampled inner ~ 2.5 kpc. The velocity curve (Figure 3), even on such small scales, is very similar to those observed in nearby rotating disc galaxies. Remarkably, the dynamical mass surface density in the central few kpc is comparable to that of bulges in local galaxies. This may suggest that a significant amount of mass could already be in place on small physical scales at $z \gtrsim 3$, which in turn would favour 'inside-out' scenarios of galaxy formation.

SINFONI AO observations: detailed anatomy of a $z = 2.38$ star-forming galaxy

Very recently (March/April 2006), we obtained a spectacular data set for a massive $z = 2.38$ star-forming galaxy. The results appeared in the 17 August issue of Nature (Genzel et al. 2006). This galaxy, BzK-15504, was selected by the 'star-forming BzK' colour criteria (Daddi et al. 2004) as part of a wide-field optical/near-infrared imaging survey (Kong et al. 2006). We benefitted from a lucky combination of a suitable AO star near the source and excellent atmospheric conditions during the SINFONI observations. This resulted in a deep 6-hour on-source integration and a spatial resolution of ≈ 0.15″, or 1.2 kpc at the redshift of the galaxy. This provides the most detailed view of the Hα morphology and kinematics for a z ~ 2 system to date.

The Hα emission of BzK-15504 has many characteristics in common with that of several of our BM/BX objects but revealed with three times better spatial resolution, and there are interesting differences too (Figure 4). The morphology is clumpy and embedded in a more diffuse low-surface brightness component that extends over nearly 2″ (16 kpc) but it is overall fairly symmetic along the major

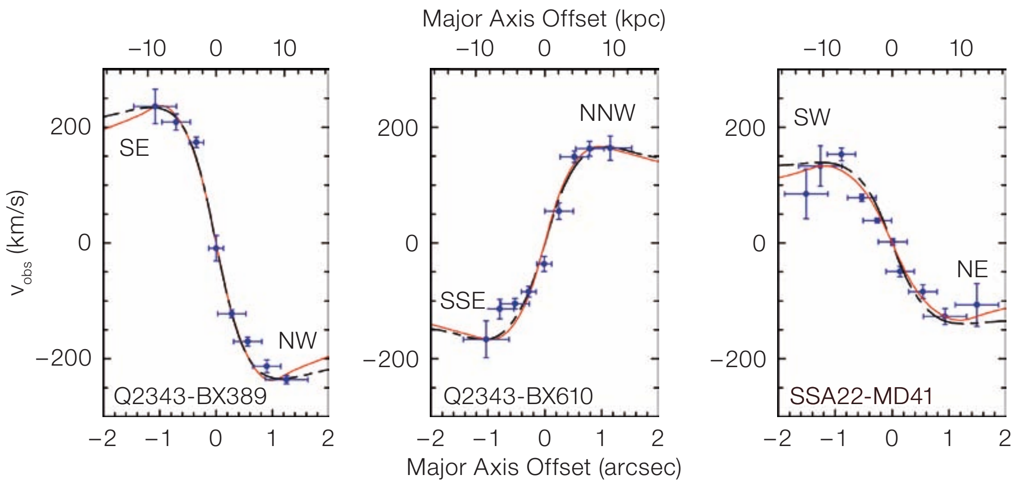
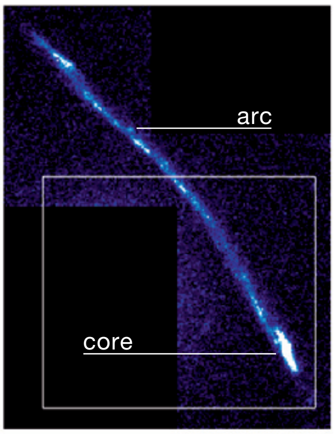


Figure 2: Rotation curves of three z ~ 2 BM/BX galaxies, derived from Hα observations with SINFONI. The blue data points show the velocities (relative to the systemic velocity) as a function of position along the kinematic major axis of each galaxy. The SINFONI data trace well the rotation curves out to their flat part. The rotation curves of the disc models that best fit the observed Hα kinematics of each galaxy are overplotted: the black dashed line for an exponential disc with central hole and the red solid line for a ring-like distribution (Förster Schreiber et al. 2006).

axis and centered on the continuum peak. The kinematics in the outer parts show a smooth velocity field and the rotation curve flattens at radii ~ 8–10 kpc, compelling evidence for a rotating disc. In the inner few kpc, the twist of the isovelocity contours relative to the larger-scale pattern suggests radial flows that could be related to inflow of material towards the nuclear regions, and/or to an outflow possibly due to an AGN present in this galaxy. The AGN, however, clearly does not dominate the global Hα line emission and kinematics. There are no obvious signs for a major merger. BzK-15504 appears to be a large, massive (dynamical mass of ~ 10^{11} $M_\odot$ within 10 kpc), gas-rich clumpy disc possibly in the process of channeling gas towards a central growing bulge and fueling an AGN.

Outlook

Our SINFONI results unveil the morphologies and kinematics of high redshift galaxies in unprecedented detail. As we pursue our SINS survey and exploit fully the rich SINFONI data sets, we can look forward to substantial progress in our understanding of galaxy formation and evolution. In this respect, SINFONI is paving the way for the science to come from similar instruments now becoming available worldwide – and in the future when KMOS at the VLT as well as facilities such as the Extremely Large Telescope and the James Webb Space Telescope will enable us to conduct these kinds of observations routinely.



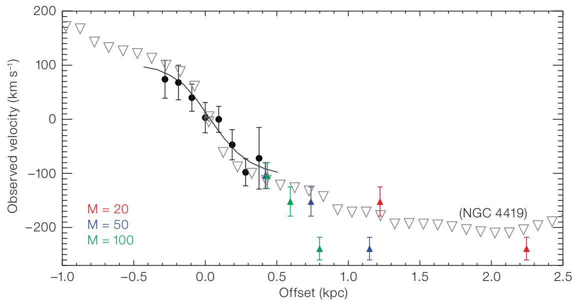


Figure 3: Left: The 1E0657-56 'arc and core,' a highly magnified $z = 3.2$ star-forming Lyman-break galaxy behind the galaxy cluster 1E0657-56, as seen in the optical with the ACS camera on-board the Hubble Space Telescope through the F814W filter. The box indicates the SINFONI field of view (~ 8″ × 8″). The high surface brightness region at the bottom right is the core while the arc curves to the upper left (north-east). **Right:** The velocity curve of the core (black dots) on scales of 200 pc derived from the SINFONI observations of the [OIII]λ5007 emission line is compared to the rotation curve of the nearby disc galaxy NGC 4419 (upside-down grey triangles). The coloured triangles indicate the velocity curve of the arc under the assumption of various magnifications: 20, 50, and 100 for red, blue, and green, respectively (Nesvadba et al. 2006).

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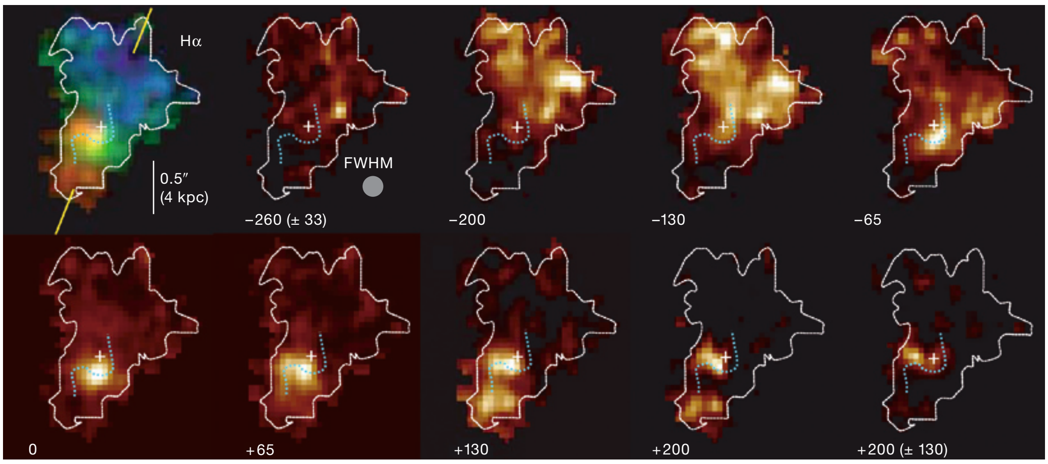

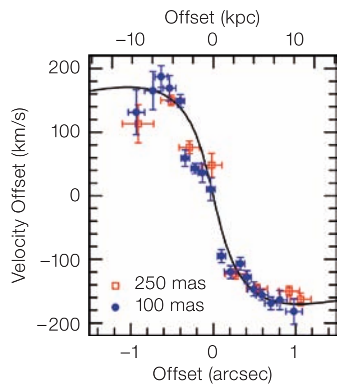

Figure 4: Left: Maps of the Hα line emission of the $z = 2.38$ star-forming galaxy BzK-15504. The SINFONI data, taken in adaptive optics mode, have an angular resolution with FWHM ≈ 0.15″, or 1.2 kpc at $z = 2.38$ (indicated by the grey-filled circle). The top left panel is a RGB composite of 'blue' (−320 to −100 km s^{-1}), 'green' (−100 to +130 km s^{-1}) and 'red' velocity emission (+130 to +320 km s^{-1}). The two yellow lines mark the orientation of the major axis of the disc. The other panels show channel maps integrated in velocity over 65 km s^{-1} wide intervals with increasing central velocity (given in km s^{-1} below each map), except for the map at the bottom right panel, which is integrated over 260 km s^{-1} and centred at +400 km s^{-1}. All velocities are relative to the systemic velocity. The vertical bar indicates the angular scale of 0.5″ and the white cross marks the position of the continuum peak. The dotted, thin white curve outlines the shape of the integrated Hα emission. The dotted, light blue S-shape traces the radial flow of gas into the central bulge region. **Right:** Rotation curve of BzK-15504 extracted from the high-resolution (0.15″) SINFONI data set (taken with the 100 mas pixel scale; blue filled circles), and from additional 0.45″ resolution SINFONI observations (taken with the largest 250 mas pixel scale; red open squares). The black solid line shows the rotation curve of the best-fitting exponential disc model to the kinematics data (Genzel et al. 2006).