Title

Extreme Ram-Pressure Stripping in the Virgo Cluster Dwarf IC 3476

Abstract

The dwarf galaxy IC 3476 in the nearby Virgo cluster is currently experiencing extreme ram pressure, leading to a strong deficit of neutral hydrogen and a spectacular multi-wavelength tail. We are likely observing the galaxy close to peak ram pressure and thus in a short-lived transitional phase from an actively star-forming to a quenched dwarf. This represents a unique opportunity to probe the impact of violent stripping on a dwarf galaxy. Here, we propose for 18.7 hours of observation time (including overhead) split across the S3-band (15h) and UHF-band (3.7h), completing the existing wide-band radio dataset of this galaxy. Due to the superb sensitivity of this data set, we will be able to probe for the presence of large-scale ordered magnetic fields in the stripped tail, as predicted by the magnetic draping scenario. Further, we will be able to meaningfully constrain the dynamics and timescales of the stripping event based on the detailed spectral modeling of the galaxy. We will also test for a polarized ridge at the leading edge, as it is expected in the case of ISM compression in the plane of the sky.

Scientific Category

Galaxy structure and evolution, Galaxy clusters

Observation Category	Proposal Type Category	Multi-year
Continuum (Including Image Plane Time Domain)	Regular	No

Team Details

Principal Investigator

Name	Email	Affiliation	Country	PhD
Henrik Edler	mail@henrikedler.eu	Netherlands Institute for Radio Astronomy	Netherlands	No

Technical Lead Same as PI
Experienced with MeerKAT data using the requested mode(s) Yes

Co-Investigators

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Observation Details

Observation type Imaging
Multiple simultaneous sub-array observation N/A

Band	Channelisation	Dump period	Center freq (MHz)	Hours for this cycle
S-band	4k	8 sec	S3: 2843.75	15
U-band	4k	8 sec	n/a	3.7

Time of day	Total hours	25% overheads assumed
No Preference	18.7	Yes

Target of opportunity N/A

Data Management Details

Total data size (TB) **4.6**
Main data reduction facility Own institution
Facility name University of Hamburg / ASTRON
Data transfer mode Via general internet
Will use SDP pipeline products No

Targets

Submitted targets (a maximum of 10 are listed below) 1 (15.0 hrs)

Name	R.A.	Dec.	Time on target (hh:mm:ss)
IC 3476	12:32:39.778	+14:03:05.48	15:00:00

Additional Information
Not supplied

Extreme Ram Pressure Stripping of the Virgo Cluster Dwarf Galaxy IC 3476

Abstract

The dwarf galaxy IC 3476 in the nearby Virgo cluster is currently experiencing extreme ram pressure stripping, leading to a strong deficit of neutral hydrogen and a spectacular multi-wavelength tail. We are likely observing the galaxy close to peak ram pressure and thus in a short-lived transitional phase from an actively star-forming to a quenched dwarf. This represents a unique opportunity to probe the impact of violent stripping on a dwarf galaxy. Here, we propose for 18.7 hours of observation time (including overhead) split across the S3-band (15h) and UHF-band (3.7h), completing the existing wide-band radio dataset of this galaxy. Due to the superb sensitivity of this data set, we will be able to probe for the presence of large-scale ordered magnetic fields in the stripped tail, as predicted by the magnetic draping scenario. Further, we will be able to meaningfully constrain the dynamics and timescales of the stripping event based on the detailed spectral modeling of the galaxy. We will also test for a polarized ridge at the leading edge, as it is expected in the case of ISM compression in the plane of the sky.

1 Scientific Justification

Introduction. The evolution of galaxies is tightly linked to their environment. In groups or clusters, environmental perturbations such as tidal interactions or ram pressure stripping (RPS) can quench (or temporarily enhance) star-forming activity by displacing and/or consuming the interstellar medium (ISM) of galaxies, thereby explaining the observed differences between cluster and field galaxies in H I content [1] and star formation rate [2]. In low-redshift galaxy clusters, RPS is the dominant quenching mechanism [3]. This process describes the removal of the ISM of a galaxy due to the hydrodynamic drag forces while moving at high velocity with respect to the intracluster-medium (ICM). Dwarf galaxies, the most common type of galaxy in the Universe and especially so in clusters, are particularly prone to being stripped because of their shallow gravitational potential wells, from which the ISM is easily removed. However, RPS events of dwarf galaxies are challenging to observe, meaning that our understanding of the process for this class of objects is limited. So should the stripping conditions, i.e. the galaxy velocity and the cluster-centric distance at which stripping occurs, be different for dwarfs compared to massive spirals. Furthermore, the lower gravitational restoring forces could translate to more violent stripping on shorter time scales.

The cluster environment also has an characteristic effect on the galaxy magnetic fields. Compression of the ISM can amplify and order the magnetic field structures on the leading edge [4]. In the tail, the magnetic field could either originate from the stripped ISM or from the draping of the $\sim\mu$G ICM magnetic field [5]. In the latter scenario, it should be highly parallely ordered. The tail magnetic field can prevent mixing of the stripped ISM and the ICM and thereby create the conditions for extra-planar star formation [e.g. 6]. Understanding the origin and nature of the tail magnetic fields can thus help to understand why a fraction of stripped galaxies show star formation in the tail.

As the closest massive cluster, the Virgo cluster is among the best suited targets to understand how the cluster environment affects dwarf galaxies. The availability of deep blind surveys in Virgo, such as VESTIGE in the Hα [7] or ViCTORIA in the radio continuum and H I [8, 9], is hereby critical to extend studies towards the low-mass end of the galaxy mass function. The outstanding multi-frequency data set available for the Virgo cluster galaxies [e.g. 7, 10] is necessary to understand the effect of the environment across different scales and gas phases.

Target selection. IC 3476 is a dwarf galaxy ($M_\star = 10^9\,\mathrm{M_\odot}$) at a projected distance of 0.5 Mpc from the center of the Virgo cluster. It is an excellent example for a lower-mass object that is currently being rapidly transformed from an actively star-forming into a dwarf elliptical or lenticular galaxy by RPS. It shows a prominent tail in the ionized gas [11], but is also among the few dwarfs with an extended radio continuum tail in local clusters (see [8] and Fig. 1 a)). This makes it a perfect target for a detailed multi-frequency radio continuum analysis.

While the massive late-type galaxies in Virgo were subject to dedicated multi-frequency fully polarimetric radio campaigns [e.g. 4, 12, 13], such observations are lacking for dwarf galaxies. The data proposed for here will fill this gap.

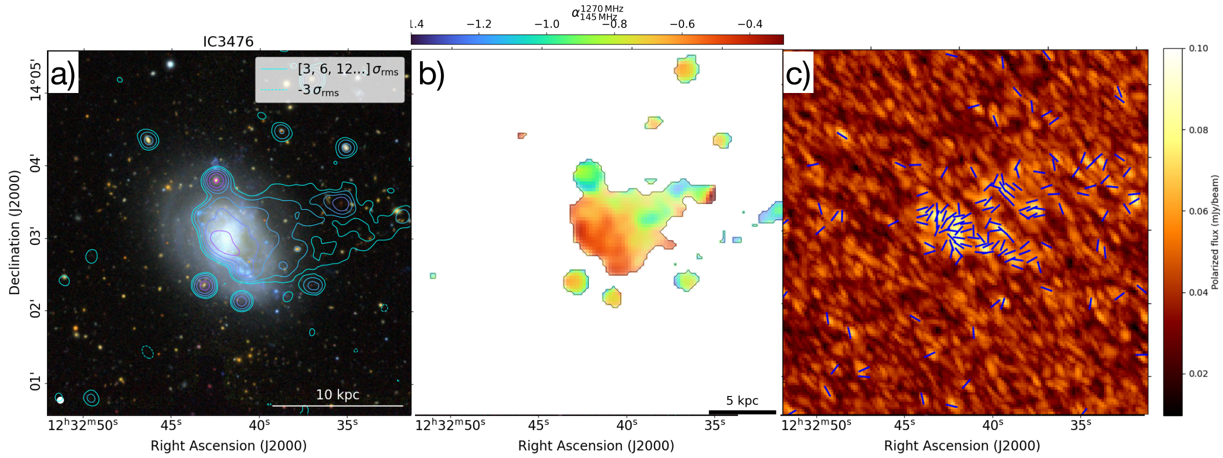

Figure 1: **a)** MeerKAT 1.3 GHz contours of IC 3476 at 10″ (0.8 kpc) resolution, starting at 3σ where $\sigma = 14\,\mu$Jy/beam, on top of the Legacy optical image. **b)** Spectral index between 144 MHz [8] and 1.3 GHz. **c)** Polarized intensity (40 min of MeerKAT L-band). Blue vectors show the B-field orientation.

Analysis. With the observations proposed here, we will address the following questions:

- On what time scales and under which conditions are dwarf galaxies stripped?
- What is the structure and origin of the tail magnetic field an what is its role in modulating extra-planar star formation?
- What is the impact of the environment on the non-thermal ISM in the disk?

These questions will be answered by the following means: We will estimate the age of the stripped plasma and derive the velocity of the galaxy from a wide-band spectral aging analysis. With highly sensitive polarization data, we will be able to probe if the tail magnetic field has a high degree of polarization parallel to the tail, allowing us to understand if it is generated by the draping mechanism. In that case, a mostly orthogonal orientation of the ICM magnetic field with respect to galaxy velocity would correspond to a greater tail magnetic field, shielding the stripped ISM and possibly enabling star formation [14]. We will further confirm or disprove the existence of a compressed magnetic field on the leading edge using the polarization data. Furthermore, the increased ISM density due to compression may lead to strong ionization losses, turning over the spectrum towards low-frequencies. The solid characterization of the spectrum obtained by the proposed observations will allow us to test this by correlating the spectral shape with the H I surface density [15].

For this proposal, we carried out a preliminary analysis of the existing 40 min L-band observation covering the target. As displayed in Fig. 1, already in this data, the spectral aging gradient and the polarized tail are partly visible, although at low significance and at a frequency affected by depolarization effects. The addition of the requested UHF- and S-band observations to the existing radio data is necessary to achieve our goals by facilitating the detailed spectral aging analysis, for which a good frequency-sampling of the resolved spectral curvature is required and by yielding considerably higher sensitivity to polarized emission at a frequency less affected by depolarization. Tuned simulations for IC 3476 exist, and are currently being extended by radio continuum emission [11, priv. comm.]. Our deep radio maps will also be used for comparison to those simulations.

In the following, we will briefly summarize the planned analysis: We will calibrate the data in full polarization using standard MeerKAT strategies. In the case of artifacts from the nearby bright source Virgo A at d=1.7°, we will employ the peeling strategy of Spasic et al. [16]. To subtract the thermal emission, which may reach >10% at S-band, we will use extinction-corrected Hα maps available from the MUSE observations in Boselli et al. [11]. The ionospheric Faraday rotation measure (RM) will be removed using satellite-based models [17]. We will then carry out RM synthesis [18] on the MeerKAT UHF- and S-band observations of this proposal combined with the existing radio data. For this, we will create combined frequency-band Q, U-cubes to obtain the

Faraday dispersion Function, which we will correct for Galactic foregrounds [19] and then deconvolve, yielding the polarized data products.

For the spectral aging analysis of the stripped tail, we will follow Ignesti et al. [20], Roberts et al. [21, 22]. Using the data from 50 MHz to 3 GHz, we will fit the spectrum in regions along the tail with the standard cosmic ray-aging model of Jaffe & Perola [23]. This yields break frequencies $\nu_{\rm break}$ that depend on the magnetic field strength B and age t. Thus, assumptions or estimates on B (such as the minimum aging or equipartition magnetic field) allow us to infer the radiative age and thus the projected velocity. Combined with the line-of-sight velocity of $\approx$1100 km s^{-1} [11] we obtain the three-dimensional velocity, a fundamental parameter for the ram pressure.

Secondary science. Targeting the rich Virgo cluster field, several objects of interest would also be covered by our observations by the large field-of-view of the UHF-band system. Most strikingly, the giant spiral M 88 at a distance of 0.4 deg is also currently being affected by RPS, giving rise to a prominent polarized ridge [24].

Existing data/other telescopes. IC 3476 is covered by the ViCTORIA survey [8, 25] using LOFAR and MeerKAT (40 min L-band, Fig. 1) at frequencies from 54 MHz to 1.6 GHz. In the Hα line, it is covered by VESTIGE [7] and MUSE [11]. This data is required for the thermal correction. Information on the molecular gas content traced by the CO(2-1) line is available due to data taken with ALMA-ACA. The data we request in this proposal will complete the existing multi-wavelength data set, facilitating a detailed analysis of the radio continuum emission. MeerKAT is the most suited instrument to carry out these observations. The JVLA does not offer the UHF-frequency band. While the uGMRT Band 4 offers a suited frequency coverage, the inferior *uv*-coverage is likely an issue for high dynamic range imaging close to Virgo A, a further issue being the strong instrumental leakage.

2 Technical Justification

Sensitivity. The driving factor for the proposed on-source time in the S-band is the search for polarized emission in the faint tail of the galaxy. At 1.3 GHz, the distant parts of the stripped tail have a surface brightness $B_{1.3}{\geq}100\,\mu$Jy/beam at 15″ resolution with a spectral index of $\alpha{\approx}-1$. This corresponds to $B_{2.8}{=}46\,\mu$Jy/beam in the S3-band. The clearest current detection of polarized emission in a stripped tail shows a polarization fraction $\geq 10\%$ [26]. To confirm or disprove polarized emission of this level above 4σ significance, we thus require a noise level in Stokes Q and U (where confusion is no concern) of at least 1.2 μJy/beam, achievable in 12 h in the S3 band (Briggs= 0.5). In the UHF-band, we are primarily driven by maximizing the sensitivity in total intensity to detect as much as possible from the stripped tail - within 3 h, we will reach 13.4 μJy/beam sensitivity at 10″ (Briggs= -1.0), which puts us in the confusion-dominated regime and guarantees a detection of all emission seen in the L-band and.

Observation mode. The requested UHF- and S-band data will allow us to tightly measure the spectral shape of the stripped tail, while the S-band data will also be critically important for the sensitive polarization analysis, avoiding depolarization effects present at lower frequencies. The S3-band was selected as a balance of increasing the frequency compared to the existing data, while ensuring a clean RFI environment and minimal off-axis leakage. The coordinates of the galaxy are suitable for usage of the standard polarization and bandpass calibrators (3C286 and J1939-6342). We will employ two visits of the polarization calibrator per observation, spread by at least 30 min, to ensure we have calibrator flux in both Q and U. We verified that the recommended overhead of 25% is sufficient for our observation using the standard calibrator setup (including the two visits of the polarization calibrator).

References • **1.** Catinella, B., et al. 2013, MNRAS, 436, 34 • **2.** Kennicutt, R. C., J. 1983, AJ, 88, 483 • **3.** Boselli, A., et al. 2022, A&ARev., 30, 3 • **4.** Vollmer, B., et al. 2007, A&AS, 464, L37 • **5.** Pfrommer, C. & Dursi, L. J. 2010, Nature Physics, 6, 520 • **6.** Lee, J., et al. 2025, arXiv e-prints, arXiv:2507.03127 • **7.** Boselli, A., et al. 2018, A&A, 614, A56 • **8.** Edler, H. W., et al. 2023, A&A, 676, A24 • **9.** de Gasperin, F., et al. 2025, A&A, 693, A189 • **10.** Brown, T., et al. 2021, ApJS, 257, 21 • **11.** Boselli, A., et al. 2021, A&A, 646, 139 • **12.** Vollmer, B., et al. 2012, A&A, 543, A33 • **13.** Vollmer, B., et al. 2013, A&A, 553, A116 • **14.** Müller, A., et al. 2021, Galaxies, 9, 116 • **15.** Gajović, L., et al. 2024, A&A, 689, A68 • **16.** Spasic, A., et al. 2024, arXiv e-prints, arXiv:2406.00781 • **17.** Mevius, M. 2018, RMextract: Ionospheric Faraday Rotation calculator, Astrophysics Source Code Library, record ascl:1806.024 • **18.** Brentjens, M. A. & de Bruyn, A. G. 2005, A&A, 441, 1217 • **19.** Hutschenreuter, S., et al. 2022, A&A, 657, A43 • **20.** Ignesti, A., et al. 2023, A&A, 675, A118 • **21.** Roberts, I. D., et al. 2024, arXiv e-prints, arXiv:2406.09221 • **22.** Roberts, I. D., et al. 2024, A&A, 683, A11 • **23.** Jaffe, W. J. & Perola, G. C. 1973, Dynamical Models of Tailed Radio Sources in Clusters of Galaxies, Tech. rep. • **24.** Vollmer, B., et al. 2008, A&A, 483, 89 • **25.** de Gasperin, F., et al. 2025, A&A, 693, A189 • **26.** Müller, A., et al. 2021, Nature Astronomy, 5, 159

Data Analysis and Management Plan

Data Analysis

The data will be analysed using standard radio-interferometric strategies. For calibration, we will employ the CARACal pipeline[1]. With this framework, will first derive the solutions for the band-pass calibrators (J0408-6545 and J1939-6342, the latter is also used for leakage calibration), the gain calibrator (J1150-0023 or J1347+1217) and polarization calibrator (3C286) and apply them to the target field data. This will also set the absolute flux density scale and polarization angle. For the fully polarimetric calibration of MeerKAT S-Band data, we will manually set the proper calibrator models in CaraCAL and swap the X and Y feeds, both of which are necessary but not yet automated for the S-band in CARACal. If sidelobes from the extremely bright source Virgo A / M 87 are an issue, we will follow the peeling approach described in Spasic et al. [1] to remove the sidelobes of the bright source M 87 ($d \approx 1.7°$). High-quality models of M 87 in both the UHF and S-band are available to our group for this. If the ionospheric activity causes noticeable direction-dependent systematic effects in the UHF band, we will correct for those using direction-dependent calibration. In general, we will perform imaging with WSClean [2, 3] and, if applying direction-dependent calibration, DDFacet [4]. For calibration, we will rely on CASA [5] and Cubical[2].

To remove the time-variable RM contributed by the Earth's ionosphere, we will use the model implemented in RMextract [3]. Astrophysical Faraday rotation will be extracted using the RM synthesis technique [6] as implemented in the code pyrmsynth[4]. Our final data products will be made publicly available via the CDS, as we did in previous related publications [1, 7].

Team

Our team consists of researchers with diverse expertise that will allow us to carry out the calibration of the data as well as the scientific analysis in a timely manner. PI Edler has expertise in the calibration and imaging of radio interferometric data, including MeerKAT data of the Virgo cluster as well as spectral aging modeling for star-forming galaxies. Co-I Spasic is leading the polarization calibration of the ViCTORIA survey. Co-I de Gasperin is an expert in radio interferometric techniques, including polarization studies, with MeerKAT in the L-, UHF- and S-bands. He is furthermore the PI of the MeerKAT Virgo Cluster Survey (MKT-22008; MKT-23067). Co-I Heesen is an expert for radio continuum studies of nearby star-forming galaxies. Co-I Boselli is a domain expert and lead the detailed MUSE study on IC 3476, also including simulations [8]. Co-Is Zabel, Serra and Fossati they are leading experts in studying environmental effects in nearby galaxy clusters.

Hardware

The raw data of the observation (18.7 h including overhead) will be a modest 4.6 TB. Our team has unrestricted access to compute clusters which are suited for the data reduction and -analysis. At Hamburg Observatory, we have access to ten compute nodes with 20 TB of storage and 64 CPU cores each. We further have access to the "Pleiadi" computing cluster (72 nodes, 2592 cores) at IRA Bologna and to the compute cluster at ASTRON. All of these machines have the required software packages available (CARACal, Cubical, WSClean, etc.) and are already used for the processing of MeerKAT data.

References • **1.** Spasic, A., et al. 2024, arXiv e-prints, arXiv:2406.00781 • **2.** Offringa, A. R., et al. 2014, MNRAS, 444, 606 • **3.** Offringa, A. R. & Smirnov, O. 2017, MNRAS, 471, 301 • **4.** Tasse, C., et al. 2018, A&A, 611, 87 • **5.** CASA Team, et al. 2022, , 134, 114501 • **6.** Brentjens, M. A. & de Bruyn, A. G. 2005, A&A, 441, 1217 • **7.** Edler, H. W., et al. 2023, A&A, 676, A24 • **8.** Boselli, A., et al. 2021, A&A, 646, 139

[1] `https://caracal.readthedocs.io/en/latest/`
[2] `https://cubical.readthedocs.io/`
[3] `https://github.com/lofar-astron/RMextract`
[4] `https://github.com/mrbell/pyrmsynth`

Feasibility Report

Summary
No feasibility issues

Technical Report
N/A

Data Management
N/A

Status of Previous Projects
N/A

Comments to PI (updated)

PANEL REPORT:

SUMMARY: This is a nice example of a continuum ram-pressure tail in a dwarf galaxy in the Virgo cluster. The proposed observations extend the frequency coverage of the observations and will attempt polarimetry in an effort to study aging, velocities and magnetic field configuration. The broader implications for ram pressure stripping and galaxy evolution could have been clearer. There may be some challenges dealing with the strong emission from the nearby source Virgo A.

STRENGTHS: Ram pressure stripping is an important process for ISM removal and quenching of star formation in and around galaxy clusters. The proposed target already has good evidence for the presence of a ram pressure tail which is visible in continuum emission. Continuum tails in dwarf galaxies are not common and may imply a high infall velocity and strong magnetic fields.

WEAKNESSES: This is an observation of substantial length. But being of a single galaxy, it's not obvious how important the implications will be for our understanding of ram pressure stripping in general, or even for similar dwarf galaxies. The presence of the powerful nearby Virgo A source may limit the ability to achieve the required thermal noise.

Comments to SARAO

Not supplied