Resolved Spectroscopy of a $z = 5$ Gravitationally Lensed Galaxy with the VIMOS IFU

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We have used the VIMOS IFU to spatially resolve and study the star-forming, galactic superwinds and metal-enrichment properties in a highly magnified gravitationally lensed galaxy at $z = 5$ (i.e., seen when the Universe was only ~ 10 % of its current age). These results are allowing us to study galaxy formation and evolution in a level of detail never before possible and provide exciting possibilities for future studies of galaxies at these early times.

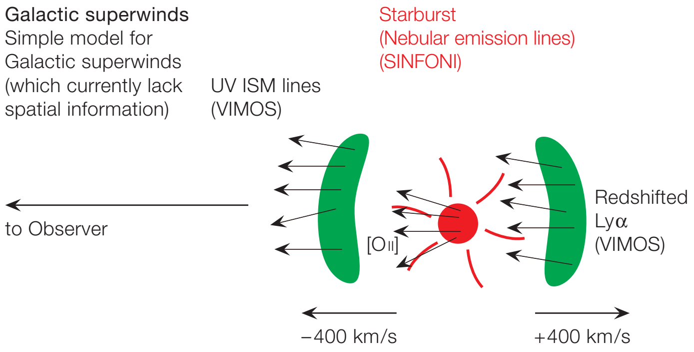


Figure 1: A cartoon of the dynamics of a galaxy with high-velocity superwinds. By observing Ly α emission and ISM lines with VIMOS and the [O II] with SINFONI we will resolve all three components of the galaxy and superwind.

The problem with galaxy-formation models is not to understand why galaxies form (this is due to the cooling and condensing of gas in dark matter halos), but to understand why such a small fraction of baryons cool to form stars. Galaxy-formation models which only include cooling predict that more than 50 % of baryons should form stars, yet a census of the baryons in the local Universe show that less than 10 % are locked up in stars, the rest is in a hot diffuse state, similar to that in the inter-cluster medium (Balogh et al. 2001). To account for this puzzling inefficiency requires some form of feedback – a method of expelling gas from galaxies, preventing them from forming stars, and hence regulating galaxy formation (Bower et al. 2004, Swinbank et al. 2005, Wilman et al. 2005).

Regulating galaxy formation: feedback

The local Universe is a largely inert place, with most activity long over. In order to understand the feedback phenomenon we must therefore look to the first galaxies that formed in the Universe (between 1 and 2 Gyr after the Big Bang, $z = 3$–5). However, since they are very distant these young galaxies are difficult to observe in great detail. Recent deep observations of distant Lyman-break galaxies suggest that, in these young systems, the collective effects of intense star-formation activity (and resulting supernovae) sweep up and drive a shell of material through the galaxy disc, eventually bursting out of the galaxy and accelerating into the ambient intergalactic medium. In these observations the wind ejecta manifests itself through the velocity offset between Lyα emission which traces the outflowing material and the rest-frame optical emission lines (such as Hα and [O II]) which trace the star-forming (H II) regions (Shapley et al. 2003). Indeed, velocity offsets of several hundred km/s have been observed. If the energy of this wind is sufficient, the gas escapes the galaxies' potential and is not recaptured and plays no further role in galaxy formation. But the evidence for this superwind is rather indirect, and based on the assumption that the outflow takes the form of an expanding spherical bubble surrounding the galaxy as illustrated in Figure 1 (the current data are limited to traditional long-slit spectroscopy, and are therefore limited to one spatial dimension). Hence, if the large velocity flow were instead within the galaxy, the wind would be unlikely to escape the gravitational potential. Of course, other interpretations are also possible: the outflow may be collimated and may not inhibit the inflow of gas in other directions; the wind might even stall and fall back onto the galaxy (a more energetic version of the Milky Way's "galactic fountain").

The key to resolving this issue is to identify these features in spatially resolved out-flows around distant protogalaxies. By comparing the velocity field of the outflow with that of the host galaxy the three-dimensional structure of the outflow can be established. However, at these great distances even a massive galaxy only spans 1″ on the sky and therefore obtaining spatially resolved information is extremely difficult.

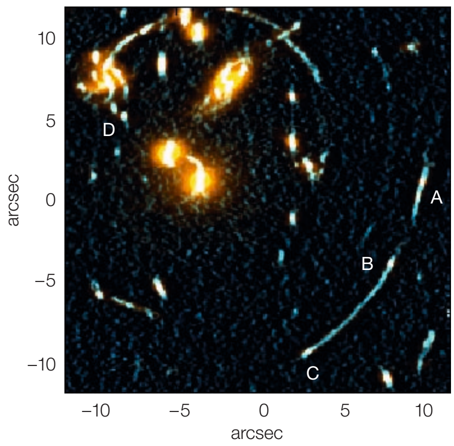
Gravitational telescopes

Fortunately nature provides us with a natural telescope with which we can study very distant galaxies in great detail. Galaxy clusters magnify the images of distant galaxies that serendipitously lie behind them (Smail et al. 1996, Ellis et al. 2001, Swinbank et al. 2003). This natural magnification causes background galaxies to be strongly amplified and stretched. It provides us with the opportunity of studying young and intrinsically faint galaxies with a spatial resolution that cannot be attained via conventional observations.

One of the most striking cases of gravitational lensing is the (highly magnified) $z = 4.88$ galaxy behind the rich lensing cluster RCS0224-002 (Gladders et al. 2002). The natural amplification caused by the galaxy cluster has two effects (i) the image of the background galaxy is magnified at a fixed surface brightness (i.e. the total brightness is increased) and, (ii) the galaxy is not simply amplified, it is also stretched, making it possible to spatially resolve components of the galaxy from the ground.

This project

In this article we report on the first results from a VLT VIMOS and SINFONI IFU study of the star-forming and kinematical properties in a z = 4.88 arc in the core of the lensing cluster RCS0224-002. In the left-hand panel of Figure 2 we show the HST image of the cluster core and mark the components of the arc *A*, *B* and *C*. As can be seen from the HST image, the lensed galaxy (or arc) is over 12″ in length and therefore is an ideal candidate for integral field spectroscopy. The arc is multiply imaged, with component *A* appearing to comprise a dense knot surrounded by a halo of diffuse material (a foreground object is also superposed). The morphology of components *B* and *C* mirror those of *A*.



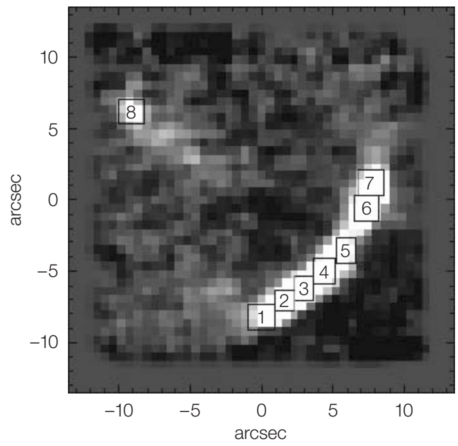


Figure 2: Left: HST false colour *VI*-band image of the RCS0224-002 cluster core showing the central cluster galaxies as well as the multiple arcs and arclets. The multiply imaged $z = 4.88$ arc is labelled *A*, *B* and *C*, whilst the radial counter-image is labelled *D* (see text).

Right: Wavelength collapsed (white light) image around the Lyα emission from the $z = 4.88$ arc made by collapsing the datacube between 7138 and 7188 Å. The $z = 4.88$ arc can clearly be seen in the Lyα image. We also note that there appears to be another strong Lyα emitter to the North-East which is the counter image of the arc.

The arc was observed with the VIMOS IFU on the VLT in December 2004. Although the target was only observed for 2 hours (the remaining 12 hours are due to be completed in the current semester), the data already offer fascinating insight into the nature of the Lyα emission in this galaxy. The VIMOS IFU provides a three-dimensional (x, y, λ) "datacube" from which we can investigate the spatial variations in the Lyα and C IV emission lines and (eventually) UV interstellar absorption features. In turn these allow us to infer the spatial distribution of star formation, metal abundance and to map the dynamics of the system's components.

Early results

In Figure 2 we have projected the datacube in the wavelength between 7138 and 7188 Å so as to map the spatial distribution of the emission. It is clear that the Lyα emission line morphology traces that seen in the imaging, with the densest knots in the HST image being the brightest in Lyα.

By extracting a series of independent spectra from the IFU datacube (Figure 3) we can investigate the dynamics of the galaxy and the nature of any outflowing material. Even the initial dataset, allows us to search for spatial variations in the Lyα emission line. As seen in other young galaxies, the Lyα emission has a characteristic asymmetric (P-Cyni) profile. To examine the structure of the emission line, we compare the emission from the regions marked 1–8 in Figure 2. The structure of the line is remarkably constant from region to region. While there is tentative evidence for structure in the red wing of the line, the blue cut-off occurs at constant wavelength (the variations are less than 30 km/s). This is particularly important: the individual star-forming regions in the underlying galaxy are expected to be moving at relative speeds in excess of 100 km/s (SINFONI observations are scheduled to confirm and map this): if the superwind was localised to these regions, the structure of the Lyα emission would vary significantly. In contrast, the superwind model (Figure 1) predicits that the sharp blue edge of the Lyα emission line (which is formed by resonant absorption in the outflow) will be uncorrelated with the velocity structure of the host galaxy. The lack of structure suggests that the superwind "bubble" is located well outside of the galaxy and is escaping into inter-galactic space.

Other primeval galaxies

We can also scan the datacube for emission lines from other galaxies within the VIMOS IFU field of view. Although the current data are only partially complete, we have already identified at least two other serendipitous sources in the field, including Lyα for $z = 3.66$ and $z = 5.09$ and as well as [O II] from an arc at $z = 1.0$.

Summary

Whilst these results are in their early stages, they are showing the power of coupling integral field spectroscopy with gravitationally lensed galaxies to spatially resolve and study the internal dynamics and star-formation properties of primeval galaxies. The signal-to-noise that we expect from the final set of observations (the remaining 12 hours of observations are expected to be completed in August/September 2005) will allow us to tightly constrain the geometry of the outflowing material and so test the geometry of the superwind ejecta. We will also be able to investigate the dynamics of the interstellar medium (spatially resolved) through the absorption lines and the metallicity of the gas through the C IV/Lyα emission line ratios (continuum and C IV emission are both detected in the first 2 hours of data, but the remaining 12 hours are required to boost the signal-to-noise and draw strong conclusions). Furthermore, by coupling this high-quality data with SINFONI IFU observations (also expected to be taken in August/September 2005) we will probe the [O II] emission from this galaxy (which comes from the star-forming regions and therefore reflects the underlying stellar populations which are responsible for driving the superwind in the galaxy; see Figure 1). These groundbreaking and exciting results will provide valuable and important insights into this important phase of galaxy evolution.

References

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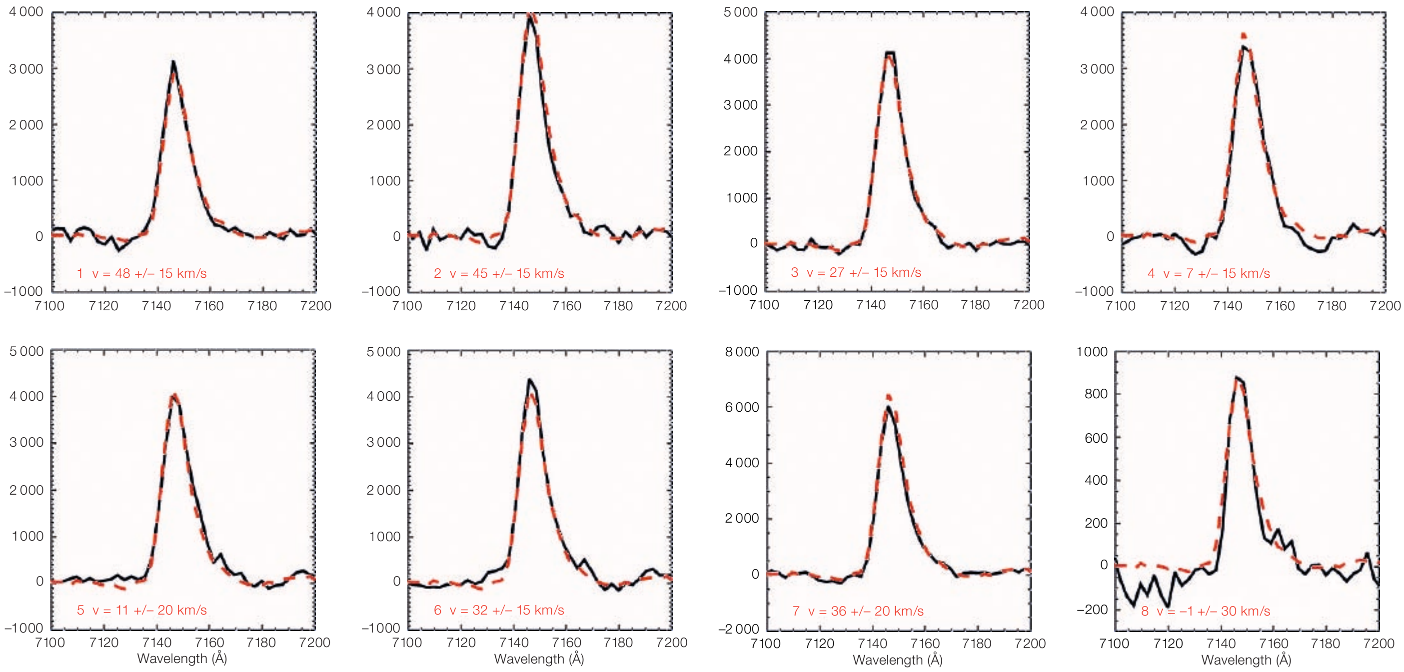


Figure 3: Spectra around the redshifted Lyα emission from the eight components labelled in Figure 2. The red dashed line shows the composite spectra from the arc (scaled in flux). In each independant pixel of the datacube we use the position and shape and intensity of the Lyα emission to study the superwind outflow. By combining these measurements with SINFONI spectroscopy of nebular emission lines we will investigate the star formation and chemical enrichment of this young galaxy.

Farthest Known Gamma-Ray Burst

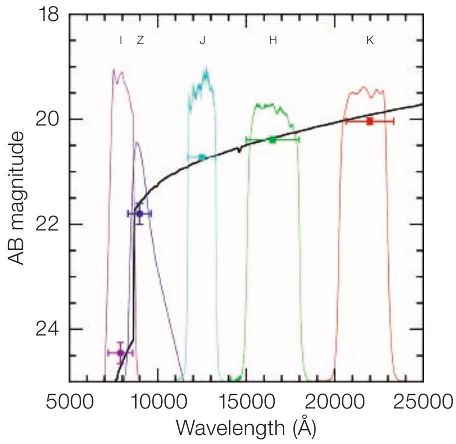
An Italian team of astronomers[1] has used the VLT to observe the afterglow of a Gamma-ray burst that is the farthest known to date with a measured redshift of 6.3. “This also means that it is among the intrinsically brightest Gamma-ray bursts ever observed”, said Guido Chincarini from INAF-Osservatorio Astronomico di Brera and University of Milano-Bicocca (Italy) and leader of a team that studied the object with ESO’s Very Large Telescope. “Its luminosity is such that within a few minutes it must have released 300 times more energy than the Sun will release during its entire life of 10 000 million years.”

[1] The MISTICI collaboration consists of astronomers from Osservatorio Astronomico di Roma (INAF), Osservatorio Astronomico di Brera (INAF), Osservatorio Astronomico di Arcetri (INAF), Università degli Studi di Milano – Bicocca, International School for Advanced Studies (SISSA) and Observatori Astronòmic of Universitat de València (Spain). In particular, Angelo Antonelli, Daniele Malesani, Vincenzo Testa, Paolo D’Avanzo, Stefano Covino, Alberto Fernandez-Soto, Gianpiero Tagliaferri, Guido Chincarini, Sergio Campana, Massimo Della Valle, Felix Mirabel, and Luigi Stella were notably active with the data analysis and observations. Prof. Guido Chincarini is the Italian Principal Investigator of the Italian research on GRBs related to the Swift satellite, which is funded by the Italian Space Agency (ASI).

Gamma-ray bursts (GRBs) are short flashes of energetic gamma rays lasting from less than a second to several minutes. They release a tremendous quantity of energy in this short time, making them the most powerful events since the Big Bang. It is now widely accepted that the majority of the gamma-ray bursts signal the explosion of very massive, highly evolved stars that collapse into black holes.

The Gamma-ray burst GRB050904 was first detected on September 4, 2005, by the NASA/ASI/PPARC Swift satellite, which is dedicated to the discovery of these powerful explosions. Immediately after this detection, astronomers in observatories worldwide tried to identify the source by searching for the afterglow in the visible and/or near-infrared. The Italian group observed the object in the near-infrared with ISAAC and in the visible with FORS2 on the VLT. By comparing the brightness of the source in the various observing bands (see Figure), the astronomers were able to deduce its redshift, and hence its distance. “The value we derived has since then been confirmed by spectroscopic observations made by another team using the Subaru telescope”, said Angelo Antonelli (Roma Observatory), another member of the team.

(Based on ESO Press Release 22/05)



This figure shows the magnitude of the Gamma-ray burst GRB 050904 as observed with FORS2 and ISAAC in the various filters. The bandpasses of the ESO filters are overplotted as well as the best-fitting template which allowed the astronomers to measure the photometric redshift. The clear drop of the flux of the object in the *I*-band compared to the others is the telltale signature of a high-redshift object.

Photo: G. Hüdepohl, ESO