A VLT Large Programme to Study Galaxies at z ~ 2: GMASS — the Galaxy Mass Assembly Ultra-deep Spectroscopic Survey

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We report on the motivation, sample selection and first results of our VLT FORS2 Large Programme (173.A-0687), which has obtained the longest targeted spectra of distant galaxies obtained so far with the VLT. These long exposures, up to 77 hours for objects included in three masks, were required to detect spectral features of extremely faint galaxies, such as absorption lines of passive galaxies at $z > 1.4$, a population that had previously escaped attention due to its faintness in the optical wavelength regime, but which represents a critical phase in the evolution of massive galaxies. The ultra-deep spectroscopy allowed us to estimate the stellar metallicity of star-forming galaxies at $z \sim 2$, to trace colour bimodality up to $z = 2$ and to characterise a galaxy cluster progenitor at $z = 1.6$. The approximately 200 spectra produced by GMASS constitute a lasting legacy, populating the "redshift desert" in GOODS-S.

Motivation

In 2002, the K20 survey provided the spectroscopic redshift distribution of a complete sample of 480 galaxies with K < 20. One of the main scientific results from this survey was the discovery of a significant population of massive K-selected galaxies at high redshift (Cimatti et al., 2002). Their spectra (Cimatti et al., 2004) showed that some of these objects were indeed very massive (10^{11} $M_\odot$) and already old (1–2 Gyr). Around this time, deep near-infrared (NIR) imaging surveys were also beginning to provide evidence of a new population of candidate massive galaxies at photometric redshifts $z > 2$ (Labbé et al., 2002), barely detectable even in the deepest optical images. The strong clustering of these red galaxies (Daddi et al., 2003) suggested that these were progenitors of local, massive early-type galaxies. The existence of a significant population of massive galaxies in the early Universe was not predicted by semi-analytic models of hierarchical galaxy formation, in which the most massive systems form relatively late through a slow process of merging of smaller galaxies. Together with the small and slow evolution in the K-selected galaxy population up to z of 1–1.5, it became clear that most (massive) galaxy assembly occurred at $z > 1.5$. In order to study the physical and evolutionary status of typical Milky Way mass (M^*) galaxies in this redshift range, we proposed to obtain ultra-deep spectroscopy with FORS2 at the VLT. As emission lines move out of the optical window and the redshift measurement, especially for the passive galaxies, depends on absorption features in the continuum, there are few galaxies known in the redshift range of interest, $1.3 < z < 2.5$, which has traditionally been known as the redshift desert.

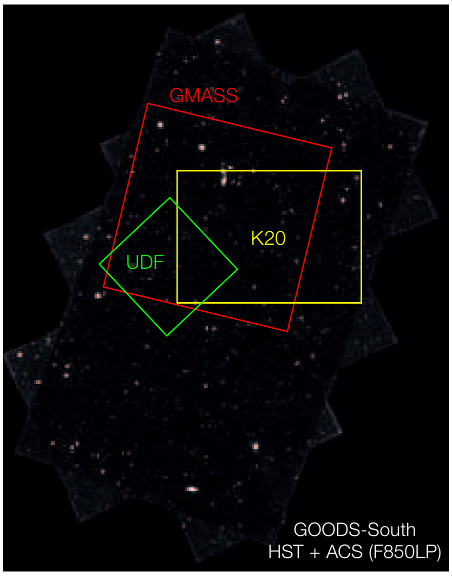

Figure 1. The location of the 6.8 x 6.8 arcminute field of GMASS (red), relative to the ACS coverage of GOODS-S (black background), the field of the K20 survey (yellow) and the Hubble Ultra Deep Field (green).

The location chosen for the survey (Figure 1) was GOODS-S in the Chandra Deep Field South, because of the available deep optical Advanced Camera for Surveys (ACS) imaging and near-infrared imaging with the Very Large Telescope (VLT) ISAAC instrument. This field would also contain the planned Hubble Space Telescope (HST) Ultra Deep Field (UDF) and contained part of the K20 survey. The proposed deep spectroscopy would be complementary to the VIMOS and FORS2 public spectroscopy surveys carried out by ESO in the GOODS-S field, which had shorter integration times and therefore targeted more luminous objects. Including overheads and pre-imaging, the total time requested for the programme was 145 hours in two semesters.

Sample selection and mask design

For the target selection, we took advantage of the very recent Spitzer/IRAC coverage of GOODS-S. The IRAC 4.5 µm photometry, which samples the 1–2 µm rest-frame for the targeted redshift range, enabled us to select on mass more reliably than possible with the *K*-band. We combined all available photometry from *U*-band to 8.0 µm to obtain photometric redshifts for the 1277 unblended sources detected at 4.5 µm (to $m_{AB} = 23.0$). These 1277 sources constitute the GMASS sample. Of this sample, we selected objects for spectroscopy according to the following constraints: $z_{phot} > 1.4$ and $B_{AB} < 26$

and $I_{AB} < 26$, excluding all objects for which spectroscopy was already available or planned. This spectroscopic sample contains 221 galaxies. Subsequently, we identified two subsamples: selecting so-called blue galaxies that were expected to have strong absorption lines below 6000 Å for the masks to be observed with the 300V grism (the blue masks); and red galaxies to be observed with the 300I grism (the red masks). For the first two pilot masks, we selected the brightest targets from both subsamples. Subsequently, we filled two blue and two red masks with fainter targets, allocating open spaces to targets already included in other masks, or otherwise to targets from the GMASS sample without spectroscopic redshifts. In total, 211 (174) objects from the GMASS (spectroscopic) sample were included in one or more masks (38 objects were included in two masks and five in three). The total exposure times for the masks were 12 h, 14 h and 15 h for the blue and 15 h, 32 h and 30 h for the red masks.

Our observational strategy for the blue masks followed the conventional optical one of having two offset positions so as to be able to correct for bad pixels, with each offset position exposed for half an hour. For the red masks, for which many variable sky emission lines make background subtraction difficult, we used four offset positions, each exposed for 15 minutes. During reduction, we computed the median value of the four positions for each pixel, which provided a reliable representation of the background. After subtraction of this background, the two-dimensional spectra were rectified and combined (taking into account the respective offsets). The remaining sky-line residuals were fitted along the columns and subtracted from the combined image. The resulting spectra have very low sky-line contamination, even above 8500 Å. We also took care to interpolate only once during the entire reduction process, to minimise any noise introduced by this process.

Redshifts obtained

After extracting the one-dimensional spectra and fitting the absorption and emission line features, 130 new redshifts at $z > 1.4$ were obtained. In addition, 37 new redshifts at $z < 1.4$ were obtained and more than twenty formerly known redshifts were confirmed and, in most cases, determined with higher accuracy. The fraction of redshifts successfully determined for the targets observed is about 85%. The same number applies to the fraction of targets with photometric redshifts $z > 1.4$ that were confirmed by spectroscopy to have $z > 1.4$ (a few of the galaxies from the spectroscopic sample were included erroneously and are not considered in this fraction). Figure 2 shows a histogram of the photometric and known spectroscopic redshifts in the GMASS field. Also shown is the fraction of known spectroscopic redshifts provided by GMASS, which increases from 30% to 85% between redshifts 1.4 and 1.8, and is 100% for most bins in the range $1.8 < z < 2.9$.

Superdense passive galaxies at $z > 1.4$

One of the main purposes of GMASS was to discover (spectroscopically) and study passive galaxies in the redshift desert. Although this desert is no longer as empty as before, the galaxies known in this redshift range are mostly UV-selected (Steidel et al., 2000) and therefore actively star-forming galaxies. Using IRAC selection, we were able, instead, to uncover 13 passive galaxies in the range $1.39 < z < 1.99$. Their spectra (see Figure 3) are similar to those of other old passive galaxies at $z > 1$, such as that of 53w091 at $z = 1.55$ (Dunlop et al., 1996).

We obtained a high signal-to-noise stacked spectrum (shown in Figure 4) by averaging all 13 individual spectra, assigning the same weight to each spectrum

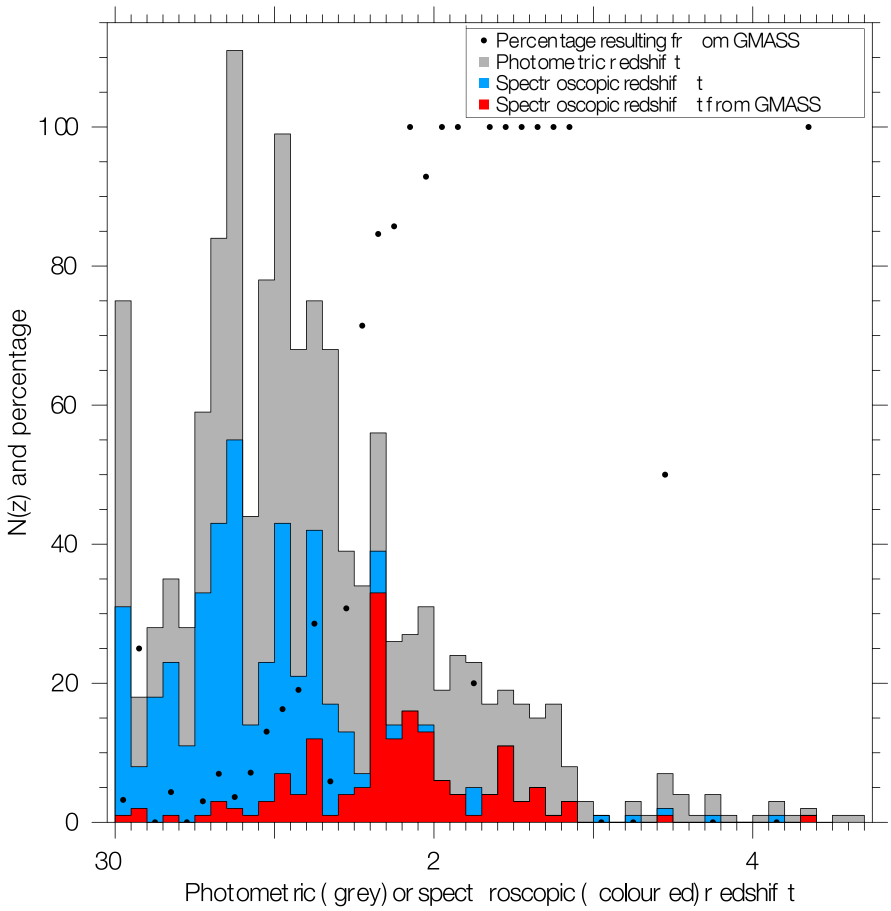

Figure 2. Histogram of photometric (grey), previously known spectroscopic redhsifts (blue) and spectroscopic redshifts resulting from GMASS (red) in the GMASS field. Also shown is the percentage of known spectroscopic redshifts determined by GMASS (black dots).

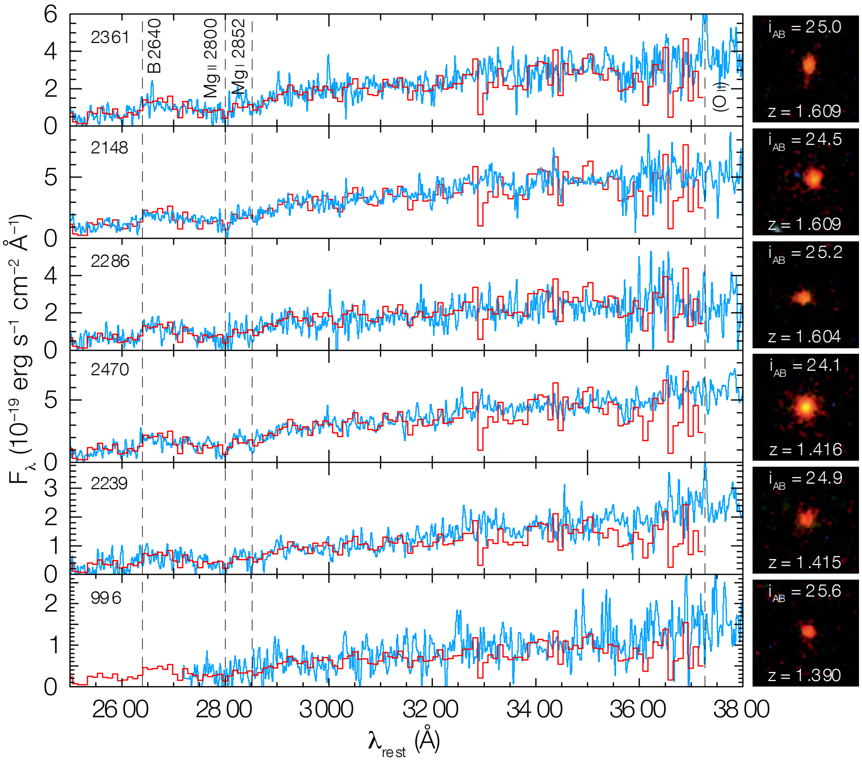

Figure 3. Individual spectra of six of the thirteen passive galaxies with GMASS spectra (blue). The spectra are very similar to the overlayed spectrum (red) of the old galaxy LBDS 53w091 at $z = 1.55$ (Dunlop et al., 1996). Shown on the right are 3.7 x 3.7 arcsecond *BVI* stamp images, constructed from HST/ACS images.

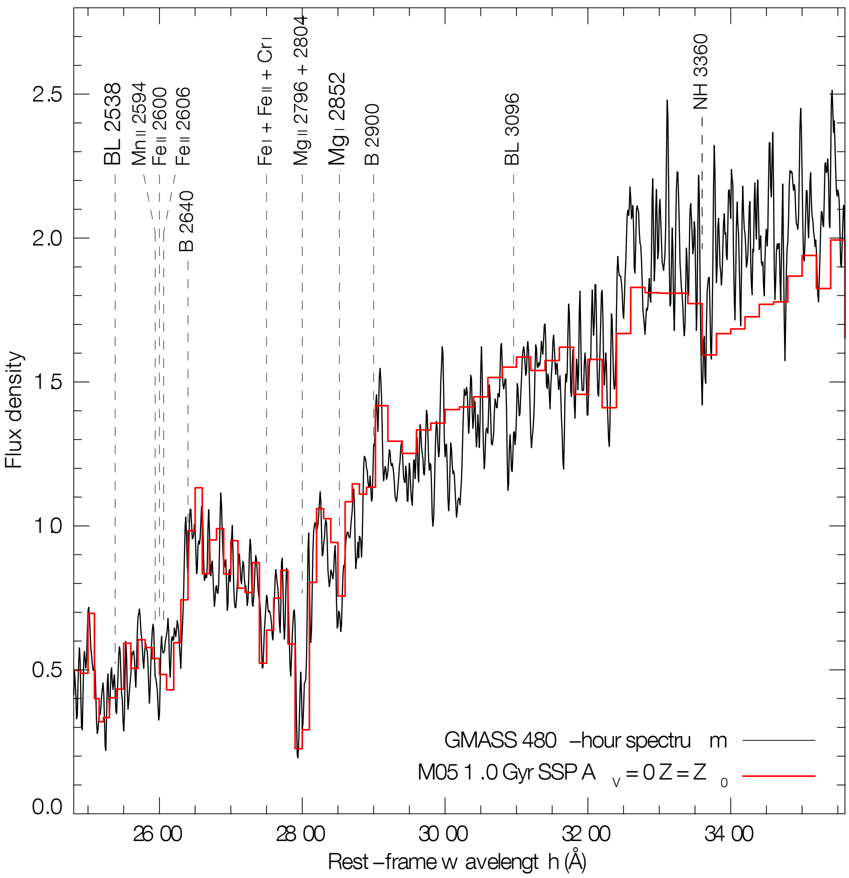

Figure 4. The stacked average spectrum of the thirteen passive GMASS galaxies (black) overlayed with the best-fit synthetic spectrum (red) from the models of Maraston (2005).

after normalisation in the 2600–3100 Å wavelength range. The stacked spectrum was compared with various libraries of synthetic spectra to estimate the age of the stellar population. In practice, using the observed rest-frame UV spectrum only, provides an estimate of the time elapsed since the last major episode of star formation. Since a degeneracy exists between the effects of age and metallicity, we calculated ages for a range of metallicities, finding best-fit ages between 0.7 and 2.8 Gyr for metallicities Z = 1.5 to 0.2 $Z_\odot$. We also fitted synthetic spectra to the available photometry (11 bands, including HST/ACS BVIz, VLT/ISAAC JHK_s, and Spitzer/IRAC 3.6, 4.5, 5.8, 8 μm) and derived a mean age, mass, and upper limit to the star formation rate (SFR) of 1.1 Gyr, 5 x 10^{10} $M_\odot$, and 0.2 $M_\odot$/yr respectively. Owing to the depth of the spectroscopy, it was possible to study galaxies that span a wide range in stellar mass: from very massive 10^{11} $M_\odot$ galaxies to systems of only 10^{10} $M_\odot$. Our analysis of the ages indicate that the bulk of the stars in these passively evolving galaxies must have formed at $2 < z < 3$, which is in excellent agreement with the evidence found for early-types observed at $0 < z < 1$, as well as for recent observations of early-types at $z > 1.4$.

A visual classification by eye of the ACS images shows that the majority of passive galaxies have a spheroidal morphology typical of early-type galaxies (Figure 3). For data acquired with the reddest available ACS filter, we modelled the surface brightness distribution by fitting a Sersíc profile, after the point spread function (PSF) was determined from ten stars in the field. Most of the passive galaxies have a Sersíc index n > 2, indicating that the bulk of the light from the galaxy comes from a bulge component. The galaxy radii are in the range 0.6–3.2 kpc with a mean

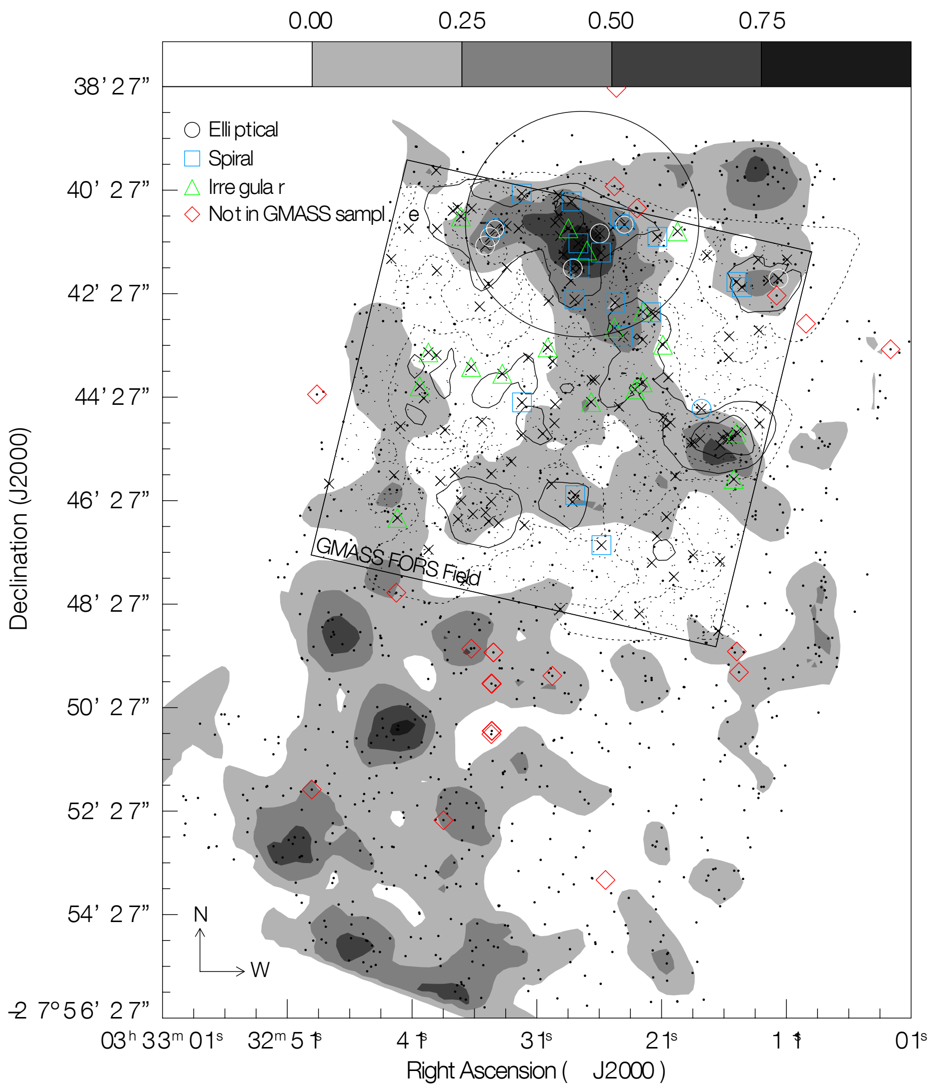

Figure 5. Density maps of galaxies at $z = 1.6$ in the GOODS-S field. Filled contours are based on GOODS/MUSIC (Grazian et al., 2006) photometric redshifts (indicated by filled circles) and solid and dashed contours are based on spectroscopic redshifts from GMASS and ESO/GOODS (indicated by crosses). Small dots indicate galaxies in the GMASS catalogue outside the redshift spike. Additional symbols are plotted according to morphology: elliptical galaxies (circles), spiral galaxies (squares) or irregulars (triangles). Diamonds indicate those galaxies in the overdensity at $z = 1.6$ not in the GMASS sample.

of 1.4 kpc. These values are much smaller than those observed in early-type galaxies of the same stellar mass in the local Universe. The small sizes that we measure are neither due to an unresolved central source, nor due to our imaging being in the rest-frame mid-UV (several authors have demonstrated that the sizes of spheroidal galaxies do not vary substantially as a function of wavelength). The measured galaxy sizes are smaller by a factor of two to three compared with $z \sim 0$ galaxies, implying that the stellar mass surface density of passive galaxies at $< z > \sim 1.6$ is five to ten times higher. Such superdense early-type galaxies with radii > 1 kpc are extremely rare in the local Universe (Shen et al., 2003).

This significant difference in size raises two questions: firstly, how did these small systems form, and what mechanisms can explain their growth in size in the past 10 Gyr? The derived constraints on the age, star formation history, and stellar masses indicate that intense star formation (SFR > 100 $M_{\odot}$/yr) must have taken place at $z > 2$. Among the possible precursor candidates, only sub-mm/mm-selected galaxies (SMGs) have sizes and mass surface densities comparable to those of the passive galaxies at $1.4 < z < 2$. In addition, the correlation lengths and estimated masses of these two populations are similar. SMGs are, however, an order of magnitude rarer than these passive descendants, which leads to an estimated sub-mm/mm galaxy duty cycle of ~ 0.15 Gyr. SMGs may therefore represent rapid and highly dissipative major mergers at $z > 2$, which become compact, superdense remnants that evolve almost passively at $z < 2$.

The other question is how superdense galaxies at $z \sim 2$ migrated to the size-mass relation at $z \sim 0$. One possibility is dissipationless (or dry) merging: according to some models, this process can increase the size and mass of a system without altering the stellar population content. The increase in size is expected to depend on the orbital properties and the mass of the merging system, with the most massive galaxies increasing their size more strongly than their less massive counterparts. If the mass-dependent size evolution is applicable, most GMASS passive galaxies would be the progenitors of early-types that today have stellar masses $10^{11}\ M_{\odot} < M < 10^{12}\ M_{\odot}$, i.e. the most massive E/S0 systems at $z = 0$.

An overdensity of galaxies at $z = 1.6$

Several spikes in the histogram of galaxy redshifts in the GOODS-S field are known. The overdensity of one of the highest redshift spikes, at $z = 1.6$, was described in Castellano et al. (2007). Within the large-scale overdensity, a peak was discerned that would evolve into a cluster of galaxies, although from the evidence at $z = 1.6$ the structure is unlikely to be virialised. Since the peak is located in our field, GMASS added 32 galaxies with confirmed $z = 1.6$ redshifts to the ten previously known (from ESO/GOODS spectroscopy). We confirm that there is a significant, narrow spike in the distribution of spectroscopic redshifts at $z = 1.610$, which forms an overdensity in redshift space by a factor of six. The velocity

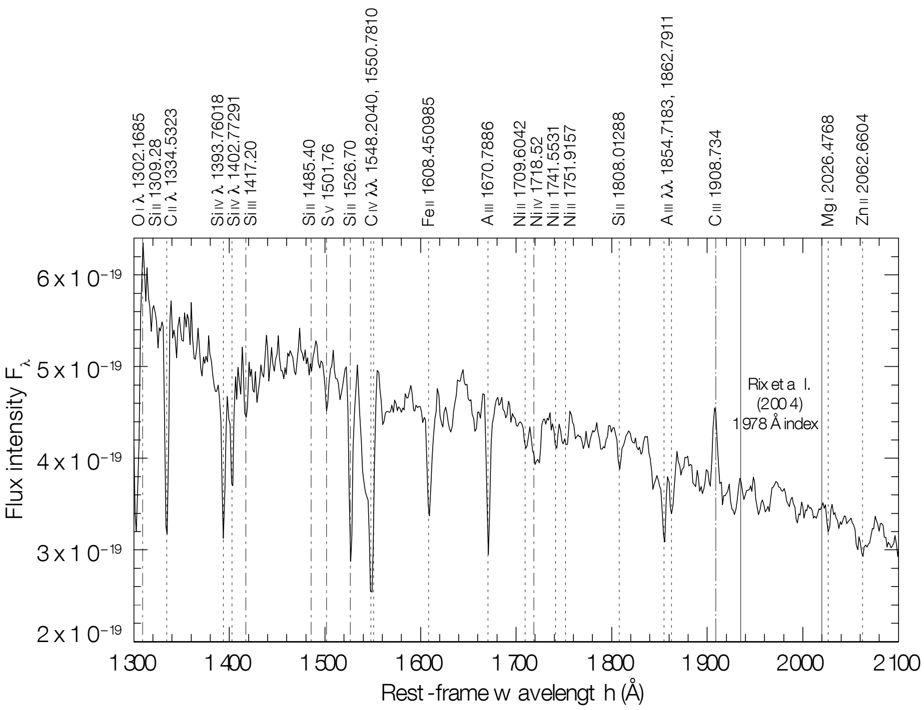

Figure 6. The average combined spectrum of 75 star-forming GMASS galaxy spectra. Lines indicate interstellar rest-frame mid-UV absorption features (dotted), photospheric absorption features (dot–short dash), and C III 1909 Å emission (dot–long dash).

dispersion of these 42 galaxies is 450 km/s, which should increase with redshift to become comparable with that of a cluster of galaxies. The redshift distribution is not Gaussian, but rather bimodal with a primary peak at $z = 1.610$ and a secondary at $z = 1.602$. Although we do not detect significant spatial separation between the primary and secondary peaks, this may be additional evidence that the structure is not yet virialised. Towards the northern part of the GMASS field, the surface density of spike galaxies is five times higher than in the remainder of the field. The properties of spike galaxies in this high density region are different from those outside: the mean age and mass are higher, while the mean star formation rate (SFR) and specific SFR (SFR per unit mass) are lower. Six out of the eight passive galaxies in the spike are in this region, three of which appear to form a sub-group of size smaller than 90 kpc. This group of passive galaxies is not located at the peak of the surface density of spike galaxies (Figure 5), but about 800 kpc away. The available NIR imaging allows a colour-magnitude diagram of the galaxies with confirmed redshifts to be compiled using the J-K colour, which brackets the 4000 Å break at this redshift. We detect a red sequence, which is consistent with a theoretical sequence of galaxies that formed their stars in a short burst at $z = 3$.

This is the first and only structure of this nature known: its redshift is higher than that of any known galaxy cluster and the structure contains spectroscopically confirmed, red, early-type galaxies. Its irregularity in angular and redshift space, including at least two localised higher density peaks, suggests that the structure is still relaxing, which is consistent with its low X-ray emission. Since this structure exhibits some of the properties typical of clusters, it may be the progenitor of a cluster of galaxies, observed at its assembly.

Other results from GMASS

Apart from the two projects described above, published in Cimatti et al. (2008) and Kurk et al. (submitted), two other papers based on GMASS spectra are published. In Halliday et al. (2008), we study the stellar metallicity of galaxies at $z \sim 2$, using a stacked spectrum of 75 star-forming galaxies (see Figure 6), corresponding to a total integration time of 1653 hours. With this spectrum, it was possible for the first time to measure the iron abundance and thus the stellar metallicity at a median redshift of $z = 1.88$. We constrain the metallicity to $\log(Z/Z_\odot) = -0.57 \pm 0.16$. Cassata et al. (2008) describe the colour bimodality in the galaxy population up to very high redshifts. We find that the red sequence of passive galaxies is recognisable up to $z \sim 2$, but then disappears. In addition, Daddi et al. (2007a,b) used GMASS spectra, in combination with other spectra of distant galaxies, to study star formation and obscured active galactic nuclei (AGN). Several more papers are in preparation, describing the survey strategy and resulting redshifts (Kurk et al.), the morphological analysis (Cassata et al.) and dust properties of galaxies up to $z \sim 2.5$. The published GMASS spectra will be publicly available through the ESO GOODS website, forming a lasting legacy for studies of high redshift galaxies.

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