MAD Science Demonstration Proposal

High-resolution K_S-band Imaging of COSMOS

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Abstract:

We propose a deep 10-hr exposure in the K_S-band of a $2'$ field centered on an asterism in the COSMOS survey area. COSMOS is one of the best studied regions of the extragalactic sky, with deep multiwavelength data in wavebands from the far-UV to the radio. We have identified the only asterism in this field which is suitable for MAD observations. We are proposing a science demonstration (SD) observation of this field to provide high-resolution, near-IR morphological information for a large sample of galaxies overlapping with the unique archival multiwavelength coverage in COSMOS (*GALEX*, far-/near-UV, Subaru/CFHT $UBVgRIz$, *Spitzer* 3.6–8, 24 and 70μm). With this combined dataset we will trace the structural evolution of the stellar mass distribution within high-z galaxies as they grow. Critically, these SD observations will also demonstrate the capabilities of the MAD demonstrator for deep imaging and thus the potential impact of panoramic MCAO imagers on morphological studies of high-z galaxies.

Scientific Case:

Recent results from deep near-IR surveys have suggested that the bulk of the stellar mass in luminous galaxies is in-place at high-z (e.g. Labbe et al. 2005). This has provided a serious challenge to current theoretical models of galaxy formation and evolution (e.g. Baugh et al. 2005). However, we still do not know how this stellar mass is distributed between the two fundamental structural components of galaxies (disks and bulges) in these high-z systems and whether stars subsequently migrate between these components (e.g. via dry mergers). For example, do massive galaxies at high-z have large disks – in contrast to the pure-spheroidal nature of the most massive galaxies locally (ellipticals)? Answering this question requires resolving the stellar components of distant galaxies.

The exquisite spatial resolution of the optical imaging from the ACS and WFPC2 cameras on-board *HST* has demonstrated the critical role that morphological information can provide in studies of high-z galaxies (e.g. Abraham et al. 1999; Giavalisco et al. 2004). Morphological information from *HST* has provided crude measures of the rate of increase in mergers and interactions with z (e.g. Conselice et al. 2004), hinting at the importance of dynamical triggers in the evolution of galaxies (capable of transferring stars from disks into bulges).

Unfortunately, there is an inherent weakness in the morphological information provided by the ACS and WFPC2 on *HST*. These cameras operate solely at optical/UV wavelengths and hence the views they provide of high-z ($z > 1$) galaxies are in the restframe far- or, at best, near-UV. These wavebands provide unreliable indications of the distribution of stellar mass within high-z galaxies – as the UV gives too much weight to young, UV-luminous stars (van den Bergh et al. 2002) – rather than tracing by the light from longer-lived stellar populations (visible in the optical/near-IR). When combined with the steep rise in the star formation rate in galaxies at high-z's, the UV bias in the morphologies critically weakens the conclusions which can be drawn with ACS or WFPC2 imaging. In particular, this bias complicates evolutionary studies of galaxy structure (e.g. bar frequency, Abraham et al. 1999) and estimates of merger rates. In part this is because such evolutionary studies rely on comparisons with local populations, which thus require similar far-UV imaging to compare morphologies in the same wavebands, which was until recently difficult to obtain. Adding in the potential for increased dust obscuration in the more actively star forming populations at high-z – whose obscuration will strongly influence the UV morphologies, and it can be seen that strong conclusions should not be drawn about the structures traced by the stellar mass in high-z galaxies or their merger rates using optical *HST* imaging (c.f. Conselice et al. 2004).

HST's instrument suite does include a near-IR imager: NICMOS. However, the very limited fields of view and sampling of this camera (as well as focus issues) have meant it has not been used for large-scale studies of the morphologies of high-z galaxies (e.g. Smail et al. 1999). Moreover, the thermal background of *HST* means NICMOS can only provide sensitive imaging in the J- and H-bands – and so cannot probe the restframe optical emission of the very highest z galaxies ($z > 2$–3).

To provide reliable structural information on large samples of high-z galaxies requires imaging them in their restframe optical/near-IR with $\sim 0.1''$ resolution (and sampling). In the restframe near-IR (i.e. observed-frame mid-IR) this will have to await *JWST*, but sensitive near-IR (restframe optical) imaging is possible with AO-equipped large-telescopes from the ground. Indeed, survey of fields around natural guide stars (e.g. Larkin et al. 2000; Baker et al. 2003; Christopher & Smail 2006) has provided the basis for AO-enhanced morphological studies of small samples of galaxies ($\sim$ 60–70, $K \leq 20$: Glassman et al. 2002; Cresci et al. 2005; Huertas-Company et al. 2007), as well as aiding in kinematic studies (Eisenhauer et al. 2003). But, again, these first-generation AO surveys were limited by the size of the fields over which good correction could be achieved using a single reference star (e.g. Cresci et al. 2005).

The new generation of Multi-Conjugate Adaptive Optics (MCAO) facilities (of which MAD is a prototype) should yield high levels of correction over much large fields ($\gg 10\times$ the area) using multiple reference stars. For example a single field surveyed with MAD will provide high-resolution morphologies for a sample of galaxies, at least doubling the size of those available from all previous studies. Moreover, the identification of a suitable asterism in a well-studied field can provide a host of multiwavelength information on these galaxies – giving the study much wider impact on our understanding of the morphologies of different classes of galaxies over a wide redshift range and the relationship between their structural properties, stellar masses and star formation/AGN activity.

We propose to obtain deep Science Demonstration imaging of an asterism in the COSMOS field (Fig. 1 & 2) in the K_S-band using the new MAD MCAO demonstrator on VLT. The depth of these observations will be sufficient to allow us to efficiently derive morphological information for samples of 10's to 100's of UV-, optical-, near-IR- and of mid-IR-selected galaxies out to $z \sim 2.5$ (Fig. 3) in this field (using the deep archival *GALEX*, Subaru and *Spitzer* imaging, respectively). These data will address a range of issues in galaxy evolution, e.g. deriving the structural properties of high-z galaxies in their restframe optical/near-IR – free from biases due to dust and recent star formation – to determine the merger/interaction rate in this population and derive the morphologies of their stellar distribution (including robust masses estimated from their restframe near-IR luminosities from IRAC). In this way we will determine if the most massive galaxies at high-z have significant stellar disks, in contrast to the spheroidal nature of such massive systems at $z \sim 0$. Reliable morphological information on the distribution of the stellar mass within these galaxies is essential to make progress on this important question.

These observations will also demonstrate the potential scientific impact of wide-field MCAO-assisted K_S-band imaging for VLT and the future E-ELT. Given the significance of morphology for studies of the properties of galaxies these observations may have profound ramifications for our understanding of this most informative galactic characteristic.

Time Justification:

We request a single $2 \times 2 + 1$ mosaic to cover a $2' \times 2'$ region centered on the only suitable asterism within the COSMOS field – one of the best-studied regions of the extragalactic sky. We note that we have also searched for similar asterisms in the ECDFS and UKIDSS/UDS fields as well as in 5,000 *HST* ACS or WFPC2 pointings with greater than 1,000 s exposure in the I_{814}-band – but have found no candidate blank-field asterisms as good as that in COSMOS.

A preliminary correction performance estimate has been computed using the YAO simulation software adapted to the MAD optical configuration. The guide stars asterism has been modelled with the correct positions and magnitudes and closed loop simulations have been carried out assuming a correction frequency of 400 Hz after a quick run of loop parameters optimization. The atmospheric model consist of 8 layers for a global seeing contribution of $0.8''$ in the V-band. The final simulation length involves 5,000 iterations. The results are shown in Fig. 4 and consist of the Strehl ratio map in K-band, PSF shape variation in the field and associated FWHMs.

Based on these simulations, we expect our proposed observations of the COSMOS MAD field will yield high-quality morphologies for a sample of 40–50 IRAC-selected mid-IR galaxies – reaching out to $z \sim 2.5$ (Fig. 3), with half the sample at $z > 1$ ($\sim$ 10 of which are detected at 24μm), as well as 100–150 $K_S \leq 20$ field galaxies and $\sim$ 10 far-UV galaxies detected by *GALEX*. The median K_S magnitudes of the mid-IR sources are $K_S \sim$ 20–20.5 and we assume scale sizes of $0.2''$ (typical of the optical sizes of faint galaxies, Smail et al. 1995) and aim for detections with SNR $\sim$ 10 to derive basic morphological information (e.g. scale sizes, ellipticities, asymmetries, etc.). This level of derived shape information is consistent with our experience working with similar SNR imaging at $0.1''$ resolution/sampling for high-z galaxies in the optical and near-IR from *HST* (Smail et al. 1997, 1999) and previous AO-assisted work by Huertas-Company et al. (2007). For the brighter half of the sample (and many of the K-selected galaxies), more detailed morphological modelling will be possible to quantitatively derive the stellar fractions in bulges and disks (e.g. using GIM2D, e.g. Balogh et al. 2002).

From the guide-line MAD sensitivities and conservatively adopting 200 mas FWHM image quality as indicated by our simulations of the delivered image quality from MAD with this asterism (Fig. 4), we expect to reach a SNR > 10 at $K \sim 20$ in 2 hrs per pointing. With five pointings in the full mosaic, this equates to a total on-source exposure time of 10 hrs. Adding a 20 min overhead for each acquisition and 2 min for the $2 \times 2 + 1$ mosaic (assuming the exposures are broken into 1–2 hr sequences), we estimate a total time of $\sim$ 12 hrs is needed for this SD programme. The COSMOS field will be visible for 6 hrs per night, above an airmass of 1.5, during the January 2008 MAD SD run. The minimum request for this proposal would be half this exposure time – 6 hrs (including overheads) – yielding SNR > 10 on $K \sim 19.5$ galaxies and SNR ~ 5 at $K = 20$ – but this would significantly reduce the sample of sources with sufficient SNR for GIM2D modeling.

We stress that there are $\sim$ 10 fainter stars detected across the whole field (Figs. 1 & 2) and we will use the PSF measured from these stars to locally correct the galaxy shapes for the effects of the anisotropic PSF across the whole field (Fig. 4) to derive the intrinsic morphologies of the galaxies with GIM2D.

We request standard calibrations.

Our team includes all the relevant experience needed to acquire (lead: Marchetti), reduce (leads: Smail & Marchetti) and analyse and model (lead: Merrifield & Kolb) these data in a timely manner.

Targets and integration time:

Target	**RA**	**DEC**	**Filter**	**Magnitudes**	**Total int. time** (sec)	**Field** (arcmin)
COSMOS-MAD-1	09 57 17.60	+02 26 45.0	K_S	$K_S = 17$–20.5	36,000	2

Guide stars list and positions:

Target: COSMOS-MAD-1

	RA$''_{rel}$	**DEC$''_{rel}$**	**V Mag**	**Note**
GS1	−48.4	+10.0	9.52	
GS2	+3.4	+28.2	12.51	7.0$''$ from faint star, $V \sim 18$
GS3	+49.6	−9.5	12.56	4.7$''$ from faint star, $V \sim 15$
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Abraham et al. 1999, MNRAS, 308, 569
Balogh et al. 2002, MNRAS, 566, 123
Christopher & Smail 2006, MNRAS, 365, 439
Cresci et al. 2005, A&A, 438, 757
Eisenhauser et al. 2003, SPIE 4841, 1548
Glassman et al. 2002, ApJ, 581, 865
Labbe et al. 2005, ApJ, 62, L81
Mobasher et al. 2007, ApJ, in press
Smail et al. 1997, ApJS, 110, 213
van den Bergh et al. 2002, AJ, 123, 2913
Baker et al. 2003, A&A, 406, 593
Baugh et al. 2005, MNRAS, 356, 1191
Conselice et al. 2004, ApJ, 600, L139
Dressler et al. 1997, ApJ, 490, 577
Giavalisco et al. 2004, ApJ, 600, L93
Huertas-Company et al. 2007, A&A, 468, 937
Larkin et al. 2001, PASP, 112, 1526
Smail et al. 1995, ApJ, 449, L105
Smail et al. 1999, ApJ, 525, 609

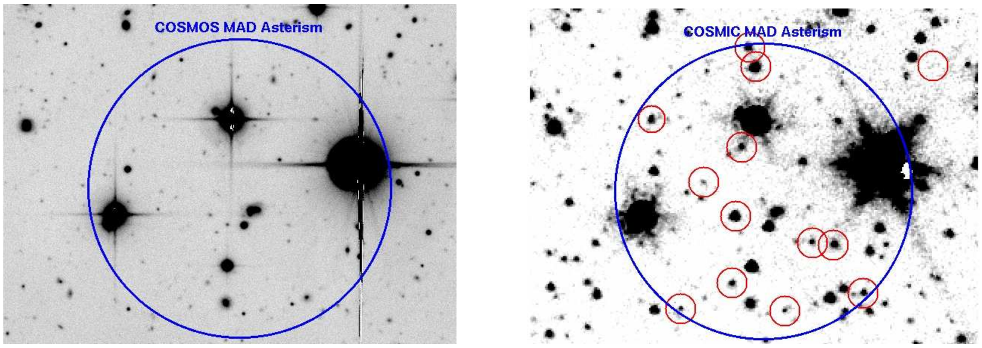

Fig. 1: Two views of the COSMOS MAD Asterism field, as seen in deep I-band, and IRAC 3.6μm (left and right respectively). These data are taken from the CFHT and *Spitzer* archival imaging of COSMOS – which also includes *GALEX* near-/far-UV, ground-based $UBVgRIz$ (from Subaru and CFHT) and *Spitzer* 3.6–8 μm IRAC imaging and 24 and 70μm observations with MIPS. We mark the $2'$-diameter FOV required by MAD and highlight on the 3.6-μm image the reddest examples from the large number of mid-IR bright galaxies which are detected in this region. The proposed MAD SD observations will provide high-quality structural information on these sources to relate their morphologies to their multiwavelength properties. This will more than double the number of faint galaxies with such high-resolution information in the K-band.

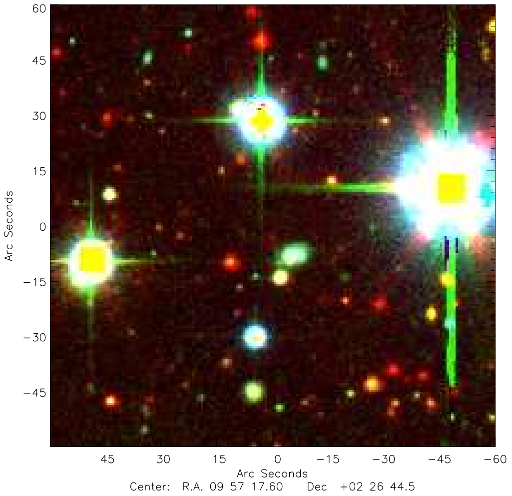

Fig. 2: A true-colour combined gI+3.6μm image of the COSMOS MAD Asterism, constructed from CFHT, Subaru and *Spitzer* imaging. This view of the field spans the wavelength of our proposed MAD K_S imaging and so is showing the emission from the same stars whose spatial distribution MAD will map on sub-kpc scales. The effective resolution of these images varies between 0.8–3$''$ FWHM – our proposed MAD observations will provide almost an order-of-magnitude improvement in resolution at the relevant wavelength. This will both demonstrate the scientific capabilities of the MAD prototype and also the enormous impact of future MCAO imaging for studies of the high-z Universe.

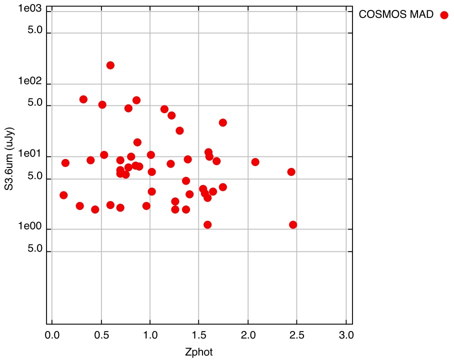

Fig. 3: The expected redshift distribution for 3.6μm-selected galaxies from COSMOS. The photometric redshifts come from Mobasher et al. (2007) and should be accurate to $dz/z = 0.03$ out to $z \sim 1$, but are worse at $z > 1$. An improved 13-band photometric redshift catalog will be available soon – significantly improving the precision at $z > 1$. Nevertheless, the current data show that this IRAC sample extends to $z \sim 2.5$ with half the galaxies at $z > 1$. We can therefore use these data to derive restframe near-infrared luminosities (and hence stellar masses) for our morphological sample – to relate the morphological and mass evolution of the galaxy population.

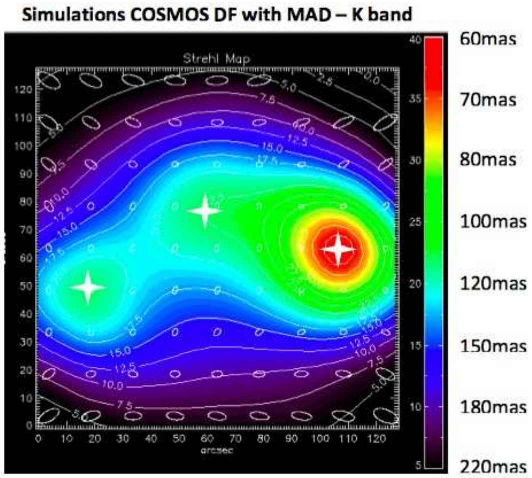

Fig. 4: A simulation of the achieved Strehl ratios, PSF shapes and indicative delivered image quality for our proposed MAD observations. This simulation uses the YAO simulation software, adopts the characteristics of the COSMOS asterism and assumes 0.8$''$ seeing in the V-band. The software emulates the characteristics of the atmospheric turbulence experienced over Paranal. There are of course a considerable number of degrees of freedom involved in these simulations, but this example should be representative of the image quality gains we would expect. Indeed, we will calibrate our observations against this suite of simulations (using the measured PSFs for the ~ 10 faint stars across the field) to exploit the simulations to guide our correction for PSF variation due to anisoplanatism across the field. Based on this simulation we have conservatively assumed 200 mas image quality over the full $2' \times 2'$ field – but we stress that the image quality in at least a quarter of this field should be sub-100 mas (including the deepest regions of our imaging at the field centre). Thus even in moderate conditions, we will obtain a large sample of sources with very high resolution morphologies.