# OmegaWINGS: A VST Survey of Nearby Galaxy Clusters

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**OmegaWINGS is a photometric and spectroscopic survey of 46 nearby galaxy clusters. The photometric part is based on OmegaCAM imaging with the VLT Survey Telescope; the field of view of one square degree covers the whole virial region, extending up to the infall regions of each OmegaWINGS cluster. The ongoing spectroscopic survey will provide about 30 000 spectra with AAOmega on the Australian Astronomical Telescope. OmegaWINGS will provide an extremely detailed and complete view of galaxy populations in clusters. The final data products will include, for each galaxy detected in the target clusters, aperture and surface photometry, morphological type and a reliable characterisation of the stellar populations. The survey will therefore be a unique tool to study the formation and evolution of galaxies in clusters and the interactions of galaxies with the environment.**

The OmegaWINGS programme builds on the WIde-field Nearby Galaxy-cluster Survey (WINGS; Fasano et al., 2006) to carry out a photometric and spectroscopic campaign of nearby galaxy clusters ($0.04 < z < 0.07$). The WINGS survey is based on *B*- and *V*-band imaging for 76 clusters over a field of view of about 30 by 30 arcminutes carried out with the Wide Field Imager (WFI) on the MPG/ESO 2.2-metre telescope and the Wide Field Camera (WFC) on the Isaac Newton Telescope (INT). With the aim of covering the virial region and extending out into the infall region, we have obtained OmegaCAM Guaranteed Time Observations (GTO) imaging in the *u*-, *B*- and *V*-bands over 1 by 1 degree for 45 fields covering 46 WINGS clusters. The *u*-band campaign is ongoing, while the *B*- and *V*-band observations have been completed. With a median seeing of 1 arcsecond in both *B*- and *V*-bands, our 25-minute exposures in each band typically reach the 50 % completeness level at $V = 23.1$ mag. Photometric catalogues are publicly available at the Centre de Données astronomiques de Strasbourg (CDS), and they will be included in the next release of the WINGS database at the Virtual Observatory, together with the OmegaCAM reduced images.

Galaxy clusters, the most massive collapsed structures in the Universe, play an important role for both cosmology and galaxy evolution studies. They are the tail of a continuum distribution of halo masses, and the most extreme environments where galaxy formation has proceeded at an accelerated rate compared to the rest of the Universe. Clusters have been a testbed for studies of galaxy formation and evolution, uncovering trends that several years later have also been found in the field. They are a repository for galaxies that have been shaped in lower halo-mass environments, but are also the sites where essentially all environmental effects are thought to take place, from strangulation to ram-pressure stripping, and even galaxy merging. As peaks in the matter distribution, galaxy clusters host those galaxies that have formed first and in the most extreme primordial conditions. At the same time they are the sites where hierarchical growth is most evident, as in the case of the brightest cluster galaxies. There is no better place than rich clusters in the low-*z* Universe to find and study the descendants of the most massive galaxies observed at high-*z*.

## The WINGS survey

The WINGS cluster survey sample consists of all clusters at redshift $0.04 < z < 0.07$ in both hemispheres at Galactic latitude $|b| > 20$ degrees selected from the ROSAT X-ray-Brightest Abell-type Cluster Sample, the Brightest Cluster Sample and its extension (Ebeling et al. [2000] and refs therein). For a subset of clusters, the original WINGS imaging in the *B*- and *V*-bands have been complemented with *J*- and *K*-band photometry obtained with the Wide Field Camera (WFCam) on the United Kingdom Infra-Red Telescope (UKIRT) and *u*-band photometry obtained with the INT, the Large Binocular Telescope and Bok telescopes. More than 6500 spectra were taken with the two-degree field instrument (2dF) on the AAT and Wide Field Fibre Optical Spectrograph (WYFFOS) on the William Herschel Telescope (WHT), both multi-fibre spectrographs.

These data allowed us to obtain aperture and surface photometry, the stellar mass and star formation history of the cluster galaxies, as well as to characterise the cluster substructure and dynamics. With these data we have conducted a number of studies on galaxy properties and evolution (a full publication list can be found at the WINGS website[1]). The WINGS data and data products are publicly available through the Virtual Observatory, as explained in Moretti et al. (2014). The WINGS dataset is unique, for the quality and quantity of data on low-*z* clusters.

The main limitation of the original WINGS data is that they cover only the cluster cores: the maximum clustercentric distance reached in (almost) all clusters by the WINGS imaging is only 0.6 times the virial radius. Crucially, what is missing is the coverage out to at least the virial radius and into the outer regions. This is of primary importance, as it links clusters with the surrounding populations and with the field. The outer regions of clusters are the transition regions between the core and the filaments and/or groups feeding the cluster, at the point where galaxies are subject to a dramatic change of environment. Indeed, observations have proved that the cluster outskirts are essential to the understanding of galaxy transformations. With the exception of a few single clusters and superclusters, this very important transition region between clusters and the surrounding field remains largely unexplored.

## The OmegaWINGS survey

With the aim of covering the virial region and extending out into the infall region, we have obtained GTO OmegaCAM imaging in the *u*-, *B*- and *V*-bands over 1 by 1 degree for 45 fields covering 46 WINGS clusters. A large spectroscopic follow-up campaign targeting these clusters is ongoing with AAOmega on the AAT. We named this extension of the WINGS survey, OmegaWINGS.

OmegaWINGS targeted clusters were randomly selected from the 57 WINGS clusters that can be observed from the VST ($\delta < +20$ degrees). We obtained service mode *B*- and *V*-band imaging for 46 of them with 45 OmegaCAM pointings. The location of the target clusters observed by the OmegaWINGS survey is shown in Figure 1.

Observations started in October 2011, occurred through Periods 88, 89, 90, 91 and 93 and were concluded in September 2014. The total exposure time was 25 minutes for both *B*- and *V*-band observations. The seeing during the observations was lower than 1.3 and 1.2 arcseconds in 80 % of *B*- and *V*-band images, respectively, with a median value of 1.0 arcseconds in both *B*- and *V*-band images. Figure 2 shows the final OmegaCAM *V*-band image of A2399. The projected radius ($R_{200}$) of the cluster and the field of view (FoV) of WINGS imaging obtained with the Wide-field Imager are shown for comparison. A complete description of the *B*- and *V*- band photometric surveys is presented in Gullieuszik et al. (2015).

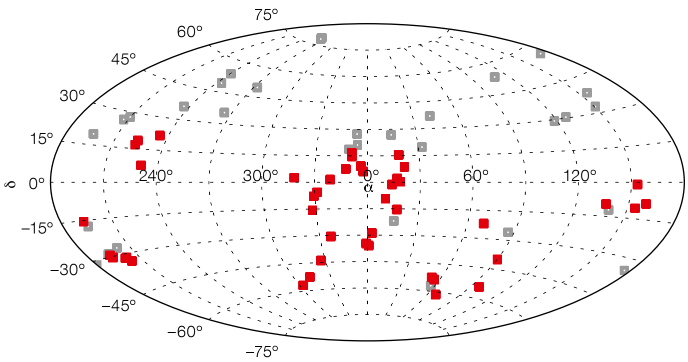


Figure 1. OmegaWINGS target clusters are shown as red squares; grey squares are all WINGS clusters.

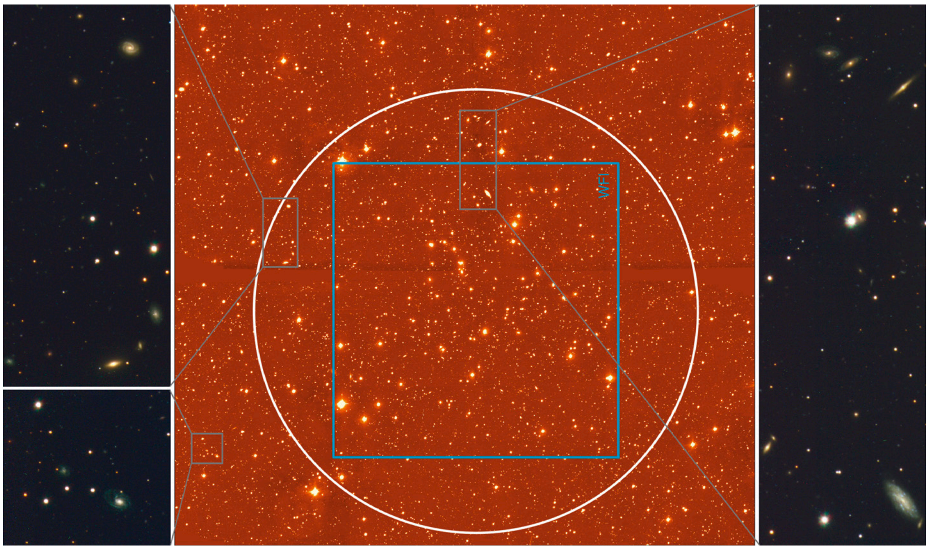


Figure 2. 1 by 1 degree *V*-band OmegaCAM image of cluster A2399. The FoV of WINGS imaging obtained with WFI is shown for comparison (grey square). The circle shows the radius (R200) of the cluster. The colour images zooming into three selected areas were obtained by combining OmegaWINGS *u*-, *B*- and *V*-band images.

## Data reduction

Image reduction and calibration are mainly based on the ESO/MVM (Multiresolution Vision Model) reduction package (also known as ALAMBIC). This is a multi-instrument reduction tool originally developed for the ESO Imaging Survey (EIS). It has been extensively used also in the production of ESO Advanced Data Products (see for instance the 30 Doradus/WFI Data Release or the GOODS/ISAAC Final Data Release). A detailed description of the package and the documentation of the algorithm structure implemented in ESO/MVM are given in Vandame et al. (2004). There are configuration files for many optical and near-infrared ESO instruments, but so far OmegaCAM is not officially supported. We therefore created a new configuration file for OmegaCAM, using the instrument description given in the VST user manual. We also developed a few modifications to the ALAMBIC pipeline in order to take into account OmegaCAM-specific issues, namely crosstalk correction, gain harmonisation and the control procedure that checks the quality of CCD #82 and masks it out should it not have worked properly during the observations (for details see Gullieuszik et al. [2015]).

OmegaCAM detectors suffer electronic crosstalk. The strongest effect, of the order of a few percent, is between CCDs #95 and #96, located in a corner of the camera mosaic. The crosstalk has been estimated by cross-correlating the signal registered on the same pixel in each pair of CCDs. The crosstalk on CCD #95 and #96 is 0.3 % and −0.8 %, respectively.

Our analysis confirms that the effect on the other detectors is negligible. After correcting all images for crosstalk we performed the standard pre-reduction of all science frames, using ALAMBIC algorithms to subtract the bias and apply flat-field corrections.

The electronic converters of each detector are different, and each CCD may have a different efficiency. Therefore, each detector has its own effective gain and, as a consequence, its own photometric zero-point. The chip-to-chip gain variation quoted in the OmegaCAM User Manual is of the order of 10 %, resulting in a chip-to-chip zero-point scatter of ~ 0.1 mag. We could not apply the standard procedures adopted by ALAMBIC to manage this problem, because of the central cross-shaped vignetting affecting OmegaCAM images taken with the segmented *B* and *V* Johnson filters. We therefore developed a variation of the original ALAMBIC procedure optimised for our specific OmegaCAM observations (see Gullieuszik et al. [2015] for details).

A well-known problem affecting wide-field cameras in particular is sky concentration, i.e., a stray-light component that is centrally concentrated. The net result is an erroneous apparent trend of the photometric zero point with the distance from the centre of the camera field of view. We corrected for this effect by deriving an illumination map from observations of a well-populated stellar field, namely Landolt SA107. The illumination map was used to correct all science frames and to obtain photometrically flat, reduced science stacks.

Astrometric calibration was performed for all frames using the 2 Micron All Sky Survey (2MASS) catalogue as reference, or the Sloan Digital Sky Survey (SDSS) Data Release 8, when available. The absolute accuracy — measured on the final stacked mosaic — is of the order of 0.2 and 0.07 arcseconds for calibrations based on 2MASS and SDSS, respectively.

## Photometric catalogues

The source extraction and measurement of photometric and structural parameters was performed using SExtractor and by using WINGS stars as photometric local standards. The classification of OmegaWINGS sources was done following the method and criteria used for the original WINGS survey. As a starting point, we classified objects on the basis of the SExtractor star/galaxy classification parameter. We then used a set of diagnostic plots, using different combinations of SExtractor parameters (e.g., magnitude, full width at half maximum, isophotal area, central surface brightness) to check the result and correct any misclassification. During the visual inspection of the diagnostic plots, we removed saturated stars from our catalogues. The complete OmegaWINGS photometric database is available at CDS.

The quality of OmegaWINGS results was tested against the WINGS ones. For each target cluster, we analysed the distribution of the differences of the coordinates and magnitudes between the two sets of catalogues. The mean values of all the distributions were found to be always negligible, proving that no relevant systematics affect OmegaWINGS photometry and astrometry. The dispersion of the distributions of sky-coordinate differences $\Delta\alpha$ and $\Delta\delta$ between OmegaWINGS and WINGS positions of all stars in each of the 46 OmegaWINGS clusters are shown in Figure 3; this provides the precision of the astrometric calibration which is shown to be accurate at a level always better than 0.25 arcseconds. The mean values of the distributions in Figure 3 are 0.1 arcseconds for both right ascension and declination, perfectly matching the precision required for the purposes of our scientific project. We note that the internal accuracy of WINGS astrometry is ~ 0.2 arcseconds (Fasano et al., 2006).

We detected no significant systematic differences between OmegaWINGS and WINGS photometry. This result proves

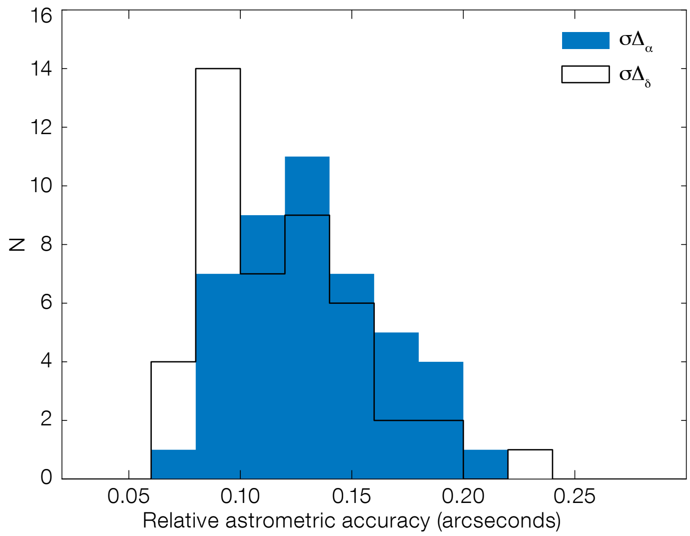


Figure 3. Dispersion of the distributions of sky-coordinate differences between OmegaWINGS and WINGS positions of all stars in each of the 46 OmegaWINGS fields. Only stars brighter than *V* = 20 were used for the comparison.

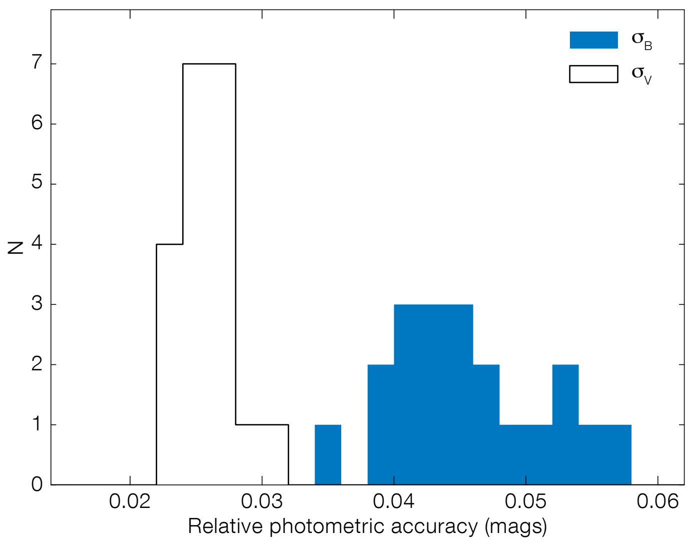


Figure 4. Relative photometric accuracy based on a comparison with SDSS Data Release 9. The histograms show the dispersion of the distributions of differences between OmegaWINGS and SDSS photometry.

the reliability of the gain harmonisation and illumination correction procedures. The relative accuracy of OmegaWINGS photometry across the OmegaCAM FoV was tested by comparing OmegaWINGS photometry with SDSS photometry (transformed onto the standard *BV* photometric system). For each of the 20 OmegaWINGS fields observed by SDSS, we calculated the dispersion of the differences between OmegaWINGS and (transformed) SDSS magnitudes for all stars with $B < 20$ mag and $V < 19$ mag. Results are shown in Figure 4. In the *V*-band the relative photometric accuracy is 0.03 mag for all clusters, while it ranges between 0.04 and 0.06 mag in the *B*-band.

The systematically higher dispersion in the *B*-band is due to non-linear colour terms in the transformations from SDSS *ugr* to *BV* photometric systems and/or a dependence of the transformations on star metallicity/colour. We also checked the spatial stability of OmegaWINGS calibration by analysing the magnitude difference between OmegaWINGS and (transformed) SDSS photometry as a function of the position on the mosaic. We found that the OmegaWINGS photometric zero point is constant within a few hundredths of a magnitude across the whole mosaic, confirming that there are no residual systematic effects, possibly due to the illumination correction and/or gain harmonisation issues.

The overall OmegaWINGS photometric completeness factor was estimated by comparing the magnitude distributions (MD) of all sources in the OmegaWINGS and WINGS catalogues. The photometric depth depends on the seeing conditions during observations, but OmegaWINGS photometry is in general 0.5–1.0 mag shallower than the WINGS one. However, when OmegaWINGS observations were carried out with seeing 1.0 arcseconds, OmegaWINGS is as deep as (and in some cases deeper than) WINGS. The overall photometric depth of OmegaWINGS was estimated by stacking together all 45 MDs. Figure 5 shows that OmegaWINGS MD peaks at $V \sim 22.5$ mag and WINGS at $V \sim 23.4$ mag.

The completeness of OmegaWINGS photometry can be estimated as the ratio of OmegaWINGS to WINGS MDs.

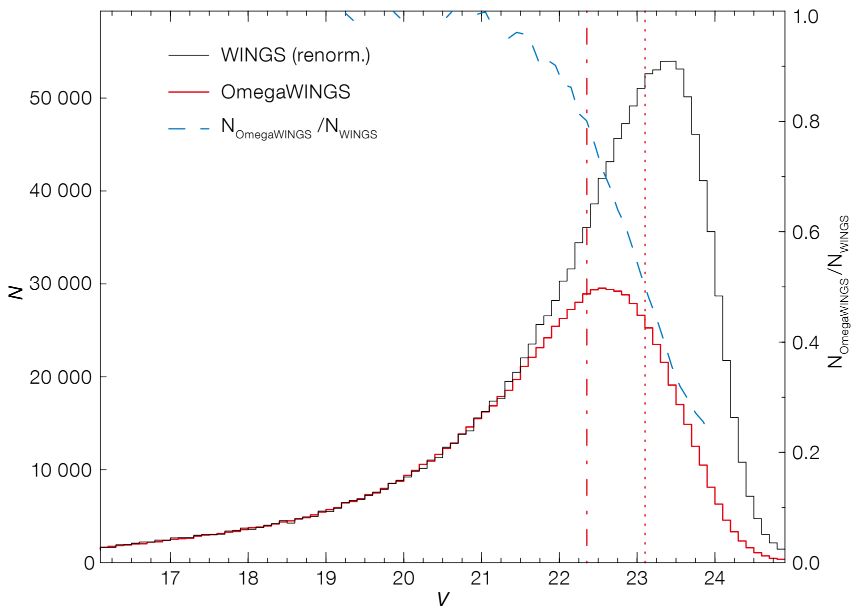


Figure 5. *V*-band magnitude distribution of all objects in the OmegaWINGS and WINGS database. The WINGS magnitude distribution was re-normalised to match the total number of OmegaWINGS sources with $16 < V < 21$ mag. The ratio of OmegaWINGS to WINGS distributions is shown as a dashed line; and the corresponding scale is shown on the right-hand axis. The vertical lines trace the magnitude corresponding to a ratio of 0.5 and 0.8 (50 % and 80 % completeness level), as dotted and dash-dotted lines respectively.

The 50 % completeness level is reached at $V = 23.1$ mag, the 80 % level at $V = 22.4$ mag (see Figure 5). This result is based on the assumption that WINGS photometry is complete at least up to $V \sim 23$ mag. We therefore performed a further test by fitting an exponential relation to the bright tail of the histogram in Figure 5. The completeness factor was obtained as the ratio of the observed MD to the best-fit exponential model. Following this approach, 50 % and 80 % completeness are found at $V = 23.3$ and 22.7 mag, respectively, confirming our results.

## OmegaWINGS spectroscopy

A large spectroscopic follow-up campaign targeting OmegaWINGS clusters is ongoing with AAOmega on the AAT. We plan to obtain spectroscopy for ~ 30 000 galaxies over the 1 square degree OmegaCAM fields. Our primary targets are galaxies in cluster regions outside the cores where the contrast between cluster members and interloper density is lower and the measure of spectroscopic redshift is crucial to disentangle the cluster population.

From the OmegaWINGS data (OmegaCAM photometry and AAOmega spectroscopy), we will study all the main galaxy properties (morphological and structural parameters, colours and colour gradients within galaxies, star formation rates, history and stellar masses) in relation to their environment. The wide area covered by our survey will allow us to characterise the environment by both global conditions (such as cluster mass, X-ray luminosity and merger history) and local conditions (e.g., clustercentric distance, local density, substructures within clusters and structures surrounding clusters).

So far, we have secured high quality spectra for ~ 30 OmegaWINGS clusters, reaching very high spectroscopic completeness levels for galaxies brighter than $V = 20$ mag from the cluster cores to their periphery. Observations are still ongoing and we plan to complete the spectroscopic survey in a few semesters.

## Ongoing scientific activity

The OmegaWINGS photometric catalogues (available at CDS) are presented in

Gullieuszik et al. (2015), together with a detailed description of the survey and the data reduction procedures summarised here. The OmegaWINGS team is currently working to extend all the analyses that were developed for WINGS data to OmegaWINGS (out to the virial radius and beyond). In particular, for each galaxy we will measure the local density, the morphological type (MORPHOT: automatic Galaxy Photometry; Fasano et al., 2015), the surface photometry parameters (GASPHOT: Galaxy Automatic Surface Photometry; D'Onofrio et al., 2014), redshift, star formation history and stellar mass (Fritz et al., 2014). A number of papers are in preparation to present and release these OmegaWINGS advanced data products. We will also release an updated version of the complete WINGS database through the virtual observatory interface, including OmegaCAM images (see Moretti et al. [2014] for a description of the WINGS database).

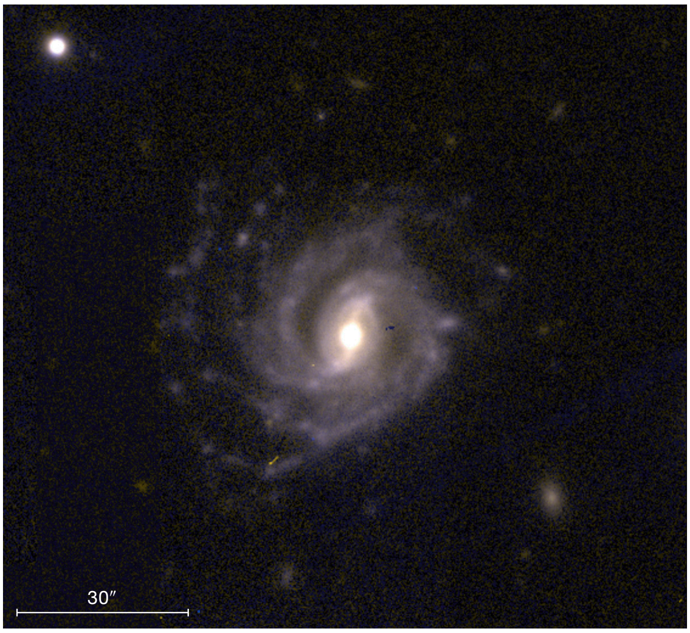


Figure 6. 2 by 2 arcminute OmegaWINGS colour image of a jellyfish galaxy (Poggianti et al., 2015) in the cluster A2589.

The wide area covered by OmegaWINGS observations allows coverage of the entire cluster extension and moreover strongly enhances the possibility of detecting and studying a statistically significant number of exotic objects. As an example, the OmegaWINGS survey has been used to carry out the the first systematic search for galaxies undergoing gas stripping and, in particular, jellyfish galaxies (Poggianti et al., 2015). These are galaxies that exhibit tentacles of debris material suggestive of gas removal mechanisms, such as ram-pressure stripping (an example is shown in Figure 6). As such, they can be used to assess the relevance of gas removal processes from galaxies, to study how, where and why gas stripping occurs, and to investigate the consequences of this phenomenon on the galaxy star formation history and on the build-up of the intra-cluster/intra-group medium.

WINGS imaging was also used to cover clusters in the northern hemisphere, while the Padova–Millennium Galaxy and Group Catalogue (PM2GC; Calvi et al., 2011), based on the Millennium Galaxy Catalogue (Liske et al., 2003) was used to study jellyfish galaxies in low density environments. The jellyfish catalogue presented in Poggianti et al. (2015) consists of almost 400 candidates in ~ 70 galaxy clusters of the OmegaWINGS + WINGS sample, and about 100 candidates in groups and lower-mass structures in the PM2GC sample, all at redshift between 0.04 and 0.07. This is the largest sample of stripping candidates known to date.

While all jellyfish galaxies previously known from the literature are in clusters, we also found striking jellyfish candidates outside clusters, in groups and lower-mass haloes of the PM2GC sample, with masses between $10^{11}$ and $10^{14}$ $M_{\odot}$. These results deserve further investigation in order to fully understand the role and the cause of gas stripping in groups, its impact on galaxy evolution in general and on the global quenching of star formation. Our sample comprises stripping candidates of all stellar masses, from $10^{9}$ $M_{\odot}$ to $10^{11.5}$ $M_{\odot}$, indicating that whatever causes the jellyfish phenomenon can affect galaxies of any mass.

To reveal the physical process responsible for gas removal in these galaxies, integral field spectroscopy (IFS) observations are required. These observations would in fact provide a measurement of the stripping timescale and the star formation rate in the stripped gas, unambiguously identifying the physical process responsible for the gas outflow and enabling directly the study of the effects on the evolution of the galaxy. Integral field spectroscopy with the Multi Unit Spectroscopic Explorer (MUSE) on the VLT was obtained for two of our OmegaCAM jellyfish galaxies. These data spectacularly reveal the emission lines (Hβ, [O III], [N II], Hα and [S II]) associated with the ionised gas in the trails, out to several tens of kiloparsecs from the galaxy (Jaffé et al., in prep.). A larger IFS study on a statistically significant subsample of our jellyfish galaxies would unveil the rich physics and implications of the stripping phenomenon in galaxies as a function of galaxy environment and galaxy mass.

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## Links

[1] WINGS website: https://sites.google.com/site/wingsomegawings