MOONS: The Multi-Object Optical and Near-infrared Spectrograph

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MOONS (Multi-Object Optical and Near-infrared Spectrograph) is a large field (500 square arcminutes), multi-object (500 object + 500 sky fibres) instrument with spectral resolution of 5000 and 20 000 proposed for the VLT Nasmyth focus. The science case for MOONS, covering Galactic structure and galaxy evolution up to the epoch of re-ionisation, is briefly outlined.

MOONS[1] is a new conceptual design for a Multi-Object Optical and Near-infrared Spectrograph, which will provide the ESO astronomical community with a powerful and unique instrument that is able to serve a wide range of Galactic, extragalactic and cosmological studies. The grasp of the 8.2-metre Very Large Telescope (VLT) combined with the large multiplex and wavelength coverage of MOONS — extending into the near-infrared (NIR) — will provide the observational power necessary to study galaxy formation and evolution over the entire history of the Universe, from the Milky Way, through the redshift desert and up to the epoch of re-ionisation at $z > 8$–9. At the same time, the high spectral resolution mode will allow astronomers to study chemical abundances of stars in our Galaxy, in particular in the highly obscured regions of the Bulge, and provide the necessary follow-up of the Gaia mission.

Science objectives

MOONS will be a versatile, world-leading instrument able to tackle some of the most compelling key questions in science: How do stars and galaxies form and evolve? Do we understand the extremes of the Universe? Here we briefly highlight some of the main science cases that are driving the design of MOONS.

Galactic archaeology

The study of resolved stellar populations of the Milky Way and other Local Group galaxies can provide us with a fossil record of their chemo-dynamical and star formation histories over many-gigayear timescales. Scheduled for launch in 2013, the ESA Gaia mission will deliver new insight into the assembly history of the Milky Way, but to exploit its full potential, ground-based follow-up is required. MOONS will provide this crucial follow-up for Gaia and for other ground-based surveys such as Pan-STARRS and UKIDSS, and the surveys with VISTA, by measuring accurate radial velocities, metallicities and chemical abundances for several million stars. Given the spectral resolutions ($R \sim 5000$ and $R \sim 20000$) and its ability to observe in the NIR, MOONS will perfectly complement the ongoing and planned surveys (see Figure 1) including the new large Gaia–ESO public spectroscopic survey. The unique features of MOONS will allow us in particular to clarify the nature of the extincted regions of the Bulge, but also to assess the chemo-dynamical structure of the Galactic thin and thick disc, understand the importance of satellites and streams in the halo, ultimately creating an accurate 3D map of our Galaxy to provide essential insight into its origin and evolution.

The growth of galaxies

Tracing the assembly history of galaxies over cosmic time remains a primary goal for observational and theoretical studies of the Universe. Even though, in recent years, large spectroscopic surveys at optical wavelengths (0.3–1 μm) have provided key information on the formation and evolution of galaxies, NIR spectroscopy is now crucial to extend our knowledge beyond $z \sim 1$. In fact, at these redshifts almost all the main spectral features are shifted at $\lambda > 1$ μm. Exploiting the large multiplex and wavelength coverage of MOONS, it will be possible to create the equivalent of the successful Sloan Digital Sky Survey, but at $z > 1$ (see Figure 2). This will provide an unparalleled resource to study the physical processes that shape galaxy evolution and determine the key relations between

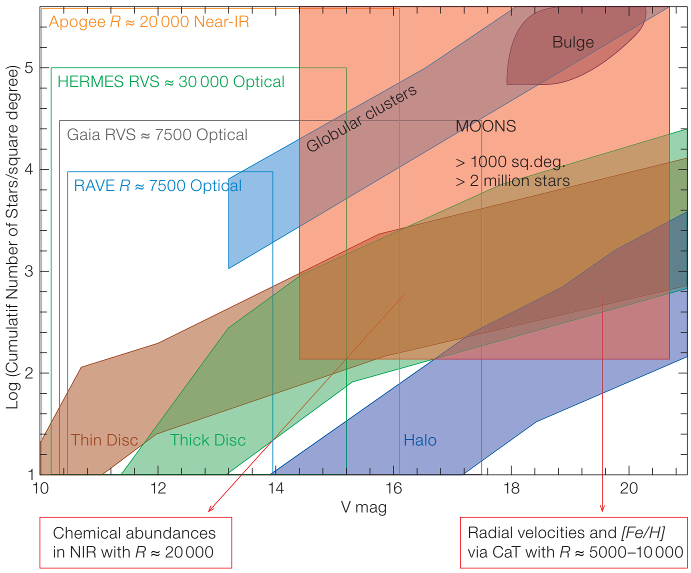
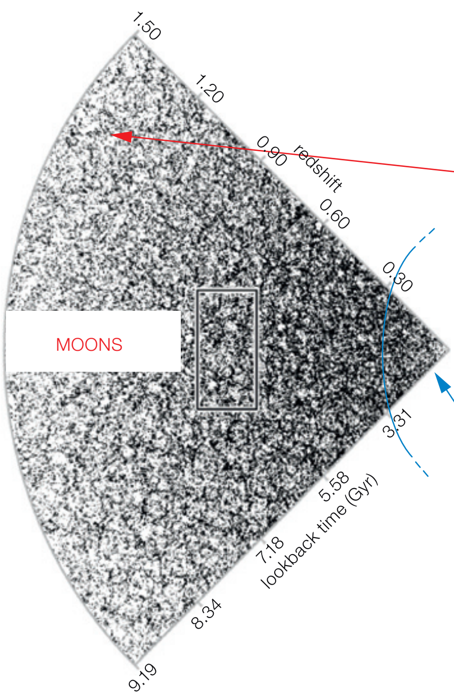
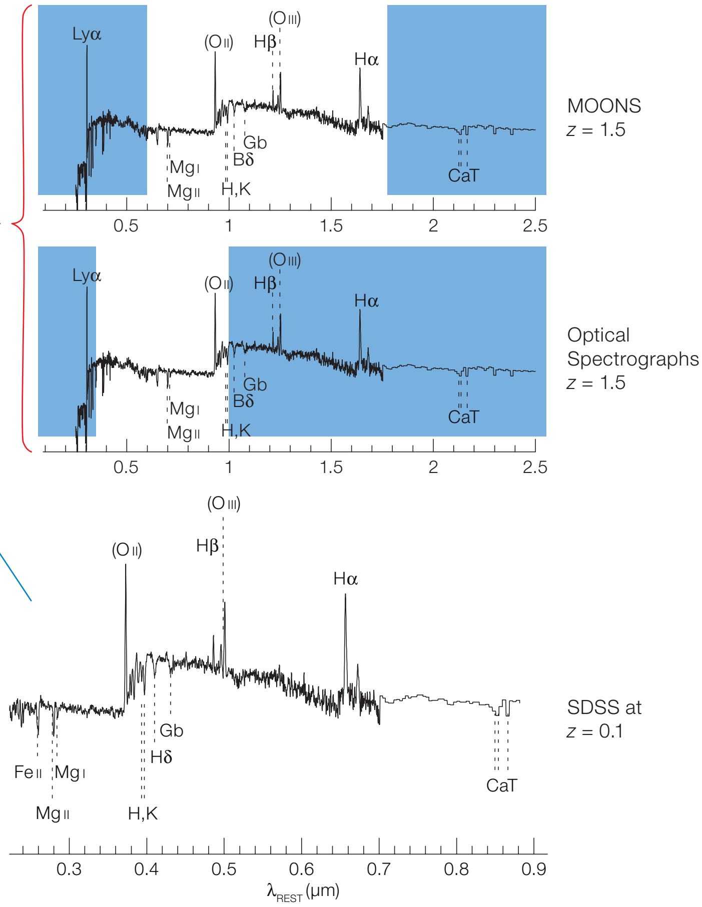


Figure 1. Number density of stars in the various components of the Milky Way shown as a function of *V*-band magnitude (figure adapted from Recio-Blanco, Hill & Bienaymé, 2009). Gaia will provide astrometry for all stars with $V < 20$, however the onboard spectrometer (RVS) will deliver chemical abundance only for stars brighter than magnitude 13 and radial velocities for stars brighter than 17. MOONS will perfectly complement Gaia and the other spectroscopic surveys (e.g., Apogee, Hermes, RAVE) providing chemical abundances via high resolution spectroscopy in the NIR (e.g., observing Ca, Si, S, Fe, Ti lines) and radial velocities via the calcium triplet.

stellar mass, star formation, metallicity and the role of feedback. Filling a critical gap in discovery space, MOONS will be a powerful instrument to unveil "the redshift desert" ($1.5 < z < 3$, see Figure 2) and study this crucial epoch around the peak of star formation, the assembly of the most massive galaxies, the effect of the environment and the connection with the initiation of powerful active galactic nuclei. MOONS will also provide the essential deep spectroscopic follow-up of imaging surveys undertaken with facilities in optical and near-IR (VISTA, UKIDSS, VST, Pan-STARRS, Dark Energy Survey, LSST) and facilities operating at other wavelengths (ALMA, Herschel in the infrared, eRosita in the X-ray and LOFAR, WISE and ASKAP in the radio).





Survey	Redshift	Volume (h^{-3} Mpc^3)	#Objects
SDSS	$0 < z < 0.2$	1×10^8	10^6
MOONS	$0.8 < z < 1.8$	5×10^7	2.5×10^6

Figure 2. A medium-deep survey by MOONS at $z > 1$ will provide a large number of spectra of similar quality and over the same restframe wavelength range and co-moving volume as the low-redshift SDSS survey. As shown by the top right panels, the crucial redshift range $1.5 < z < 2.5$, encompassing the peak of star formation, has proved to be the hardest to explore spectrally (because the major features are redshifted out of the optical range) and gained the nickname "redshift desert". As shown MOONS will cover this gap and properly trace the evolution of galaxies throughout the redshift desert.

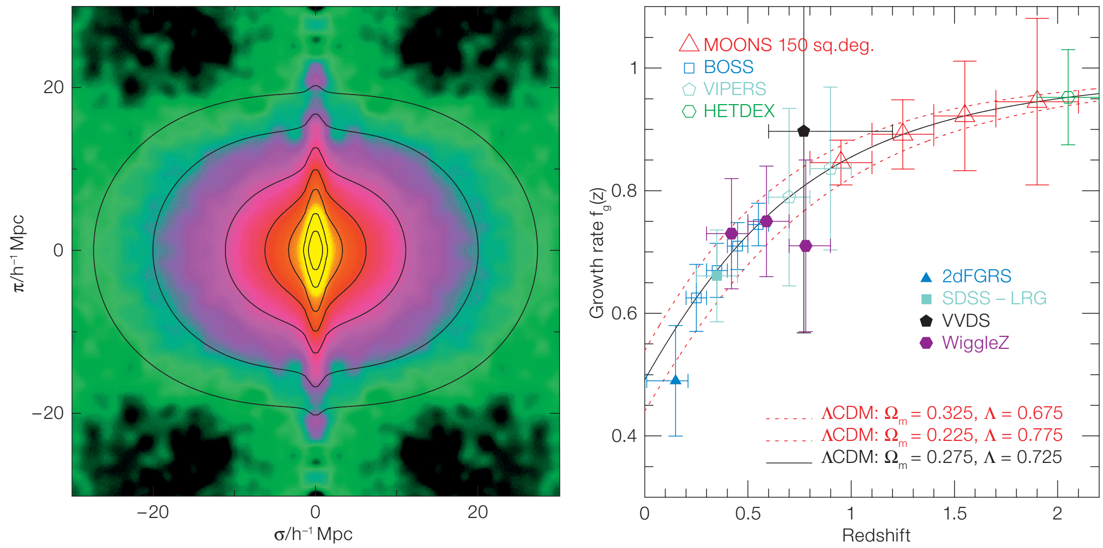


Figure 3. Left: The redshift–space correlation function for the 2dFGRS, $\xi(\sigma,\pi)$, plotted as a function of transverse (σ) and radial (π) pair separation at $z < 0.3$ from the 2dF galaxy redshift survey (Peacock et al., 2001). This plot clearly displays redshift space distortions, with "fingers of God" elongations on small scales and coherent Kaiser flattening at large scales, the signature of the growth rate of structure on galaxy clustering measurements. Right: Comparison of growth rate-measurements, $f_g(z)$, for currently available measurements (solid symbols, with 2dFGRS, SDSS-LRG, WiggleZ and VVDS) and to projected measurements (open symbols) of ongoing surveys (BOSS, VIPERS and HETDEX). Open triangles show the prediction for the growth rate measurement that will be obtained with MOONS using ~ 1 million galaxies over 150 square degrees. No other ground-based survey is able to probe the redshift range considered by MOONS.

The first galaxies

The shining of the first galaxies, just a few hundred million years after the Big Bang (at redshift $7 < z < 12$) is of enormous importance in the history of the Universe since these first galaxies hold the key to furthering our understanding of cosmic reionisation. Although recent advances obtained by deep NIR imaging have been dramatic, very little is known about when and especially how this re-ionisation happened. The unique combination of 8-metre aperture, wide area coverage and NIR spectroscopy (key since at $z > 7$ even the Lyα line is shifted to $\lambda > 1$ μm) offered by MOONS, will provide accurate distances, relative velocities and emission line diagnostics, without which the power of these photometric surveys is severely limited. The capabilities of MOONS will give us the first realistic chance to perform a systematic, wide-area spectroscopic study of the very high redshift galaxies and establish the physics of reionisation.

Cosmology

Over the last two decades several observational keystones have considerably changed our knowledge of the Universe. Measurements of the cosmic microwave background, high-redshift supernovae and large-scale structure have revealed that 96 % of the density of the Universe consists of currently unexplained dark energy and dark matter, and less than 4 % is in the form of baryons. Understanding the nature of these dark components — which dominate the global expansion and large-scale structure of the Universe — is amongst the most fundamental unsolved problems in science. Complementary to other spectroscopic surveys at $z < 1$ (e.g., Vipers, BOSS, WiggleZ, BigBOSS), the capabilities of MOONS will allow us to constrain the cosmological paradigm of the Λ Cold Dark Matter model by determining the dark matter halo mass function and obtain crucial constraints on the nature of dark energy and gravity via detailed measurements of the growth rate of structure at $z > 1$, extending previous determinations, such as that by the 2dF galaxy redshift survey at $z < 0.3$ (Peacock et al., 2001) and shown in Figure 3.

Instrument specifications

To address such fundamental science questions MOONS will exploit the full 500 square arcminute field of view offered by the Nasmyth focus of the VLT and will cover the wavelength range 0.8 μm–1.8 μm, with a possible extension down to 0.5 μm. A new pick-off system will allow a fast positioning of the fibres and the observation of 500 targets simultaneously, each with its own dedicated sky fibre for optimal sky subtraction. MOONS will have both a medium resolution ($R \sim 5000$) mode and a high-resolution ($R \sim 20\,000$) mode to allow detailed dynamical and chemical studies. Such characteristics and versatility make MOONS the long-awaited workhorse NIR multi-object spectrograph for the VLT, which will perfectly complement the optical spectroscopy performed by FLAMES and VIMOS.

MOONS INSTRUMENT PERFORMANCE

Telescope	VLT
Field of view	500 sq. arcmin.
Number of targets	500 objects + 500 sky
Wavelength	0.8(0.5)–1.8 μm
Resolutions	Medium = 5000
	High = 20 000

References

Peacock, J. et al. 2001, Nature, 410, 169
Recio-Blanco, A., Hill, V. & Bienaymé, O. 2009, Proc. French Society of Astron. & Astrophys. SF2A-2009

Links

[1] MOONS: http://www.roe.ac.uk/~ciras/MOONS.html