Unveiling the early star formation history of the Triangulum galaxy (M33) using precision chemistry

Scientific Category: Stars and Stellar Populations

Alternate Category: Nearby Galaxies to Cosmic Noon

Scientific Keywords: Chemical abundances, Disk galaxies, Dwarf galaxies, Galaxy kinematics, Galaxy stellar halos, Galaxy structure, Local Group, Star formation, Stellar populations

Instruments: NIRSPEC, NIRCAM

Proposal Size: Small

Exclusive Access Period: 0 months (less than default of 12 months)

Allocation Information (in hours):

Science Time: 29.3

Charged Time: 45.4

Abstract

We propose JWST spectroscopic observations to perform a study of the chemical properties of stellar populations in Local Group dwarf galaxy M33. Utilizing precision chemistry information delivered by JWST's NIRSpec instrument, we will determine individual star-by-star elemental abundance measurements probing several nucleosynthetic channels, including Fe-peak elements (Fe, Ni, Mn), alpha elements (Mg, Si, Ti), light elements (C, N), and odd-Z elements (Al). Using these data, we will: 1) unveil the early history of star formation and mass assembly of one of the most massive and mysterious satellite galaxies in the Local Group; 2) map the chemical abundance patterns with precision chemistry of a lower-mass disk galaxy, measure its potential α-knee/α-bimodality, and in turn place M33 between two galaxies whose mass and chemical abundance patterns we know well (Milky Way and LMC); 3) elucidate the nature and origin of M33's stellar halo.

Our proposed JWST proposal is a detailed program aiming to obtain medium resolution high signal-to-noise near-infrared spectra of ~500 bright giant disk and halo M33 stars within four mosaics (NN, NW, SS, SW) of the NE quadrant in the PHATTER survey. The results from this study will address fundamental questions about the early evolution of the largest satellite of Andromeda, will expand our repertoire of extra-Galactic archaeological samples, and will help constrain galaxy formation theory in the lower-mass regime.

Target Summary:

Target	RA	Dec
M33-PREIMAGING	01 34 9.0000	+30 31 16.00
WCEN-VAC-GAIADR3	13 26 38.6172	-47 28 0.01
M33-MAIN-TOPRIGHT-GOLDEN	01 33 59.6149	+30 46 18.26

Observing Summary:

Target	Observing Template	Flags	Allocation *
M33-PREIMAGING	NIRCam Imaging *F277W, F150W*	*SEQVISITS*	1,552 / 8,405
M33-MAIN-TOPRIGHT-GOLDEN	NIRSpec MultiObject Spectroscopy *F100LP*	*SEQVISITS*	87,552 / 123,212
WCEN-VAC-GAIADR3	NIRCam Imaging *F277W, F150W*	*SEQVISITS*	1,552 / 7,918
WCEN-VAC-GAIADR3	NIRSpec MultiObject Spectroscopy *F100LP*		14,592 / 23,597

* Science duration / charged duration (sec)

Total Prime Science Time in Hours: 29.3

Total Charged Time in Hours: 45.4

Observing Description

The Triangulum galaxy (M33) is an ideal candidate for expanding large-scale stellar surveys of lower-mass disk (satellite) galaxies beyond the MW. We propose a pilot program to obtain precision chemistry of ~130 resolved old stars in M33 whose mass sits between that of typical dwarf galaxies and the MW/M31. Lower-mass disc galaxies like M33 provide the ideal target to study galaxy formation at the intersection between the low- and high-mass regime. The proposed pilot program will use NIRSpec spectroscopy to measure precise (~0.1 dex scatter) element abundances (C, N, Mg, Si, Ti, Al, Fe, Cr, Ni, Mn) for M33 stars, from which the star formation history and stellar mass of M33 can be inferred, as well as the more recent mass assembly history of M33. More specifically, with these data we will:

1) Measure the detailed chemical abundance patterns in the disk/stellar halo of M33 in a wide spectrum of element abundances at unprecedented precision ([X/Fe]~0.1 dex), thus delivering * for the first time* detailed elemental abundances (ie., [X/Fe]) in M33, one of the most unique and mysterious lower-mass disk galaxies in the Local Group.

2) Measure the α-Fe knee, and in turn constrain the mass of M33.

3) Constrain the early history of star formation and mass assembly of M33, and compare its detailed chemical patterns to systems with a range of masses in the Local Group.

4) Elucidate the reality and nature of M33's stellar halo, and its connection to M33's disk.

In addition, these data will be modelled using sophisticated galactic chemical evolution models, compared to precision chemistry obtained in the Milky Way and its closest satellites, and contrasted against expectations from high-resolution cosmological simulations (e.g., FIRE: Hopkins et al 2018), allowing us to place M33 in the context of Local Group galaxies.

Investigators:

Investigators and Team Expertise are included in this preview for your team to review. These will not appear in the version of the proposal given to the TAC, to allow for a dual anonymous review.

Role		Investigator	Institution	Country
CoI	*	Dr. Carlos Allende-Prieto	Instituto de Astrofisica de Canarias	ESP
CoI	*	Dr. Lara Cullinane	Leibniz-Institut fur Astrophysik Potsdam (AIP), Germany	DEU
CoI		Dr. Katia Cunha	University of Arizona	USA/AZ
CoI		Dr. Julianne Dalcanton	University of Washington	USA/WA
CoI		Dr. Ivanna Escala	Space Telescope Science Institute	USA/MD
CoPI		Dr. Karoline Gilbert	Space Telescope Science Institute	USA/MD
CoI		Ms. Katya Gozman	University of Michigan	USA/MI
CoI		Dr. Jon A. Holtzman	New Mexico State University	USA/NM
PI	&	Dr. Danny H Horta	Flatiron Institute	USA/NY
CoPI		Dr. Steven R. Majewski	The University of Virginia	USA/VA

Role	Investigator	Institution	Country
CoI *	Mr. Andrew Crombie Mason	Liverpool John Moores University	GBR
CoI	Dr. Pol Massana	NOIRLab	USA/AZ
CoPI	Dr. David Moise Nataf	University of Iowa	USA/IA
CoI	Dr. David Nidever	Montana State University - Bozeman	USA/MT
CoPI *	Dr. Ricardo Schiavon	Liverpool John Moores University	GBR
CoI	Dr. Verne V. Smith	NOIRLab - (AZ)	USA/MD
CoI	Dr. Erik Tollerud	Space Telescope Science Institute	USA/MD

Number of investigators: 17

* ESA investigators: 4

& Contacts: 1

Team Expertise:

Our team is comprised of experts in both galaxy evolution theory and spectroscopic observations and modelling. Specifically, we are all members of a significant and large scale spectroscopic survey of stars in the Milky Way. A number of the team members are directly and closely involved in the analysis and production of data sets for this survey. Outside of this, our expertise resides in, but is not limited to: a) stellar population studies of resolved stellar populations in the Local Group (and M33 specifically), b) Galactic chemical evolution and the interpretation of element abundance, kinematic and spatial data for stellar populations in the Galaxy, c) spectroscopic analysis including detailed element abundance and stellar parameter measurement, d) analysis and interpretation of large cosmological simulations and zoom-in simulations, e) Galactic dynamics.

The specific roles of each team member on the project will be as follows:

- Horta will coordinate and oversee the data analysis and catalogue generation, generate predictions from numerical simulations and perform the final analysis of the reduced data set to determine the presence of an alpha-iron knee and general distribution in the chemical abundance plane. Horta will also help with the data reduction.

- Schiavon will be primarily in charge of performing the data reduction, and relevant spectroscopic analyses and spectral synthesis.

- Allende-Prieto and Holtzman will also aid in the analysis of the gathered spectroscopy and will perform the bulk of the necessary spectral synthesis.

- Nataf will provide support in the chemical abundance measurements and interpretation of the dataset.

- Mason will help with the data analysis and intepretation of the comparison with taylored cosmological numerical simulations.

- Cunha and Smith will aid in the analysis of zero point calibration for the elemental abundance determination using the Omega Centauri globular cluster.

- Dalcanton, Gilbert, Escala, Nidever, Majewski, Cullinane, Massana, Gozman, and Tollerud will assist in the data analysis

■ Scientific Justification

Stellar population studies leverage their correlations in chemistry-age-kinematic space to generate robust constraints on galaxy formation theory. For studying systems beyond the Milky Way (MW), **JWST's NIRSpec instrument is the perfect tool** for such an endeavor and the Local Group (LG) is the ideal starting point for that journey. We propose a detailed program to obtain **precision chemistry (C, N, Mg, Al, Si, Ti, Cr, Fe, Ni, Mn at ~ 0.1 dex scatter) and line-of-sight (LOS) velocities of ~ 500 resolved intermediate-to-old stars in the Triangulum galaxy (M33)**. Lower-mass disc galaxies like M33 provide the ideal target to study galaxy formation at the intersection between the low- and high-mass regime. Specifically, we propose to obtain the needed high SNR spectra (SNR$\sim$ 130) to make these measurements for targets within four mosaics (NN, NW, SS, SW) in the PHATTER survey's (Williams et al., 2021) brick B01 (Fig 1). With these data —unattainable from the ground due to seeing and sky brightness limitations— we will help shed new light into several key science areas: *i*) the early history of star formation and mass assembly of M33; *ii*) the chemical abundance patterns of a lower-mass disc galaxy; *iii*) the structure, composition, and therefore origin of M33's stellar halo.

1 Why extra-Galactic archaeology and why M33

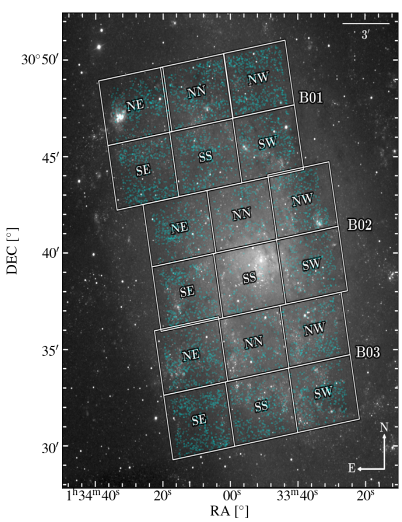

Figure 1: Targets will be selected from the PHATTER survey fields, shown here.

Massive spectroscopic surveys of the MW have revolutionised our understanding of its formation and evolution by providing detailed chemical-dynamical information for its stars. However, **the MW is just one Galaxy.** It is imperative that we begin to obtain high-precision data in other galaxies for a theoretical formulation of galaxy formation that unifies the existing evidence at all scales. We propose to capitalize on the observational capabilities offered by JWST to perform **extra-Galactic archaeology**. **M33** is the ideal candidate for starting this journey enabling to further our understanding of galaxy formation and evolution between the dwarf and spiral galaxy regime. With a stellar mass that sits between the Large Magellanic Cloud and the Milky Way ($M_{\star,M33} \sim 5{\times}10^9\ M_\odot$; e.g., Corbelli et al., 2014), M33 is the most massive satellite of Andromeda and one of the most massive satellite galaxies in the LG; it is also the smallest spiral galaxy in the LG. M33 is classified as a disk galaxy that lacks a significant bulge component (Kormendy & McClure, 1993; McLean & Liu, 1996), and it has been observed to host a weak bar (Elmegreen et al., 1992; Corbelli & Walterbos, 2007). In addition, due to its relatively low stellar surface density, **M33 stellar populations are more easily resolvable than those in other LG galaxies at similar distances**, such as M31 and M32. In fact, M33's proximity allows us to resolve stars down to the ancient main sequence (Williams et al., 2009). **M33 will also be easier to interpret** as its mass sits between two galaxies whose chemical compositions we know well (namely, the MW and LMC). While previous attempts have been made to determine element abundance ratios for *young* stars in M33's disk (e.g., Cioni, 2009; Peña & Flores-Durán, 2019), **there is very little knowledge on the chemical properties of older populations in M33**, and little known about its early star formation history.

2 Constraining M33's Star Formation History with Precision Chemistry

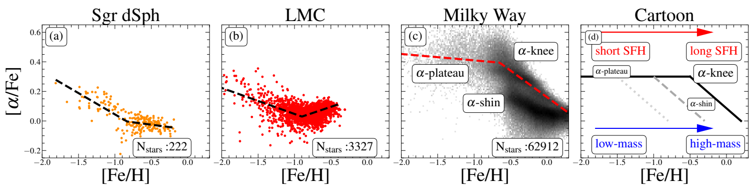

Figure 2: α-Fe distribution for MW satellites (a,b), and MW (c, where the fit is to the high-α disc sequence) using APOGEE DR17 red giant data. (d) depicts a cartoon in the Tinsley-Wallerstein diagram showing the α-Fe morphology for different systems. Plotted as a red/black dashed lines in (a-c) are piece-wise linear models fitted to the data, where the break corresponds to either the α-Fe knee (MW) or an inflection point (Sgr dSph and LMC). For (a)/(b), the upturn seen in [α/Fe] is caused by a star formation burst (Nidever et al., 2020).

The distribution of the stellar populations of galaxies in the [α-Fe]-[Fe/H] ("α-Fe" or Tinsley-Wallerstein) plane is a powerful indicator of star formation history. In the dwarf galaxy regime, [α/Fe] is typically lower closer to solar [Fe/H] at fixed [Fe/H] than for larger-mass systems (Tolstoy et al., 2009). So far, the α-Fe plane has been mapped in some detail in MW satellites (e.g., Nidever et al., 2020; Hasselquist et al., 2021; Horta et al., 2022) where it is found to vary strongly from system to system (Fig 2). In all star forming systems, the point at which the predominant source of chemical enrichment of heavy elements transitions from core-collapse SN dominated (SN II) to white dwarf in binaries (SN Ia) is marked by what is commonly referred to as an α-knee. The [Fe/H] at which this turnover occurs is postulated to be related to the mass of the system and its early star formation history/efficiency (Mason et al., 2024). Moreover, in some cases, there is a clear higher metallicity inflection towards constant or even increasing [α/Fe] (e.g., Sgr dSph and LMC), conjectured to be due to a recent star formation burst (see Fig 2a,b). In the MW disk, a bimodal distribution on the α-Fe plane has also been shown to exist (Fig 2c). The data we seek to obtain for M33 stellar populations will help establish **where in the spectrum of known distributions on the α-Fe plane the older disk of M33 is located**, and in turn it will teach us how its history of star formation compares with those of the MW and its satellites. Questions we will be able to answer from these data include: *Does M33 display a classical α-knee and/or α-bimodality? Which chemistry does M33 most resemble, a dwarf or MW-mass galaxy? What does the placement of the α-knee say about the early star formation efficiency of M33?*

Moreover, we must note the importance of the recent discovery of a stellar halo in M33 (Gilbert et al., 2022). In that study, the halo fraction for the NE region (Fig 1) was found to be on the order of $\sim 23\%$. Thus, we expect that ~ 120 of the ~ 500 stars we will observe will likely be halo stars. In fact, the origin of the M33 dynamically hot halo component is not fully understood, and is postulated to originate from either an accretion, from an situ disk, or a combination of the two (Cullinane et al., 2023). **The precise chemistry we will obtain for ~ 120 stars in M33's stellar halo (discriminated by their LOS velocities) will help distinguish the possible genesis scenarios**, and in turn will provide a powerful initial constraint on the early history of mass assembly of M33.

3 Precision Chemistry in M33 with NIRSpec

The science we propose to conduct **can only be performed using the spatial resolution, low background, and multi-object spectroscopic capabilities of JWST.** Our program will target a field of M33's disk to derive precision abundances (Fig 3) of a multitude of elements (~ 10) covering various nucleosynthetic pathways (SNe II, SNe Ia, AGB), **which is unprecedented for M33.**

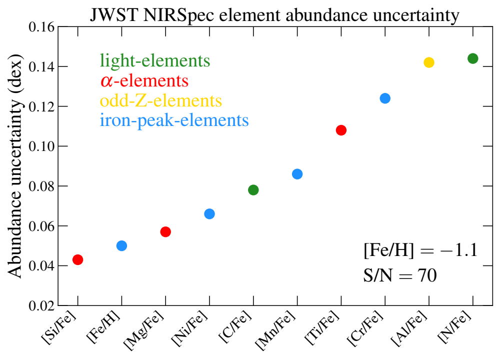

Figure 3: Precision of individual element abundances we will obtain with JWST/NIRSpec for a star at [Fe/H]$= -1.1$ (similar to the mean of M33, $\langle[\mathrm{Fe/H}]_{\mathrm{M33}}\rangle = -1.15$ Cioni, 2009) at a much S/N lower than what we will obtain (see Technical Justification).

To ensure the data we seek will allow us to measure the proposed observables, we have simulated the α-Fe plane by injecting JWST uncertainties, and find that we are able to recover the α-knee and α-bimodality with a parent sample of ~ 400 M33 disk stars. **JWST offers the only available means to reach our objectives thanks to the telescope's sharp point spread function (PSF).** Ground based attempts are limited by: *i*) Earth's atmosphere, which blocks much of the spectrum between $0.8 - 5\mu$m due to water and carbon dioxide (amongst others) molecules; *ii*) crowding to the outskirts of the M33 disk that increases photometric uncertainties. JWST's spatial resolution is key to overcoming crowding. The ability of NIRSpec to cut through dust extinction and background contamination yields the high S/N required for precision abundance determinations with relatively short exposure times. In the $0.9-1.8\mu$m (near-infrared, NIR) regime, such abundances can be well constrained in cool giant spectra from modelling of atomic lines (Fe, Mn, Cr, Ni, Mg, Ti, Si, Al) and molecular bands (C, N). The ability of JWST to observe in the NIR without being affected by absorption features in the Earth's atmosphere also allows vast increases in achievable S/N, since the spectro-photometry is not limited to the *J,H,K* bands. Besides examining the distribution of M33 stars in a multitude of chemical planes, we will combine abundances of C, N, Mg, and Al to identify possible globular cluster (GC) escapees (e.g., Schiavon et al., 2017; Horta et al., 2021). This will be achieved by identifying field stars with enhanced N and Al and depleted C and Mg, a chemical abundance anti-correlation only observed in second generation GC stars (Bastian & Lardo, 2018).

■ Technical Justification

Goal: **We propose to obtain medium resolution, high S/N, spectra for** ~ 500 **bright M33 disk and halo giants** within a narrow range of $T_{\rm eff}$ and log g. The spectra will be used for the derivation of precision element abundances that will yield the distribution of intermediate-to-old M33 stars in ~ 10 different chemical composition planes. This will be achieved by deriving stellar parameters and chemical abundances ($T_{\rm eff}$, log g, [Fe/H], and [α/Fe]) using a 4-D grid of synthetic spectra (Synspec; Hubeny & Lanz, 2011, 2017) convolved to the resolution ($\approx$4000; V. Smith, private communication) of the JWST NIRSpec G140H/F100LP spectra (0.9–1.8μm). We will use the `FERRE` software package (Allende-Prieto & APOGEE Team, 2015) to search the grid (performing χ^2–minimization) for the best-fitting spectra. In detail, the data analysis will proceed in two complementary ways: (i) Combining synthetic distributions of stellar populations in various chemical planes, state of the art model atmospheres and spectral synthesis, and an error model; we will forward model the distribution of spectral features for comparison with our measurements. The input distributions will include both theoretical predictions from numerical simulations and APOGEE-based observations of dwarf MW satellites; (ii) We will infer the abundances of a large number of elements, sampling various nucleosynthetic pathways. This includes Fe-peak elements (Fe, Ni, Cr, Mn), α elements (Mg, Si, Ti), light elements (C, N), odd-Z elements (Al). Finally, the **LOS velocity precision (see below) will be good enough to afford a distinction between halo and disk populations in M33**, where M33's velocity distribution is well-known from ground-based spectroscopy (Cullinane et al., 2023).

Field and target selection: We select targets from the PHATTER survey (Williams et al., 2021) located within four mosaics in Brick B01, in the north-west quadrant of M33's projected disk (Fig 1). This field has no substantial contamination by spiral arms, low levels of extinction, and is dominated by stars older than ~1 Gyr. Its location roughly 1.4 scale lengths from the centre of M33 (Regan & Vogel, 1994) means that its stellar populations may contain a non-negligible contribution from the halo of M33 (Gilbert et al., 2022). To minimize for the impact of extra mixing of the C and N abundances along the upper giant branch, we select targets within a narrow magnitude range (18.7 < F160W < 19.3). According to the PARSEC theoretical isochrones (Marigo et al., 2017), assuming a distance modulus of 24.57, and $A_{\rm F160W}$ ~0.02 (Conn et al., 2012), stars in this position of the CMD have typically $T_{\rm eff}\sim$ 3900 K and log $g \sim 0.5$ for $[{\rm Fe/H}] = -1$ and $[\alpha/{\rm Fe}] = 0$. In addition to the M33 field, we will leverage globular cluster data from: 1) stars from a well studied cluster, ω-Centauri, that spans a range in metallicities similar to M33. By targetting ω-Centauri, we will be able to calibrate across a range of [Fe/H] using solely one cluster; 2) globular cluster data taken in the same science configuration from collaborators (Nidever, private communication) for M 71, NGC 6791, and NGC 2808, which span a wide range of metallicties ($-1.5 < [{\rm Fe/H}] < 0.5$).

Instrumental setup: **We will adopt the G140H/F100LP grating/filter combination to cover the $\lambda 0.9 - 1.8\mu$m spectral range**. In addition, several tens of measureable atomic lines due to the atomic species of interest are included in this spectral region (Rayner et al., 2009). Because the outstanding performance of the PSF of JWST, NIRSpec is delivering unprecedented resolution (R$\sim 4000 - 5000$) for point sources than the nominal R = 2700. Therefore, our abundance analysis approach will consist of the combination of automatic minimization against our huge synthetic spectral library based on state of the art model atmospheres and line lists with a classical interactive analysis to ascertain the fidelity of the automatic approach. Because of the sharp PSF delivered by the JWST optical system, the projected line spread function of the NIRSpec spectra is severely undersampled (FWHM $\sim$ 1 pixel). To mitigate this problem our observational design includes subpixel dithers in the dispersion direction. To keep every star within the slitlet for every exposure we adopt a "Constrained" source centering constraint. We expect our data not to be background dominated, so we adopt 1 Shutter Slitlet design.

S/N and Exposure time requirements: A detailed mapping of the distribution of M33's stellar populations in the α-Fe plane requires abundance precision of the order of ~ 0.05 dex. Our tests show that such precision can be achieved with S/N$\sim$ 80/pixel for Mg, Si, and Fe, but a higher S/N (~ 130) is required for such precision for additional abundances (Fig 3). The ETC (Workbook ID 226893) tells us that, for a star with F160W = 19 we obtain S/N/pixel$\gtrsim$ 130 at 1.15μm, adopting 25 groups/integration, 2 integrations/exposure, and a total of 3 dithers, with a NRSIRS2 readout pattern. Exposure patterns were adjusted to obtain similar S/N for ω Cen stars. Pre-imaging is requested for both sets of observations (M33 and ω Cen).

Special Requirements (if any)

We request to not be scheduled after observations of very bright targets to avoid persistence.

Special Requirements (if any)

Justify Coordinated Parallel Observations (if any)

Justify Duplications (if any)

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