HARMONI: A Single Field, Visible and Near-infrared Integral Field Spectrograph for the E-ELT

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HARMONI provides a powerful E-ELT spectroscopic capability, in the visible and near-infrared (0.47–2.45 μm), at resolving powers ~ 4000, 10 000 and 20 000. Its integral field delivers ~ 32 000 simultaneous spectra, at scales ranging from seeing-limited to diffraction-limited.

HARMONI is conceived as a workhorse instrument, addressing many of the key E-ELT science cases, to exploit the scientific niche resulting from its unique combination of collecting area and spatial resolution. At scales close to the diffraction limit, it will capitalise on the D^4 sensitivity gain of the E-ELT to transform the landscape in visible and NIR astronomy. Even in seeing-limited conditions (or at wavelengths where AO cannot provide high Strehl ratios), HARMONI provides impressive gains with respect to the current generation of VLT instruments, e.g., a gain of ~ 25 in speed relative to MUSE at the ESO–VLT. HARMONI will provide complementarity and synergy with ALMA and JWST, with similar angular resolution to the former, and higher spectral and spatial resolution than the latter at very competitive sensitivities.

Science drivers

The detailed science cases for HARMONI address many of the major questions of astrophysics, such as distant supernovae as key diagnostics of dark energy, the nature of other planetary systems, the role of black holes and AGN in limiting the growth of massive galaxies, the properties of the highest redshift objects and the epoch and mechanism of reionisation. We summarise two cases, part of the E-ELT core science case, selected to illustrate the versatility of the instrument.

Resolved stellar populations

The chemical and dynamical evolution of galaxies is imprinted in their resolved stellar populations, which provide the archeological record of their star formation history and dynamical assembly. One of the principal goals of the E-ELT is to study the resolved stellar populations of massive galaxies spanning the full range of morphologies (including, for the first time, giant ellipticals), going beyond the Local Group to reach the Virgo cluster. The galaxy groups Centaurus (3.5 Mpc) and Leo (10 Mpc) are well within reach (including two ellipticals: Centaurus A and NGC 3379), as are spiral systems in Sculptor, starburst galaxies and compact dwarf elliptical galaxies.

Direct measurements of the chemo-dynamical properties of resolved stars require accurate velocity measurements combined with metallicity indicators for significant numbers of stars in each sub-component (e.g., thin disc, thick disc, halo, bulge). Key chemical elements are released by stars with different mass progenitors (e.g., α-elements from Type II SNe compared to iron peak, C, N and *s*-process elements from Type Ia SNe), and on different time scales (~ 10 Myr *vs.* ~ 1 Gyr). The [α/Fe] abundance ratio is thus a powerful tracer of the relative enrichment by Type II and Ia SN at any given time in the star formation history (SFH) of a galaxy. Homogenous spectroscopic surveys enable an accurate study of the current dynamical state and thus dark matter masses and distributions in these systems as well as their chemical evolution (Battaglia et al., 2006).

Simulations around the Ca II triplet (~ 850 nm) at a resolution of 10 000 and 20 000 show that HARMONI can provide the accurate measurements of velocity and metallicity (Rutledge et al., 1997) to the required precision (velocities ± 5 km s^{-1} for dwarf galaxy types and ± 20 km s^{-1} for large galaxies and [Fe/H] ± 0.3 dex) for main sequence stars in globular clusters and the field throughout the halo of the Milky Way (thus augmenting the picture of halo assembly built by Gaia), Magellanic Cloud globular clusters (multiple main sequences and possibly enhanced He abundances) and massive elliptical galaxies. HARMONI can make precision measurements of velocity and metallicity for 1000 stars below the tip of the red giant branch (RGB) in Centaurus A, sampling three different radii, in 90 hours.

The physics of high-redshift galaxies

The global properties of high-redshift galaxies (luminosity functions, stellar and total masses, sizes, spectral energy distributions [SEDs]) and their evolution with redshift is being revealed through deep, large area, multi-wavelength galaxy surveys. These studies have helped us to develop and constrain the theory of galaxy assembly; however, we have little (c.f. Swinbank et al., 2009) or no data to test the physical mechanisms at work, as we cannot yet probe the internal structure of high-redshift galaxies. Detailed studies with HARMONI of the internal kinematics, stellar population gradients, dust distribution, ionisation structure, nuclear properties, and interaction with the intergalactic medium (IGM) will show how the different physical processes are interrelated, and how they give rise to the integrated physical properties (see Figure 1).

Ultraluminous infrared galaxies (ULIRGs) are rare in the local Universe, but are much more common at high redshift (Le Floc'h et al., 2005). Intense star formation (and AGN activity), driven by large reservoirs of gas and dust, powers these dust-enshrouded objects, which are the likely progenitors of the most massive galaxies. In many cases ULIRGs show clear signs of an ongoing merging process. The merger may trigger star formation through gas transport, and also feed the central AGN, whose energetic outflows may provide the feedback that limits the growth of massive galaxies (Sanders & Mirabel, 1996). HARMONI can probe the properties of these objects over a wide range of spatial scales. In particular we can detect nuclear discs or rings, non-rotational flows such as starburst-induced superwinds, tidally induced motions, or nuclear gas inflows (Figure 2), measure rotation curves and infer the possible subsequent evolution of ULIRGs into normal ellipticals by measuring their fundamental plane parameters.

The combination of high spatial and spectral resolution provided by HARMONI+LTAO will allow the processes occurring within galaxies to be probed on scales of individual H II regions. Such observations promise to yield the distribution of star formation, gas dynamics, metallicity and outflow properties of high-*z* galaxies in unprecedented detail, testing the route by which primitive systems form their bulges, distribute their metals and how efficiently

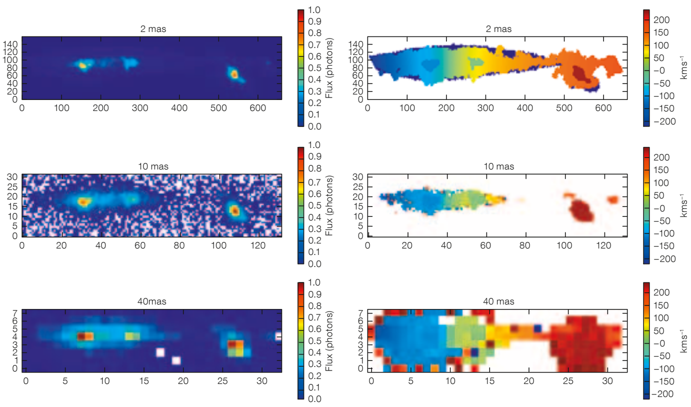

Figure 1. Emission line maps and velocity fields of an edge-on Lyman-break galaxy at $z \sim 3$, observed with HARMONI at various spaxel scales. The top panel shows the input to the simulations. The complementarity between sensitivity to extended structure and spatial resolution is clearly seen.

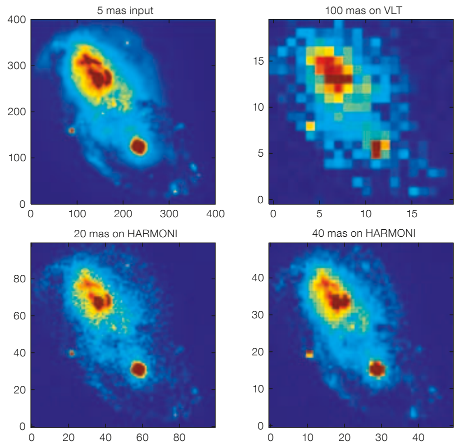

Figure 2. Simulations showing a ULIRG at $z \sim 2$, imaged in the K-band (rest frame Hα) using HARMONI with SCAO or LTAO at two different spaxel scales (20 and 40 mas, bottom panels). The corresponding VLT view is shown at top right, and the simulation input at top left.

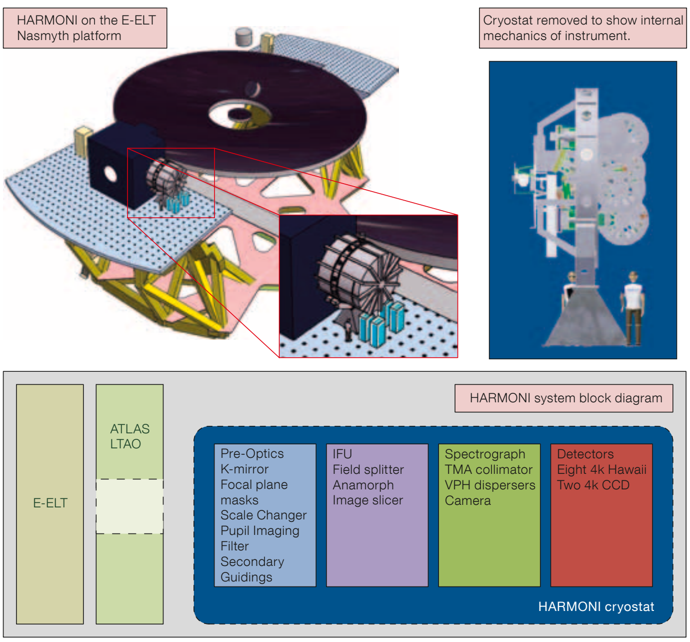

Figure 3. HARMONI deployed at the E-ELT Nasmyth focus (top left). A CAD rendering of the inside of the cryostat (top right) shows all the optomechanical components organised into four subassemblies, as shown in the block diagram below. The ATLAS LTAO module (ring geometry) introduces no optical surfaces within the HARMONI FoV.

baryons are ejected from the galaxy potential and into the IGM.

Instrument design concept

HARMONI provides a range of spaxel scales (0.04, 0.02, 0.01 and 0.004 arcseconds) to match a wide range of science programmes. The coarsest scale provides a 5 × 10 arcsecond FoV, well suited to seeing-limited observations. The FoV scales with spaxel size for other scales. The rectangular FoV allows nodding-on-IFU, providing accurate sky subtraction with no sky overheads. With its large range of spaxel scales, HARMONI can easily adapt to any flavour of adaptive optics — GLAO, LTAO and SCAO, or even with no AO at all!

HARMONI is conceptually simple, and will be easy to calibrate and operate, providing the E-ELT with a "point and shoot" spectroscopic capability. It is based on a proven concept, and requires no significant R&D before it can be built.

The instrument concept (Figure 3) employs an optical de-rotator ("K-mirror") at the input, allowing for a fixed cryogenic instrument with a constant gravity vector, and eliminating flexure-induced variations. Secondary (on-instrument) guiding, using faint stars/compact galaxies, ensures absolute focal plane stability of the de-rotated field. Scale-changing pre-optics provides four spaxel scales, selectable "on-the-fly", and also accommodates the filter wheel, shutter, and pupil imaging mechanism. The "heart" of the instrument is the integral field unit, comprising a four-way field splitter feeding image slicers. The back-end spectrographs disperse the pseudo-slits on to eight 4k × 4k NIR detectors, with grating wheels providing the different dispersions and wavelength ranges. The design is entirely reflective up to the dispersers, allowing two additional disperser–camera units to be easily accommodated, providing visible wavelength (0.47–0.8 μm) coverage.

Performance

With its very high throughput (> 35 %, including detector), and superb image quality (FWHM < 1 detector pixel, both spatially and spectrally), HARMONI provides excellent performance. A signal-to-noise ratio of 5 per spectral pixel (in-between the OH lines) for point sources (20-mas spaxel sampling) is achieved in 5 hours (900 s exposures, 0.8-arcsecond seeing, LTAO correction) for $R_{AB} = 25.4$ and $H_{AB} = 27.4$, at $R \sim 4000$. For extended sources, SNR of 5 per spectral and spatial (40 mas) spaxel is achieved for $R_{AB} = 22.7$ arcsecond^{-2} and $H_{AB} = 21.1$ arcsecond^{-2}. HARMONI will be more sensitive than JWST in the NIR for medium/high resolution spectroscopic work, where the angular resolution gain over JWST will be a factor of seven.

References

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