

Uncovering the Early Stages of Galaxy Evolution: Multi-Object Spectrometry with JWST/NIRSpec

Giovanna Giardino,¹ Catarina Alves de Oliveira,² Santiago Arribas,³
Tracy L. Beck,⁴ Stephan M. Birkmann,² Torsten Boeker,² Andrew J. Bunker,⁵
Stephane Charlot,⁶ Jacopo Chevallard,¹ Guido De Marchi,¹ Pierre Ferruit,¹
Marijn Franx,⁷ Roberto Maiolino,⁸ Samuel H. Moseley,⁹ Bernard J. Rauscher,⁹
Hans-Walter Rix,¹⁰ Marco Sirianni,² and Chris J. Willott¹¹

¹*European Space Agency (ESTEC), Noordwijk, The Netherlands;*
ggiardin@cosmos.esa.int

²*European Space Agency (STScI), Baltimore, Maryland, USA*

³*Centro de Astrobiologia (INTA-CSIC), Madrid, Spain*

⁴*Space Telescope Science Institute, Baltimore, Maryland, USA*

⁵*University of Oxford, Department of Physics, Oxford, U.K*

⁶*UPMC-CNRS, Institut d'Astrophysique de Paris, France*

⁷*Leiden Observatory, Leiden University, The Netherlands*

⁸*Cavendish Laboratory, University of Cambridge, U.K.*

⁹*Goddard Space Flight Center, NASA, Greenbelt, Maryland, USA*

¹⁰*MPIA, Heidelberg, Germany*

¹¹*Herzberg Institute of Astrophysics, NRC, Victoria, Canada*

Abstract. The James Webb Space Telescope (JWST) will be one of the great observatories of the next decade. NIRSpec (Near Infrared Spectrograph) is the near-infrared multi-object spectrograph of the JWST and it features a $3'' \times 3''$ Integral Field Unit, a set of high-contrast fixed slits, and 730×342 individually addressable shutters of $0.2''$ (width) \times $0.5''$ (cross-dispersion), covering a 9 arcmin^2 field for multi-object spectroscopy in the wavelength range $0.6\text{--}5.0 \mu\text{m}$, at a spectral resolution of $100\text{--}1000$. The instrument is already integrated in the JWST payload module and has recently undergone a series of detailed calibration tests in a cryogenic environment, confirming its excellent capabilities. Here we provide an overview of the MOS mode of NIRSpec and its performance, and discuss how the combination of NIRSpec multiplexing and high sensitivity will allow observations of thousands of galaxies throughout a wide redshift range (typically 2–8) to be obtained, shedding new light onto the physics of galaxy assembly and evolution.

1. Introduction

The James Webb Space Telescope (JWST) is a scientific endeavor lead by NASA, with major contributions from the European Space Agency (ESA) and the Canadian Space Agency (CSA). It is scheduled for launch in October 2018 from ESA's spaceport in Kourou, French Guyana, on board an Ariane 5 rocket. Placed in orbit at 1.4 million km from the sun at the Lagrangian point L2 of the Sun-Earth system, with a segmented primary mirror of 6.5 m in diameter, and passively cooled to ~ 50 K by a sun-shield the size of a tennis court, the JWST will be a large and cold telescope optimized for the infrared (Gardner et al. 2009). On board the JWST, the instrument that will enable multi-object slit spectroscopy (MOS) is NIRSpec. Indeed, NIRSpec will be the first slit-based astronomical multi-object spectrograph to fly in space. Besides the MOS mode, NIRSpec also features an Integral Field Unit (IFU) for 3D spectroscopy of extended objects with a 3×3 arcsec field of view, and five fixed slits for high contrast spectroscopy. Here, however, we will focus on NIRSpec's MOS capabilities.

NIRSpec was developed by ESA, with Airbus Space and Defence Germany (formerly Astrium Germany GmbH) as the prime contractor and many sub-contractors from various ESA member states. A picture of the fully integrated instrument is shown in Fig. 1. The image was taken at the end of 2012 before NIRSpec underwent an extensive test and calibration campaign in cryo-vacuum conditions, in the first half of 2013, at the IABG testing facilities in Germany – see Böker et al. (2012); Birkmann et al. (2012). In the Fall of 2013, the spectrograph was delivered to NASA to be mounted onto the JWST Integrated Science Instrument Module (ISIM), together with the other three science instruments of JWST: NIRCам, MIRI and NIRISS.

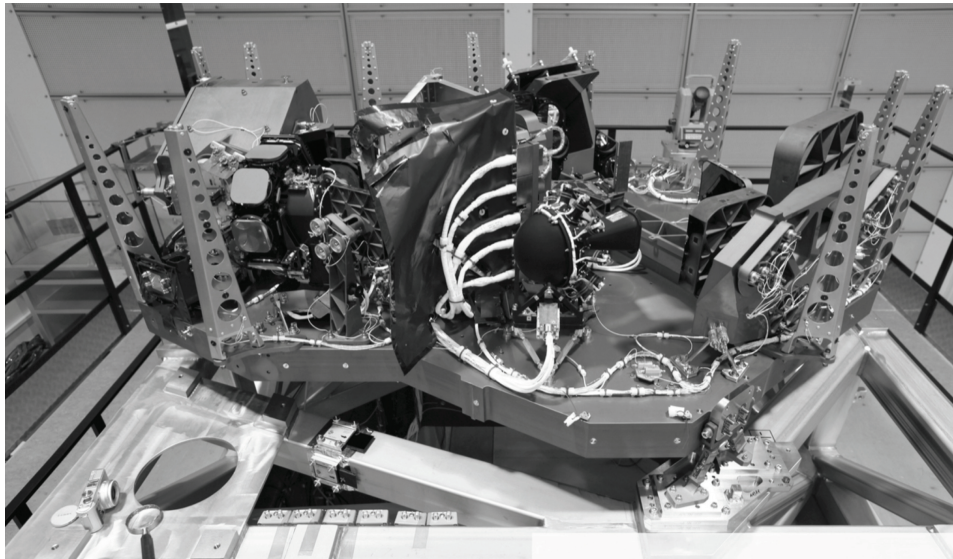


Figure 1. NIRSpec fully assembled at the end of 2012, before undergoing an extensive test and calibration campaign in 2013

2. NIRSpec main characteristics and capabilities

The NIRSpec focal plane is equipped with two 2048×2048 pixel ($18 \mu\text{m}$ pixel pitch), $5.3 \mu\text{m}$ cutoff, Teledyne HAWAII-2RG sensor chip assemblies, provided by NASA Goddard; HAWAII-2RG (H2RG) is short for HgCdTe Astronomy Wide Area Infrared Imager with Reference pixels and Guide mode (Beletic et al. 2008). NIRSpec H2RG are ultra low-noise, state-of-the-art near-IR detectors covering the $\lambda = 0.6 - 5.3 \mu\text{m}$ spectral range.

There are seven dispersers mounted on the instrument's Grating Wheel Array: a double pass prism covering the entire $0.6 - 5.3 \mu\text{m}$ wavelength range at a resolution of approximately 100 and three medium ($R \sim 1000$) and high resolution ($R \sim 2700$) gratings, which in combination with four low-pass filters cover the wavelength ranges: $0.7 - 1.2 \mu\text{m}$ (F070LP), $1.0 - 1.8 \mu\text{m}$ (F100LP), $1.7 - 3.1 \mu\text{m}$ (F170LP) and $2.9 - 5.2 \mu\text{m}$ (F290LP).

The work-horse of NIRSpec's slit-based multi-object spectroscopy is the Micro Shutter Assembly (MSA). This element, also built at NASA Goddard, features 4 arrays of 365×171 micro-shutters each, arranged in a 2×2 mosaic, thereby covering a $4.2'' \times 4.2''$ field of view with $\sim 250,000$ individually addressable slitlets. The micro shutters have been implemented using micro electro-mechanical switches (MEMS), each with a size of $80 \mu\text{m} \times 180 \mu\text{m}$, which is about the thickness of a human hair, corresponding to an angular size of $\sim 0.2'' \times 0.5''$ projected on the sky. Early in 2015, a new MSA was installed in NIRSpec. This new assembly has better contrast performance compared to the previous model and $\sim 90\%$ functioning micro shutters: a key parameter in achieving a high level of multiplexing.

A quarter of a million slits allows for many spectra to be taken simultaneously; for example, using the prism (whose individual spectra cover a smaller detector area than those from the gratings), of the order of 100 sources can be observed at once. The way of optimizing the pattern of open micro shutters in the MSA in an exposure of a real astronomical scene is, however, a non-trivial problem; for this reason, the NIRSpec team and software developers at the Space Telescope Science Institute (STScI) have been implementing specialized algorithms and tools to facilitate the complex planning process of NIRSpec MOS observations, and their calibration and processing, as discussed in the contributions to this proceedings by Karoline Gilbert, Diane Karakla, and James Muzerolle.

The throughput of the instrument was verified during the cryo-vacuum calibration campaign of 2013 and stands at 40-50% (Birkmann et al. 2014). In addition, in January 2015, NIRSpec was fitted with two new H2RG Teledyne detectors, that, as verified from detector-level testing, meet the specification of $\sim 6 e^-$ total noise over 1 ks of integration time, for a dark exposure (Rauscher et al. 2014). NIRSpec low noise and high throughput properties, combined with the large collecting area of the JWST and the cold space environment, makes for a uniquely sensitive instrument, as illustrated in Fig.2. In this diagram, the sensitivity of different observing facilities is compared in terms of line flux detected at 10 sigma, in a 10 ks observation: at a flux sensitivity level of $10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2}$, NIRSpec will be, for the near-IR, the most sensitive spectrograph available towards the end of this decade.

Thus, NIRSpec is finally in its flight configuration and meets the performance specifications required to achieve its scientific objectives (Birkmann et al. 2014). These will range from the analysis of the atmospheres of exo-planets to the studies of the birth

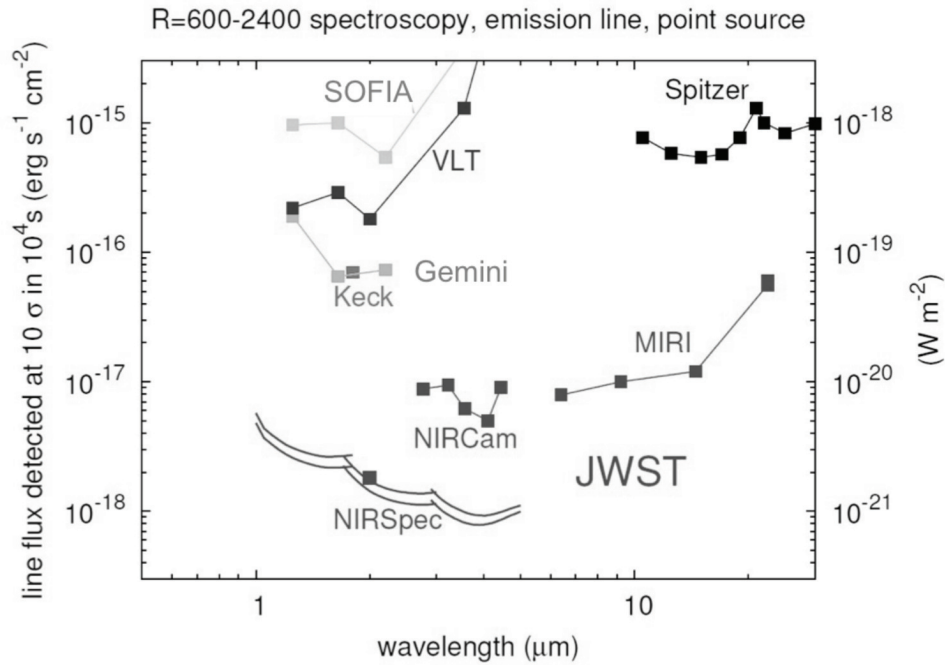


Figure 2. NIRSpect sensitivity compared to that of other instruments/facilities. The six segments in NIRSpect sensitivity curve refer to the three medium resolution grating (bottom/higher sensitivity) and the three high resolution gratings.

of stars and formation of protoplanetary systems, from probing the physical conditions of primeval galaxies to understanding the processes driving galaxy assembly. To illustrate the instrument MOS capabilities, we choose here to focus on studies of galaxy formation and evolution.

3. Addressing the study of galaxy formation and assembly with NIRSpect

In our current theoretical picture, galaxies are assembled through a process of hierarchical merging of dark matter concentrations. Small objects formed first, and were drawn together to form larger ones. Galaxies undergo very rapid halo growth and changes in star formation rate (SFR) from their birth, in the so-called dark ages at redshift $z > 10$, throughout the reionization era, up to the peak of the SFR at $z \sim 2$; see e.g. Birrer et al. (2014). The key objectives of the studies of galaxy formation are to characterize the very early stages of a galaxy's life and to determine how galaxies and dark matter, gas, stars, metals, morphological structures, and active nuclei within the galaxies evolved from the epoch of reionization to the present day. Thanks to its high sensitivity and multiplexing capabilities, NIRSpect will be able to make significant contributions to both of these objectives.

Deep exposures will be performed with NIRSpect to acquire the spectra from high redshift objects which today are only accessible photometrically (if at all). The S/N level of these data will allow us to unambiguously derive the objects' redshifts and to constrain their physical properties via the measure of powerful UV emission lines such

as Ly- α , C ν , C III (which for $z > 8$ fall in the near-IR spectral region) as well as O II , that is accessible in the NIRSpec wavelength range up to $z \sim 12$. The observation of UV emission from these primeval galaxies will also help to understand their contribution to the cosmic reionization process.

At the same time, thanks to its high-multiplexing capabilities, NIRSpec will be able to acquire low and medium resolution spectra of a large sample of galaxies with redshifts $2 < z < 8$. We estimate that roughly 500 hours of telescope time will be necessary to observe approximately 10,000 galaxies. In the redshift interval $2 - 8$, important diagnostic emission lines such as H α , H β , O III and O II , fall within the NIRSpec wavelength range. The immediate use of the spectra in such a large and homogeneous sample will be to derive for each galaxy an accurate redshift (and hence place the object at the correct point in time) and to measure the emission lines to constrain a number of fundamental parameters and characteristics of the galaxy, such as: its SFR, the level of attenuation by dust, the ionization state and the metallicity of the interstellar gas, and the presence of an active nuclei at its center. This extensive data set can then be used to characterize the overall properties of the galaxy population, for example by deriving the galaxy luminosity function, mass function, mass metallicity relation and SFR over cosmic time.

For larger galaxies, the MOS and IFU capabilities of NIRSpec will provide spatially resolved information with which to constrain the growth of galactic structures and study rare sources, such as galaxies undergoing a merger, a process that appears to play a significant role in galaxy assembly.

In conclusion, JWST/NIRSpec has the capabilities to make fundamental contributions to uncovering the early stages of the formation of galaxies and to understanding the physical processes that drive their growth and evolution.

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