Onsala Proposal

Hess O2024b02

WEAVE-Apertif CO follow-up: connecting star formation with all ISM phases

Semester: nov2024 **Science Cat.: External galaxies**

Abstract

The WEAVE-Apertif (WA) project aims to study galaxy evolution by exploring the transition from the blue cloud to the red sequence across the color-magnitude diagram. Utilizing a combination of spatially resolved HI and optical data from Apertif and WEAVE, WA provides new insights into star formation quenching and the impact of environmental and internal processes. The survey will observe 400 galaxies selected by their HI morphology, covering a wide range of stellar masses, star formation rates, and environments. It will be unique in the landscape of IFU surveys by selecting galaxies by their resolved HI morphology and not their optical properties, offering an orthogonal perspective of galaxy evolution. We propose CO(1-0) observations for an initial subset of 35, already observed, WA galaxies using OSO 20m. This will provide spatially resolved CO maps to measure the ratios of SFR to M(H2) and M(H2) to M(HI), allowing the study of environmental effects on star formation and gas conversion. The combined IFU, HI, and CO dataset will create a comprehensive resource with substantial legacy value.

Applicants

Name	Affiliation	Email	Country		Potential observer
Dr. Kelley Hess	Chalmers University of Technology (Space, Earth and Environment)	kmhess.astro@gmail.com	Sweden	Pi	Yes
Jesus Falcon-Barroso	IAC	jfalcon@iac.es	Spain		Yes
Isabel Perez	Universidad de Granada (Física Teórica y del Cosmos)	isa@ugr.es	Spain		
Paolo Serra	INAF	paolo.serra@inaf.it	Italy		Yes
Dr Yago Ascasibar	Universidad Autónoma de Madrid	yago.ascasibar@uam.es	Spain		Yes
Anne-Marie Weijmans	University of St. Andrews	mw23@st-andrews.ac.uk	United Kingdom		Yes
Dr. Helmut Dannerbauer	Instituto de Astrofísica de Canarias	helmut@iac.es	Spain		Yes
Anelise Audibert	Instituto de Astrofísica de Canarias	anelise.audibert@iac.es	Spain		
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Applicants are continued on the last page

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Is this a long term proposal: No

Overall scheduling requirements

No constraints. In consultation with Henrik, we plan to first observe the central pointing for 4-5 of the most nearby galaxies to test and refine the observing strategy before mapping, and before going on to the larger target list, or re-evaluating the choice of targets.

Observing runs

run	telescope	instrument	time request (minimal)	frequency (GHz)	weather (pwv)	LST range	comments/constraints
A	OSO20M	3mm Receiver (85-116 GHz)	126h (126h)	114.129		11.5-15.5	2.5 GHz bandwidth, dual polarization
B	OSO20M	3mm Receiver (85-116 GHz)	94h (94h)	112.825		10.25-16.6	2.5 GHz bandwidth, dual polarization

Targets

Source	RA	Dec	Epoch	Vlsr (km/s)	Duration (min)	Runs	Comments
WA-CO_05	11:57:24.90	+57:55:48.0	J2000	1199.0	378	A	
WA-CO_31	15:07:48.37	+55:11:08.3	J2000	3297.0	378	A	
WA-CO_26	14:00:43.69	+31:53:39.0	J2000	4197.0	378	A	
WA-CO_01	10:15:11.42	+56:40:19.5	J2000	7794.0	378	B	
WA-CO_13	12:26:08.10	+58:19:21.0	J2000	599.0	378	A	
WA-CO_10	12:14:18.08	+59:36:55.6	J2000	4197.0	378	A	
WA-CO_15	12:44:26.20	+37:07:16.4	J2000	6895.0	378	B	
WA-CO_02	10:25:24.21	+55:31:29.8	J2000	7495.0	378	B	
WA-CO_29	14:29:58.37	+36:52:23.6	J2000	599.0	378	A	
WA-CO_07	12:05:20.97	+63:09:23.9	J2000	2998.0	378	A	
WA-CO_04	11:43:27.28	+52:42:40.0	J2000	5696.0	378	B	
WA-CO_30	14:37:59.94	+40:06:22.2	J2000	7794.0	378	B	
WA-CO_24	13:54:35.23	+38:26:57.7	J2000	5696.0	378	B	
WA-CO_21	13:35:55.20	+35:35:17.7	J2000	2098.0	378	A	
WA-CO_20	13:22:32.48	+54:49:05.5	J2000	3597.0	378	A	
WA-CO_14	12:41:44.55	+35:03:45.9	J2000	6895.0	378	B	
WA-CO_06	12:04:59.06	+58:06:26.0	J2000	2398.0	378	A	
WA-CO_08	12:09:30.19	+53:06:17.8	J2000	1199.0	378	A	
WA-CO_19	13:15:47.12	+31:50:47.1	J2000	5096.0	378	B	
WA-CO_23	13:53:17.83	+33:29:26.9	J2000	2398.0	378	A	
WA-CO_25	13:56:51.02	+37:47:50.0	J2000	2998.0	378	A	
WA-CO_22	13:49:44.33	+39:59:05.1	J2000	2398.0	378	A	
WA-CO_32	15:07:51.83	+54:45:10.0	J2000	2998.0	378	A	
WA-CO_03	11:26:40.44	+53:44:48.0	J2000	599.0	378	A	
WA-CO_27	14:20:26.48	+35:11:19.7	J2000	3597.0	378	A	

Targets are continued on the last page

Scientific Rationale

Our understanding of the global parameters of galaxies and how those properties have developed over the lifetime of the Universe are primarily based on samples that have been selected through their stellar content. Surveys such as the Sloan Digital Sky Survey (SDSS, York et al. 2000) have revealed the global stellar and ionized-gas characteristics of galaxies in the local Universe − their morphologies, colors, star formation rates, stellar populations, stellar masses, and black hole accretion rates. Local galaxy integral-field surveys (e.g. CALIFA, Sánchez et al. 2012; SAMI, Croom et al. 2012; MANGA, Bundy et al. 2015) suffer from an optical selection bias that makes a study of the effects of star formation and the environment in their evolution difficult to address. Taking advantage of state-of-the-art radio-telescope facilities (e.g. *Apertif* on the Westerbork Synthesis Radio Telescope), it is possible to start asking similar questions of galaxies that are selected by their gas content: What are their dynamical masses, star formation rates (SFRs), stellar populations, gas content, large-scale distribution in the Universe, and how did they come to have these properties? How do galaxies acquire and lose their gas, and how do the environments in which they live impact their evolutionary histories?

WEAVE-*Apertif* (WA) is a project dedicated to understanding the evolution of galaxies by unravelling the role different physical mechanisms play in their from the blue cloud to the red sequence across the color−magnitude diagram. A large-scale integral-field survey with WEAVE[1] (Jin et al. 2024) creates a strong synergy with the HI *Apertif* imaging surveys (Adams et al. 2022; van Cappellen et al. 2022), increasing the power of each dataset on its own. **The unique combination of spatially-resolved HI and optical observations from the *Apertif* and the WEAVE LIFU will yield valuable metrics to constrain the timescales of star formation quenching driven by the interaction of galaxies with their environment.**

WA will address these topics by observing a representative sample of 400 galaxies, with a typical angular size of 1 arcmin, homogeneously spanning a wide range in HI mass and morphology, stellar masses, specific star formation rates and local environment. The WEAVE LIFU observations will provide stellar population and kinematic parameters including spatially resolved mean stellar ages, metallicities, and detect kinematic twists, warps, and decoupled components. The survey will also provide spatially resolved ionized gas metallicities and star formation rates, complemented by the neutral atomic gas from *Apertif* data, resulting in a rich dataset. The WA survey will be unique in the current landscape of integral-field surveys in that it selects galaxies through knowledge of the resolved HI morphology and not purely their optical properties thus offering an orthogonal perspective of galaxy evolution. It is the only IFU survey with both large spatial coverage (1.5×1.3 arcmin) and high spectral resolution ($R \sim 10000$).

Why CO observations? The unresolved cold gas scaling relations in the nearby Universe, such as $M_{\rm HI}$ vs. $M_\star$, $M_{\rm H_2}$ vs. $M_\star$, SFR vs. $M_{\rm HI}$, SFR vs. $M_{\rm H_2}$, and $M_{\rm H_2}$ vs. $M_{\rm HI}$ are characterized by a large scatter (Saintonge & Catinella 2022). This scatter is likely due to the diverse evolutionary histories of galaxies: the relationships between $M_\star$, SFR, HI, and H_2 are influenced by the specifics of gas cooling, accretion, heating, and removal processes. These details are, in turn, influenced by interactions with the environment.

To advance our understanding of the origins of these complex relations, we aim to add global measurements and spatially resolved CO(1-0) maps to our WA sample. This will allow us to quantify the variation in the ratios of SFR to $M(\rm H_2)$, and $M(\rm H_2)$ to $M(\rm HI)$ across galaxy disks. Locally, these ratios can be affected by environmental interactions that alter the efficiency of star formation and the conversion of atomic to molecular gas. Additionally, these ratios are influenced by gas accretion and feedback from stars or AGN. WA galaxies are selected based

[1] WEAVE (WHT Enhanced Area Velocity Explorer) at the William Herschel Telescope (WHT) on La Palma is a multi-object, multi-fiber spectrograph, with integral-field spectroscopic capabilities, designed to provide detailed spectroscopic data for large areas of the sky. Primary goals include the formation and evolution of the Milky Way, the properties of galaxies and galaxy clusters, and the nature of dark matter and dark energy. **The large integral-field unit (LIFU) mode is commissioned and observations for WA have started already.**

on their HI morphology and therefore represent different stages of environmental interaction. By uniformly populating a parameter space that includes HI morphology, stellar mass, position relative to the star formation main sequence, and environmental density, while incorporating spatially resolved CO data, we can better explore the causes of these complex relations (Fig 1).

Proposed observations

This proposal aims to obtain **CO(1-0) observations with the OSO 20 m for a subset of 35 WA galaxies already observed with WEAVE and** *Apertif*. By choosing the lowest CO transition (in combination with a single dish telescope) we ensure to reveal the bulk of the cold molecular gas, the fuel of star formation, which might be widespread, low-density and sub-thermally excited gas even outside of star-forming regions. This initial sample covers a diverse range of stellar and HI properties (see Figure 2). They are all in the blue cloud, and cover the full range of sample selection parameters.

The ∼30" beam of the 20 m spans 3 linear resolution elements of the WEAVE LIFU, and is comparable to the 40" resolution *Apertif* data that we use to classify the HI morphology (Fig 2; we also have access to the $\sim 15'' \times 15\sin(\delta)''$ resolution data). We therefore anticipate detecting extended, spatially-resolved CO measurements for all galaxies, providing molecular gas flux density and kinematic maps at comparable spatial scales to the *Apertif* data. The combination of high-resolution IFU data (i.e. few kpc) and lower-resolution gas maps (tens of kpc) enables the connection of small-scale star formation processes with large-scale gas dynamics to investigate how the global gas content and distribution influence localized star formation and how feedback from star formation affects the gas reservoir on larger scales.

Facilities Requested

We request observations with the 3 mm receiver at the Onsala 20 m. This is a pilot survey which will be used to evaluate the feasibility of observing the full WA sample, or a bright subsample, as well as what adjustments may be required to the observing strategy. All our targets are between 25-60 deg declination, essentially requiring a northern hemisphere telescope.

Observing requirements, plan, and schedule requirements

We propose to observe in dual sideband mode with the 3mm receiver and OSA spectrometer backend. The 2.5 GHz bandwidth to record both linear polarizations is more than sufficient to observe the full width of the CO (1-0) line in any galaxy, and the 76 kHz (0.19 km/s) resolution will be binned to 7.7 MHz (∼20 km/s). Our targets span the RA ranges (10-16h and 22-3h), avoiding the Milky Way. We have no strong scheduling requirements.

For an elevation of 45 deg, an observing frequency of 114.0 GHz, and spectrometer resolution of 20.0 km/s, the OSO 20 m exposure time estimator predicts 6 min per pointing to reach a sensitivity of 6.0 mK. We plan to map a field around each galaxy of 2'x2'. Assuming a beam FWHM of 30 arcsec and Nyquist sampling (pointings separated by 17.5")[2], overlapping beams of which reduces the needed exposure time by a factor of ∼1.7, require 2.72 hours per galaxy, or 5.5 h with beam switching and 6.3 h including overheads. To cover 35 galaxies, we are requesting 220 h in total. In consultation with Henrik Olofsson, we propose to start with a subset of 4-5 galaxies for which we will observe the central position and then evaluate that the SNR and baseline quality is sufficient to continue with mapping and adding further sources.

References

Adams E. A. K., et al. 2022, A&A, 667, A38 • Bundy, K., et al. 2015, ApJ, 798, 7 • Croom, S. M., et al. 2012, MNRAS, 421, 872 • Jin, S., et al. 2024, MNRAS, 530, 2688 • Loni, A., et al. 2023, MNRAS, 523, 1140 • Sánchez, S. F., et al. 2012, A&A, 538, A8 • Saintonge, A. & Catinella, B. 2022, ARA&A, 60, 319 • van Cappellen, W. A., et al. 2022, A&A, 658, A146 • York, D. G., et al. 2000, AJ, 120, 1579

[2] https://www.atnf.csiro.au/computing/software/miriad/userguide/node168.html

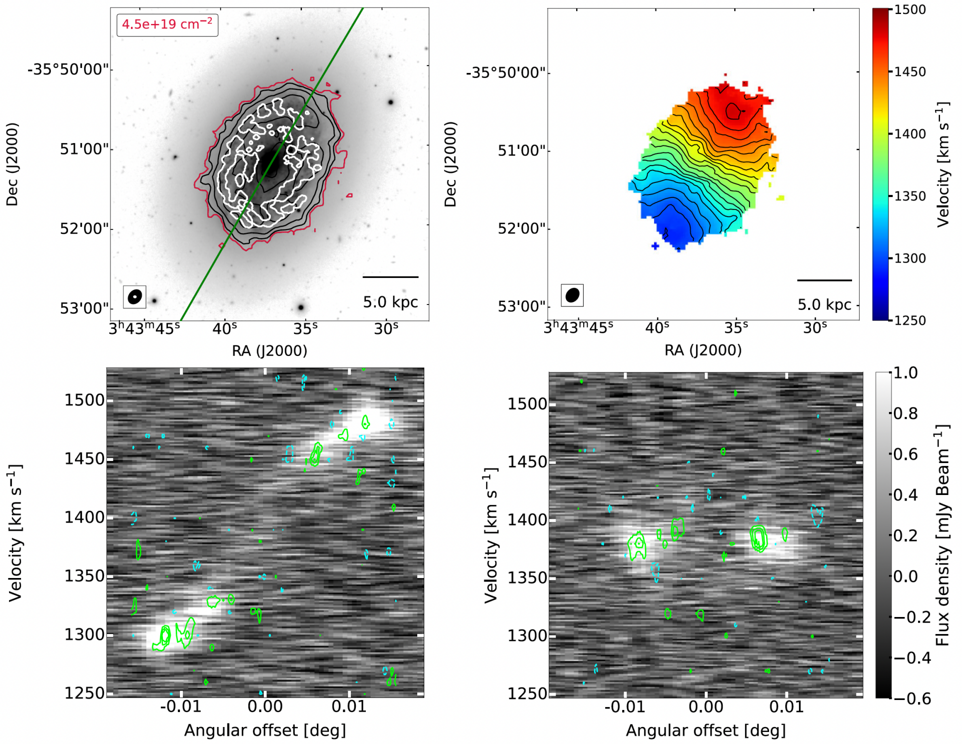

Figure 1: Example of NGC 1436, from Loni et al. 2023) that combines IFU (MUSE, not shown), HI (MeerKAT) and CO (ALMA) information. With this combined multiwavelength data they were able to track the evolutionary path of the Fornax Cluster galaxy NGC 1436, which is known to be currently transitioning from a spiral into a lenticular morphology. Top-left: the HI and CO distribution from the MeerKAT (red and black contours) and ALMA (white) data, with corresponding beam sizes shown in the lower-left corner of this panel (black and white, respectively). Top-right: CO velocity field. Bottom panels: PV diagram of HI (background) and CO (green contours at 2.5σ, increasing in steps of 2; cyan at -2.5 sigma) along the major and minor axes.

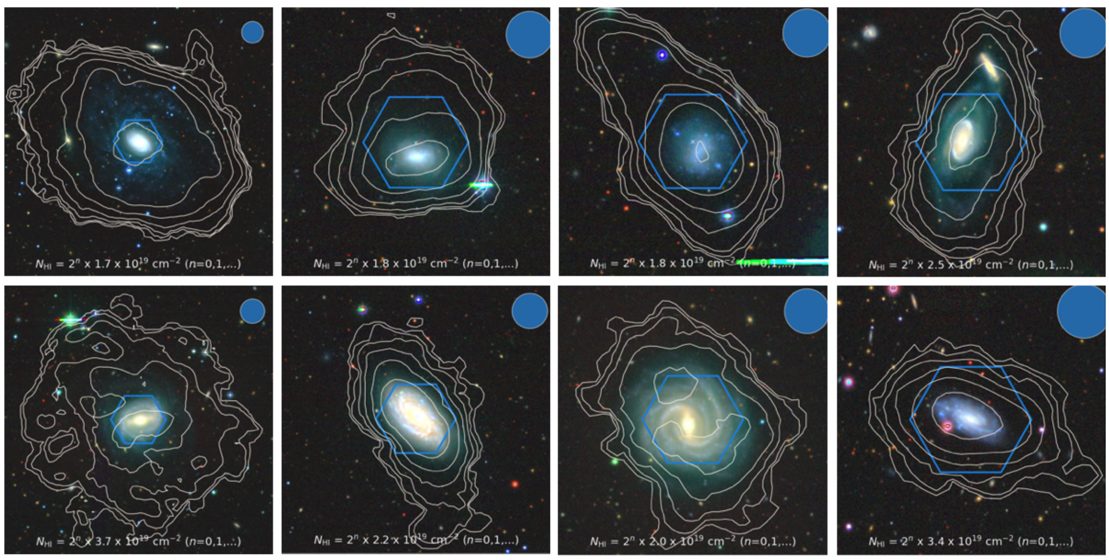

Figure 2: DeCALS color images of galaxies, already observed, in the WA sample. White contours represent HI column density from our *Apertif* data, with levels as indicated at the bottom of each panel. HI beam size is indicated on the top-right corner ($\sim$40 arcsec). Blue hexagon indicates the WEAVE/LIFU footprint (1.5$\times$1.3 arcmin). The figure illustrates some of the diversity of HI and optical properties in the existing sample (e.g. regular, lopsided, and disturbed distributions).

No PhD Students involved

Linked proposal submitted to this TAC: No

Linked proposal submitted to other TACs: No

Relevant previous Allocations: No

No additional remarks

Observing run info :

Applicants

Name	Affiliation	Email	Country		Potential observer
Dr Helga Denes	Yachay Tech University (School of Physical Sciences and Nanotechnology)	helgadenes@gmail.com	Ecuador		Yes
Prof Tom Oosterloo	Netherlands Institute for Radio Astronomy	oosterloo@astron.nl	Netherlands		Yes
Marc Verheijen	University of Groningen (Kapteyn Astronomical Institute)	verheyen@astro.rug.nl	Netherlands		

Targets

Source	RA	Dec	Epoch	Vlsr (km/s)	Duration (min)	Runs	Comments
WA-CO_17	13:00:16.13	+36:15:14.8	J2000	8394.0	378	B	
WA-CO_16	12:48:45.87	+35:19:57.7	J2000	3897.0	378	A	
WA-CO_33	15:33:27.86	+56:33:34.9	J2000	599.0	378	A	
WA-CO_28	14:22:46.69	+37:59:42.9	J2000	8094.0	378	B	
WA-CO_34	16:21:42.29	+55:05:09.7	J2000	5096.0	378	B	
WA-CO_18	13:06:05.87	+53:36:48.6	J2000	8994.0	378	B	
WA-CO_32	15:07:51.83	+54:45:10.0	J2000	2998.0	378	A	
WA-CO_35	16:34:14.95	+52:56:27.9	J2000	8694.0	378	B	
WA-CO_09	12:11:33.46	+57:44:14.9	J2000	4796.0	378	B	
WA-CO_11	12:20:47.53	+58:05:33.0	J2000	2998.0	378	A	
WA-CO_12	12:21:05.50	+61:05:14.2	J2000	5996.0	378	B	