SF2A 2019
P. Di Matteo, O. Creevey, A. Crida, G. Kordopatis, J. Malzac, J.-B. Marquette, M. N'Diaye, O. Venot (eds)

PROBING THE Hα, HI AND FIR EMISSION IN LOW SURFACE BRIGHTNESS TAILS OF VIRGO GALAXIES AND THEIR CONNECTION WITH THE VIRGO INTRA-CLUSTER COMPONENT

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Abstract. Understanding the formation and evolution of structures remains a primary goal of modern astrophysics. Both observations and simulations point to a scenario in which structure formation follows hierarchical laws where galaxies and clusters grow by mergers and accretion of smaller subsystems. No model for structure evolution, however, can be complete without a detailed understanding of the physical mechanisms that take place. Hence, it is only through the detailed study of the local volume that we can hope to understand the role of the interactions in the hierarchical assembly of baryonic substructures. In this work we carry out a multi-wavelength mapping of the intra-cluster component, a direct product of the interactions within a cluster. The focus of this project is on the nearby Virgo cluster, for which we have unique multi-frequency data in terms of extension, sensitivity and resolution, allowing us to study galaxies that show low surface brightness tails of stripped material with ionised gas emission (Hα) that also present HI (neutral) and FIR (dust -HeViCS data-) emission.

Keywords: galaxies: clusters: individual (Virgo cluster) - galaxies: cluster: intracluster medium - galaxies: evolution

1 Introduction

In galaxy clusters a fraction of the baryonic content is represented by the intra-cluster component (ICC), i.e. a fraction of matter that is gravitationally bound to the cluster potential. Galaxy interactions, as well as tidal interactions between galaxies and the cluster potential, are believed to play an important role in the production of the ICC (Willman et al. 2004; C. S. Rudick et al. 2006), even though a portion of it may come from in-situ star formation (Puchwein et al. 2010), wherein stars form in cold gas clouds stripped from infalling substructures. In a complex environment, such as galaxy clusters, it is plausible that all these processes are involved in the building up of the ICC and that different paths of formation are followed depending upon the dynamical evolution of the system. While the ICC is an important component to study and its existence is well established, historically it has proved difficult to analyse, due to its low surface brightness. A clear census on the fraction of matter that form the ICC has not been reached yet, and no uniform information as yet been gathered on its properties across the electromagnetic spectrum. IC stars are studied through their optical properties (e.g., Mihos et al. 2017), and near infra-red (NIR) analyses of optically identified IC features show that these have NIR emission (Krick et al. 2011). Finally, the hot IC plasma, or ICM, is studied through X-ray data (e.g., Nulsen & Bohringer 1995; Simionescu et al. 2017). However, little is known about its properties in the form of gas, and the diffuse IC dust has long been tried to be detected (e.g., Muller et al. 2008), but the results are still controversial and inconclusive. In this work we look for the on-going build up of the Virgo cluster ICC studying the tails of stripped gas and dust through state-of-art observations.

2 The Virgo cluster: a unique laboratory for astrophysics

At a distance of 16.5 Mpc (Mei et al. 2007), the Virgo cluster is the dominant mass concentration in the local universe and the largest concentration of galaxies within ∼35 Mpc. Characterised by both spatial and kinematic

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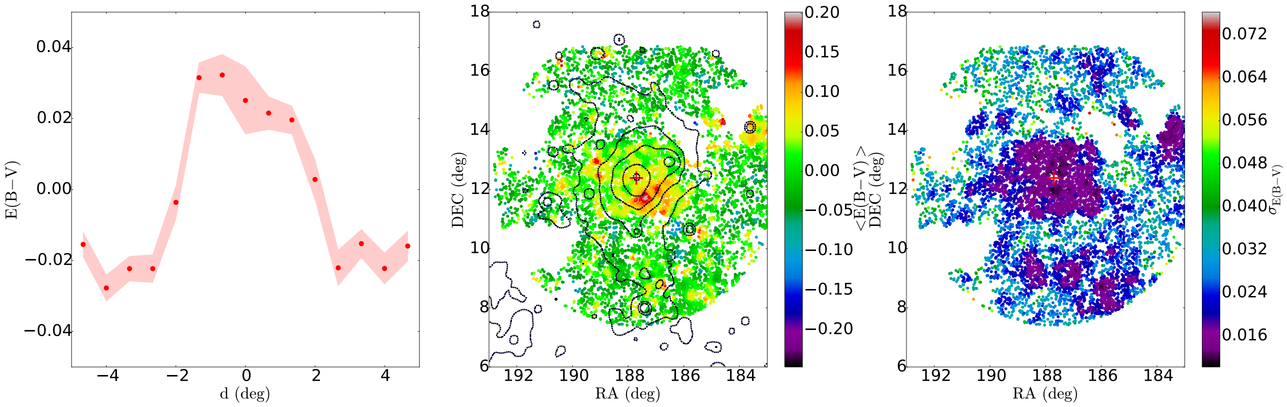

Fig. 1. Left Panel: Radial profile of the E(B-V) extinction of the Virgo IC dust component (filled dots) and its uncertainty (shaded area) from the centre of the cluster out to 5 degrees (1440 kpc); Positive and negative distances trace the northern and southern halves with respect to the cluster's centre. The radial distribution shows a centrally concentrated profiles on both sides of the galaxy. **Central Panel:** Spatial distribution of the SDSS background galaxies colour-coded according to the smoothed means of the E(B-V) values. Black contours trace the cluster X-ray emission as traced by the ROSAT All-Sky survey in the hard band. **Right Panel:** Errors on the smooth extinction map computed by means of Monte Carlo simulations. Closer to the centre of the cluster E(B-V) values are statistically significant, and higher than what is measured going outwards. The peak measured south-west of M87 traces the presence of a background clustered galaxies characterised by redder colours.

substructures, with different subgroups possessing different morphological mixes of galaxies (Binggeli et al. 1987), Virgo has historically played a key role in studies of how galaxies form and evolve in dense environments. The physical properties of late-type galaxies vary dramatically from the periphery (where galaxies are unperturbed in terms of gas content and star formation activity) to the cluster core (dominated by systems deprived of their gas reservoir and with a significantly reduced star formation activity (Boselli et al. 2014)), and a wealth of observational evidence consistently indicates that Virgo is a young cluster still in formation (e.g., Mihos et al. 2005; Conselice et al. 2001). Virgo can thus be considered a local analogue of the over-dense regions in the high-redshift universe, and an ideal laboratory for studying the perturbing mechanisms that shaped galaxy evolution. The information astronomers have gathered on the Virgo system is unique, with an extended collection of multi-frequency data that survey this system at good/optimal resolution and sensitivity. Dedicated surveys made it possible to gather X-ray (ROSAT; Nulsen & Bohringer 1995), UV (the GALEX Ultraviolet Virgo Cluster Survey, GUViCS; Boselli et al. 2011), and deep broad-band optical (NGVS; Ferrarese et al. 2012, BSDVCS; Mihos et al. (2017)) and narrow-band Hα (VESTIGE; Boselli et al. 2018) data. In addition to this, NIR (SPITZER; Werner et al. 2004), FIR (Herschel Virgo Cluster Survey, HeViCS; Davies et al. 2010, ; Planck, http://www.esa.int/Planck), and radio HI (VIVA; Chung et al. 2009) surveys allowed astronomers to complete the mapping of the different constituents of the cluster.

3 The Virgo intra-cluster component formation: study of the tails of stripped galaxies

On a theoretical side the presence of an ICC in clusters is a natural result of the fact that young concentrations of mass are still in the process of forming. However, observationally its detection across the entire spectrum has been elusive, mainly due to its very low surface brightness. Here we aim in identifying the ICC in the form of gas and dust in the dynamically young Virgo cluster by looking at the stripped material from processed galaxies in the system. This study is motivated by the wealth of information we have on the Virgo ICC. Optical studies, that used Planetary Nebulas (PNS) and Globular Clusters (GCs) to trace the Virgo IC light (ICL) have shown that at the centre of Virgo the ICL is superposed to, however dynamically separated from, the stellar halo of the cluster's central, M87. They both grow through accretion events, however they have different velocity, and density distribution and parent stars, consistent with the M87 halo being redder and more metal rich than the ICL. Moreover the Virgo ICL is found to have a total dynamical mass of $M_{ICC} = 10.8 \pm 0.1 \times 10^{11}\, M_{\odot}$ within 1 deg radius from the cluster's centre (Longobardi et al. 2018a), and it is the accreted component from low and intermediate mass star-forming and dwarf-ellipticals galaxies (Longobardi et al. 2013, 2015a, 2018a,b). In

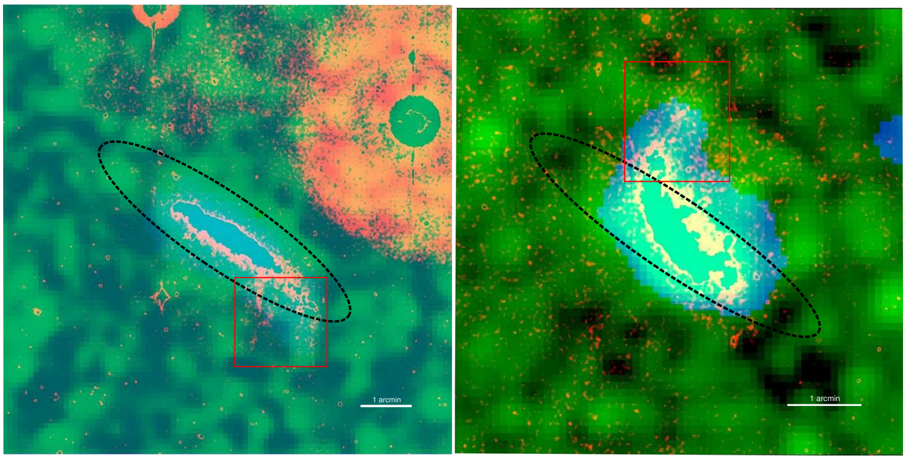

Fig. 2. From left to right, RGB colour composite images of NGC 4330 and NGC 4522, sub-sample of the galaxies studied in this work. Red, green and blue colours trace the Hα (VESTIGE), FIR (HeViCS), and HI (VIVA) emissions, respectively. The red boxes identify the regions we will propose to follow-up with ALMA, all enclosing the low surface-brightness tails of gas and dust extending outside the optical disk (black dotted ellipses). 1 arcmin scale bars are in white. North is up, East to the left.

parallel, studies of the gas/dust content in cluster members has shown that systems approaching regions of high density are found to be redder and gas/dust deficient with respect to the population of galaxies in the field (Boselli et al. 2006; Gavazzi et al. 2010; Cortese et al. 2012), scenario even more dramatic for low-mass galaxies (Davies et al. 2010; Boselli et al. 2014). If then the Virgo ICL is built up predominantly by tidal stripping of low mass star-forming and dwarf-elliptical galaxies, we do expect the presence of gas and dust in the IC space. They, in fact, could be removed from the cluster galaxies and transported to the IC component by the same environmental processes which remove their stellar content and/or by additional ram pressure phenomena (Cortese et al. 2010, 2012). In agreement with this scenario is a recent finding (Longobardi et al. 2019, in prep.) showing that it exists a diffuse dust component in the Virgo intra-cluster space (Fig.1), and characterised by a centrally concentrated profile, hence in agreement with what has been measured for its optical counterpart (Mihos et al. 2005; Longobardi et al. 2015b, 2018a,b). Thus, we have a unique opportunity to hunt for the ICC in the process of forming. Thanks to the complete and unique set of multifrequency data available for Virgo, the study is based on galaxies with clear HI (VIVA survey) and Hα (VESTIGE survey) asymmetric morphologies, that show similar distribution in their Herschel FIR emission. NGC4302, NGC4330, NGC4396, NGC4522, are four Virgo late-type galaxies with long tails of neutral and ionised gas, and dust. They are systems with stellar masses of the order of $\mathrm{M}_* \sim 10^9\ \mathrm{M}_\odot$, sitting at different distances from the cluster's centre, however all within 4 degrees from the cluster's core where the IC diffuse dust emission peaks (Longobardi et al., 2019, in prep.). Moreover, their low surface brightness tails of stripped material present patchy morphologies in their ionised gas distribution, that may trace recent star formation events, and lie outside the galaxies' optical disks (see Fig.2). Thus, they are likely going to be removed from the cluster spirals and to contribute to the ICC. The regions of interest for this study reach levels of Hα surface brightness $\Sigma_\alpha \sim 0.5\times10^{-17}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$, HI column densities of the order of $2\times10^{19}\,\mathrm{cm^{-2}}$, hence dust flux densities $\mathrm{I_D} \sim 0.1\,\mathrm{MJy\,sr^{-1}}$*.

4 Summary and Conclusions

The ICC production in a cluster is an inevitable consequence of the hierarchical structure formation. It can reveal a great deal of information about the cluster's accretion history and its evolutionary state being tightley connect with the transformation and evolution of the galaxies in the cluster. The Virgo cluster is a dynamically young cluster where its IC stars are the accreted component from low and intermediate mass star-forming and dwarf-ellipticals galaxies. Based on this result, we are carrying out a multi-wavelength analysis of Virgo

*The dust flux densities have been obtained from the measured HI column densities via the relations described in Planck Collaboration et al. (2014), adopting $\mathrm{T} = 20\,\mathrm{K}$ and a dust emissivity index, $\beta = 2$. Consistent values have been obtained when dust flux densities are estimated directly from the HeViCS FIR images galaxies subject to environmental processing with the aim of tracing the undergoing formation of the ICC in the form of neutral and ionised gas, and dust. NGC4302, NGC4330, NGC4396, NGC4522, are our sample of Virgo late-type galaxies with clear HI (VIVA survey) and Hα (VESTIGE survey) asymmetric morphologies, that show similar distribution in their Herschel FIR emission. This study is tracing the relative fraction of the different components that constitute the IC content, also allowing us to answer the open question as to whether dust-to-gas ratios as measured in the main body of the galaxies also apply to the tails of the stripped material. Future follow-up observations with ALMA (Fig.2) will be able to resolve the FIR emission within compact regions of star formation providing the missing observational evidence of the in-situ origin of the ICC. Moreover, the VESTIGE survey is revealing for the first time long tails of ionised gas in several Virgo cluster galaxies also observed to have long HI tails. Similar studies will be then proposed to pursue a similar analysis on a larger sample of targets, with different physical properties (mass, environment, etc.), providing strong constraints for hydrodynamic simulations of structure formation.

This study is supported by the French Centre National d'Etudes Spatiales (CNES).

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