bourhood. And, of course, the use of high-precision astrometric measurements with instruments like the VLTI or the Keck interferometer will survey “nearby” stars for long-period systems. Altogether, these coming observational facilities will definitely help us to construct a new and more complete view of how planetary systems are born and how they evolve.

References

FIDES: Ultratide Near-Infrared Imaging with ISAAC of the Hubble Deep Field South

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1. Introduction

Between October 1999 and October 2000 an undistinguished high-galactic latitude patch of sky, the Hubble Deep Field South (HDF-S), was observed with the VLT for more than 100 hours under the best seeing conditions. Using the near-infrared (NIR) imaging mode of the Infrared Spectrometer and Array Camera (ISAAC, Moorwood 1997), we obtained ultratide images in the $J_s$ (1.24 $\mu$m), $H$ (1.65 $\mu$m) and $K_s$ (2.16 $\mu$m) bands. The combined power of an 8-metre-class telescope and the high-quality wide-field imaging capabilities of ISAAC resulted in the deepest ground-based NIR observations to date, and the deepest $K_s$-band in any field. The first results are spectacular, demonstrating the necessity of this deep NIR imaging, and having direct consequences for our understanding of galaxy formation.

The rest-frame optical light emitted by galaxies beyond $z \sim 1$ shifts into the near-infrared. Thus, if we want to compare $1 < z < 4$ galaxies to their present-day counterparts at similar intrinsic wavelengths – in order to understand their ancestral relation – it is essential to use NIR data to access the rest-frame optical. Here, long-lived stars may dominate the total light of the galaxy and the complicating effects of active star formation and dust obscuration are less important than in the rest-frame ultraviolet. This therefore provides a better indicator of the amount of stellar mass that has formed. Compared to the selection of high-redshift galaxies by their rest-frame UV light, such as in surveys of Lyman Break Galaxies (LBGs, Steidel et al. 1996a,b),
selection in the NIR $K_s$-band gives a more complete census of the galaxies that contribute to the stellar mass content of the early universe. And, by studying these systems over a substantial redshift range, we can directly see how they were assembled as we look further back in time. Very deep optical-to-infrared data in many filters are required not only to access the rest-frame optical light of galaxies and constrain their stellar composition, but also to determine the redshifts of faint distant galaxies from their broadband photometry alone. The majority of the galaxies detected are too faint to be observed spectroscopically, even with powerful telescopes like the VLT.

Here, we discuss the full NIR data set of the HDF-S. The observations, reduction techniques, the catalogue of sources, and the photometric redshifts are described in detail in Labbé et al. (2002). Throughout, we will assume a flat $\Lambda$-dominated cosmology ($\Omega_M = 0.3, \Lambda = 0.7, H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$) and all magnitudes are expressed in the Johnson photometric system unless explicitly indicated by the subscript AB for the AB magnitude system.

2. Observations

The observations of the HDF-S are part of the Faint InfraRed Extragalactic Survey (FIRA, Franx et al. 2000), a large public programme carried out at the VLT consisting of very deep NIR ISAAC observations of two selected fields with existing deep optical WFPC2 imaging. The second and somewhat shallower field around the $z = 0.83$ cluster MS1054-03 ( Förster Schreiber et al. in preparation) was observed for 80 hours over an area four times larger than the HDF-S. The full NIR data set of the HDF-S consists of 33.6 hours of imaging in $J_S$, 32.3 hours in $H_S$, and 35.6 hours in $K_S$ with ISAAC, which has a 2.5′ × 2.5′ field of view. The effective seeing in the reduced images is approximately 0.46′′ in all bands, close to the best seeing that can be reasonably obtained from Paranal. We reach a depth of 25.9 in $J_S$, 24.8 in $H_S$, and 24.4 in $K_S$ (total magnitudes for point sources, 3σ).

Complemented by ultradeep HST/ WFPC2 imaging (version 2, Casertano et al. 2000) in the optical filters $U_{050}$, $B_{550}$, $V_{606}$, and $I_{814}$ bands (the subscript indicating the effective wavelength), we assembled a $K_S$-selected catalogue containing 833 sources, of which 624 have seven-band photometry, covering 0.3–2.2 μm. We determined the photometric redshifts of all extragalactic sources using a method detailed in Rudnick et al. (2001, 2002a in preparation). Comparison with spectroscopic redshifts available for 49 sources in the field shows excellent agreement: $|z_{\text{spec}} - z_{\text{phot}}|/(1+z_{\text{spec}}) = 0.08$.

3. Evolved Galaxies at High Redshift

Remarkably, the HDF-S contains many high-redshift sources that are relatively bright in the infrared and extremely faint in the optical, whereas the HDF-N contains far fewer such galaxies. This is clearly visible in Figure 2, which shows the $V_{606}$–$H$ colours versus the infrared $H$ band magnitudes of NIR selected galaxies between redshifts $2 < z < 3.5$. The filters are chosen to match those used in Figure 1 (Papovich, Dickinson & Ferguson 2001), allowing a direct comparison with the HDF-N. For a similar survey area and similar limiting depth, we find 7 galaxies redder than $V_{606} = H > 3$ and brighter than $H_{AB} < 25$, compared to only one in the HDF-N. Galaxies with S/N < 2 for the $V_{606}$ measurement (triangles) are plotted at the 2σ confidence limit in $V_{606}$, indicating a lower limit on the $V_{606}$–$H$ colour. Galaxies having red ($J_S - K_S > 2.3$ colours (open squares) are also shown. The number of candidates for red, evolved galaxies is much higher than in the HDF-N for a similar survey area, as shown in an identical plot in Figure 1 of Papovich, Dickinson & Ferguson (2001). The transformation of the $V_{606}$–$H$ colour from the AB system to the Johnson magnitude system is $V_{606} - H_J = (V_{606} - H)_{AB} + 1.26$.

The colour image shown in Figure 1 combines HST $I$-band data with ISAAC data in the $J_S$ and $K_S$ bands. Most sources visible are very faint distant galaxies and a rich variety in their optical-to-infrared colours is readily apparent. Some high-redshift galaxies, visible as red sources, are hardly detected or even absent in the optical $I$-band. The photometric redshifts of all extragalactic sources using a method detailed in Rudnick et al. (2001, 2002a in preparation) shows that the red colours are produced by evolved systems at redshifts $z > 2$. In our $K_S$-band selected catalogue we find 13 relatively bright galaxies ($K_S < 22$) that have red $J_S - K_S > 2.3$ colours (Franx et al. in preparation), compared to 37 U-dropouts to the same flux limit. The photometric redshifts of these galaxies, determined from the optical-to-infrared spectral energy distributions (SEDs), are between 2 < $z_{\text{phot}}$ < 4. Yet, most of the red galaxies are so faint in the observers optical that they would be missed by standard optical selection criteria, such as the U-dropout method. In principle, the red colours can be
caused by dust, by contribution of prominent emission lines falling in the Ks-band, or by the redshifted Balmer or 4000 Å break, which indicates the presence of evolved stars. Although emission lines have been detected in spectroscopically confirmed \( J_s - K_s > 2.3 \) galaxies in the FIREs MS1054-03 field by van Dokkum et al. (in preparation), their contribution to the broadband NIR photometry is estimated to be small. In many cases the spectral energy distributions show a clear break between \( J_s \) and \( K_s \), which is more easily explained as an aging effect than as a result of dust reddening. These galaxies contribute significantly to the rest-frame optical luminosity density (Rudnick et al. 2002a in preparation) and from their red rest-frame optical colours – implying high mass-to-light ratios – we estimate that they contain a substantial fraction of the total stellar mass present in all galaxies at \( z \approx 3 \).

The morphologies of the red galaxies are generally very compact at all wavelengths, as can be seen in Figure 3. A notable exception is the galaxy in Figure 3c which is clearly extended and has an exponentially decreasing surface brightness profile out to 1″ radius in the H-band. This galaxy seems to host blue knots which could form a spiral arm in the optical WFPC2 images, while it has an extended disk-like appearance with a prominent bulge in the centre in the ISAAC H and Ks images; possibly these are actively star-forming sites embedded in a larger mature host galaxy.

### 4. Strong Clustering of Faint Red Galaxies at \( 2 < z_{\text{phot}} < 4 \)

Presumably, high-redshift galaxies with red \( J_s - K_s \) colours are among the oldest and most massive galaxies at their cosmic epoch and they have formed at the highest density peaks in the matter distribution at significantly earlier times. If so, this population should be more clustered than less massive and less evolved (bluer) objects at similar redshifts. Using the FIREs data of the HDF-S, Daddi et al. (2002) have studied the clustering behaviour of \( K_s \)-selected galaxies at \( 2 < z_{\text{phot}} < 4 \), finding that the amount of clustering depends strongly on the \( J_s - K_s \) colour of galaxies, with red galaxies more clustered than blue galaxies, very similar to what is observed in the optical in the local universe. Dividing the sample at \( J_s - K_s = 1.7 \) in two subsamples reveals that the galaxies with \( J_s - K_s > 1.7 \) colours have the largest-ever level of clustering measured for \( z > 2 \) galaxies (see Fig. 4). The derived correlation length for the faint red galaxies is \( r_0 = 8.3 \pm 1.2 \) Mpc (comoving): a factor of 3–4 higher than that of Lyman

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**Figure 3:** Morphology of bright red \( J_s - K_s > 2.3 \) galaxies in the HDF-S. The left grayscale panels show the averaged WFPC2 V+I data, and right-hand panels show our VLT/ISAAC J, H, Ks data. The intensity is proportional to \( F_\lambda \), with arbitrary normalization for each galaxy. The colour images show a combination of I, J, Ks data, after matching the image quality to that of the Ks-band. The right-hand column shows the spectral energy distributions. Many of these galaxies are small and show prominent breaks in the infrared (rest-frame optical). Note that the galaxy in the top row is barely visible even in Js. The SED of the object in the middle is consistent with a strong Balmer/4000 Å break at \( z \approx 2.5 \). The galaxy in the bottom row is very extended in the rest-frame optical. It shows faint emission in the H-band out to 1″, consistent with an exponential profile.

**Figure 4:** The angular two-point correlation function for galaxies with red \( J_s - K_s > 1.7 \) colours between redshifts of 2 and 4, with the best fitting power-law (solid line) and 1-sigma errors (dotted lines). A positive and large clustering signal is detected, suggesting that these red FIREs galaxies are strongly clustered in real space, with a correlation length \( r_0 = 8.3 \pm 1.2 \) h\(^{-1}\) Mpc comoving. This is the largest level of clustering ever found for distant, \( z > 2 \) galaxy populations.
Break galaxies over similar redshift ranges and with similar number densities. The overall properties of this red $J-K > 1.7$ strongly clustered population suggest that they are the progenitors of present-day massive ellipticals and extremely red objects (EROs) at $z = 1.5$.

5. Large Disk-Like Galaxies at High Redshift

The high-redshift galaxies in HDF-S show a large variation in both morphologies and spectral energy distributions. Spectacularly, we find some $z > 2$ galaxies that are very large in the rest-frame optical and show profound differences between the intrinsic ultraviolet and optical morphologies (Labbé et al. in preparation). Three of the galaxies, shown in Figure 5, are LBGs (selected by applying the U-dropout criteria of Madau et al. 1996), while one is the previously described red galaxy in Figure 5c. Their spectral energy distributions show a pronounced break in the rest-frame optical, identified as the age-sensitive Balmer/4000 Å break. It is well possible that we have discovered the predecessors of the large disk galaxies we see in the lower-redshift universe. Morphological studies in the rest-frame UV light of LBGs have always emphasized the compact and small sizes of the galaxies (Giavalisco et al. 1996, Lowenthal et al. 1997), as indeed is true for the bulk of our sample. However, galaxies that are large in the rest-frame optical with classical spiral morphologies have never been seen before, in particular not in the HDF-N (Dickinson et al. 2000) even though such structures would have been well recognizable in their deep WFPC2 and NICMOS imaging.

Follow-up VLT/FORS spectroscopy (Rudnick et al. 2002b in preparation) confirmed the redshift of the galaxy in Figure 5c, a disk-like U-dropout at $z_{\text{spec}} = 2.793 \pm 0.003$, implying a scale length of $10^{-3}$kpc for the latter.

Figure 5: Same as Figure 3 for the three largest Lyman-break galaxies in the HDF-S. The K-band images (rest-frame optical) are more centrally concentrated than the WFPC2 images; this is a real change in light distribution and not caused by the decreased image quality in the NIR. The redshifts of galaxies (a) and (c) have been confirmed spectroscopically; they have $z = 2.027$ and $z = 2.793$ respectively, implying a scale length of $10^{-3}$kpc for the latter.

These first results on the HDF-S demonstrate the necessity of extending deep optical observations to near-IR wavelengths for a more complete census of galaxies in the early universe. In particular, the deepest-ever $K_s$-band data have proven to be invaluable, probing well into the rest-frame optical at $2 < z < 4$, where long-lived stars may dominate the light of galaxies.

Provided with a new window on the early universe we find previously undiscovered populations of galaxies, with possible far-reaching consequences for our understanding of galaxy formation. We find that the HDF-S has many more galaxies at $z \sim 3$ with very red $V_{\text{606}} - H$ colours than the HDF-N; these are candidates for relatively massive evolved systems. Closely connected, we find a substantial population of red $J_s - K_s > 2$ galaxies at $z > 2$, many of which are barely detectable even in the deepest optical images, and would be missed by optical colour selection techniques such as the U-dropout method. Yet, these galaxies probably contribute substantially to the total stellar mass present in the early universe at $z \sim 3$. We detect strong clustering ($r_c = 8.3 \pm 1.2$ Mpc, comoving) of galaxies with $J_s - K_s > 1.7$ colours at $2 < z_{\text{phot}} < 4$. The strong clustering and their red $J_s - K_s$ colours, suggest that there is a direct evolutionary link between these systems, EROs at $z \sim 1.5$, and massive elliptical galaxies in the local universe. We also find high-redshift systems that are very large in the rest-frame optical with morphologies similar to those of nearby giant spiral galaxies, containing a red bulge surrounded by a diffuse disk and with scattered patches of star-formation. While these are only a few...
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References


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