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# MULTIFREQUENCY SURVEYS OF THE VIRGO CLUSTER: ALFALFA, HEVICS, SMAKCED, NGVS, GUVICS

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**Abstract.** The Virgo cluster, the largest nearby concentration of galaxies, is the target of several multifrequency surveys aimed at studying the effects of the environment on galaxy evolution. These blind or pointed surveys are: the Arecibo Legacy Fast ALFA Survey (ALFALFA; PI. R. Giovanelli), the Herschel Virgo Cluster Survey (HeViCS; PI J. Davies), the Stellar content, MAss and Kinematics of Cluster Early-type Dwarfs (SMAKCED, PI T. Lisker), the Next Generation Virgo Cluster Survey (NGVS; PI L. Ferrarese) and the GALEX UV Virgo Cluster Survey (GUViCS; PI A. Boselli). I briefly describe the surveys mentioning some of the most interesting results obtained so far.

Keywords: galaxies: clusters: individual: Virgo, galaxies: evolution; radio lines: galaxies; infrared: galaxies; ultraviolet: galaxies;

## 1 Introduction

A complete understanding of the matter cycle in galaxies, i.e. of the process that transforms the primordial atomic gas into molecular clouds where stars are formed, and of the metal production and the formation of dust grains requires a multifrequency analysis. Indeed, the atomic gas can be directly observed using the 21 cm emission line, while the molecular component is generally traced through the emission of carbon monoxide emission lines. Star formation can be quantified under some assumptions through the observations of the ionised hydrogen or of the UV stellar continuum emitted by the youngest stellar populations. Dust, formed by the aggregation of metals produced in the final phases of stellar evolution and injected into the interstellar medium by stellar winds and supernovae explosions, absorbs the stellar radiation and re-emits the acquired energy in the infrared domain (e.g. Boselli (2011)).
In cluster galaxies this matter cycle can be easily modified by the perturbations induced by the hostile environment in which galaxies reside (e.g. Boselli & Gavazzi (2006)). The atomic gas, distributed on a disc of size $\sim$ two times more extended than the optical disc, is easily perturbed by the interaction either with the hot intergalactic medium (ram pressure stripping, Gunn & Gott (1972); thermal evaporation, Cowie & Songaila (1977); viscous stripping, Nulsen (1982)), or by the flyby encounters with other cluster members (galaxy harassment, Moore et al. (1998)). These perturbations might induce nuclear gas infall (Kennicutt et al. 1987) or the truncation of the gaseous disc with, as a consequence, a radial decrease of the star formation activity (Boselli et al. 2006). In dwarf galaxies the gas can be totally removed, and the star formation activity totally stopped, transforming gas rich, late-type systems into quiescent dwarf ellipticals (Boselli et al. (2008a), Boselli et al. (2008b)). Frozen in the interstellar medium, the dust component can be also removed during the interaction with the hostile environment (Cortese et al. (2010a), Cortese et al. (2010b), Cortese et al. (2012)).
With the aim of gathering a complete and coherent view on the different processes acting on galaxies in high density environments we have recently undertaken several blind surveys of the Virgo cluster, the largest concentration of galaxies within 35 Mpc. There are several reasons why Virgo has been chosen for these studies: it is a close, rich cluster, whose distance (16.5 Mpc, Gavazzi et al. (1999); Mei et al. (2007)) is such that galaxies spanning a wide range in morphology and luminosity can be studied, from giant spirals and ellipticals down to dwarf irregulars, blue compact dwarfs (BCDs) and dwarf ellipticals (dE) and spheroidals (dS0). Furthermore, Virgo is still in the process of being assembled, so that a wide range of processes (ram-pressure stripping, tidal

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interactions, harassment and pre-processing) are still taking place. The blind surveys that i describe are: the 21 cm Arecibo Legacy Fast ALFA survey (ALFALFA, Giovanelli et al. (2005)), the far infrared Herschel Virgo Cluster Survey (HeViCS, Davies et al. (2012)), the optical Next Generation Virgo Cluster Survey (NGVS, Ferrarese et al. (2012)), and the UV GALEX ultraviolet Virgo Cluster Survey (GUViCS, Boselli et al. (2011)). I also briefly describe the Stellar content, MAss and Kinematics of Cluster Early-type Dwarfs (SMAKCED, Janz et al. (2012)), a near infrared and kinematical survey of dwarf early-type galaxies in the Virgo cluster.

## 2 The Virgo cluster surveys

### *2.1 ALFALFA: the Arecibo Legacy Fast ALFA survey*

The Arecibo Legacy Fast ALFA survey (ALFALFA)[i] is a blind HI survey covering 7000 deg$^2$ in the declination range $0^o <$ dec$< 32^o$ and velocity range -1600$< vel <$ 18000 km s$^{-1}$ with a spectral resolution of 5 km s$^{-1}$ down to a sensitivity limit of 2.4 mJy, corresponding to $\sim 10^{7.5}$ M$\odot$ at the distance of Virgo (Giovanelli et al. (2005)). The survey, which has already completed the Virgo cluster region, has been designed to provide the basis for studies of the dynamics of galaxies within nearby superclusters, allow measurement of the HI diameter and mass function, and enable a first wide-area blind search for local HI tidal features and HI absorbers. The first catalogue of data has been published in Giovanelli et al. (2007), Kent et al. (2008) and Haynes et al. (2011). The analysis of the data done so far revealed, for instance, that the HI cloud without optical counterpart observed by Minchin et al. (2005) is atomic gas stripped from NGC 4254 through an harassment process (Haynes et al. (2007)). It also allowed the detection of other HI clouds without optical counterparts (Kent et al. (2007)). Combined with an H$\alpha$ imaging survey of HI detected galaxies, we have also studied the statistical properties, including the present day star formation activity, of HI selected objects in Virgo and in the field (Gavazzi et al. 2008, 2012)).

### *2.2 HeViCS: the Herschel Virgo Cluster Survey*

The Herschel Virgo Cluster Survey (HeViCS)[ii] (Davies et al. (2012)) is a blind far-IR survey of 60 deg$^2$ in five photometric bands from 100 to 500 $\mu$m with PACS and SPIRE on the Herschel Space Observatory down to the confusion limit (at 250 $\mu$m; 286 hrs allocated as an open time key program on Herschel). The HeViCS project is done in tight collaboration with the Herschel Reference Survey (Boselli et al. (2010b); HRS), a similar project aimed at studying relatively isolated galaxies at the same distance than Virgo ideally selected for comparison in environmental studies. Figure 1 shows the surveyed region, and the infrared image obtained using the Herschel data. The bright point like sources are mainly Virgo cluster galaxies, while the filamentary structures are Galactic cirri. Data for the bright infrared galaxies can be found in Davies et al. (2012) and Ciesla et al. (2012), this last paper including also HRS galaxies.

The goal of this survey is to study the dust properties of cluster galaxies, including the extended dust distributed around galactic discs or associated with tidal debris and low surface brightness galaxies, and to reconstruct the far-IR luminosity function as well as to detect dust in the intra cluster medium. The preliminary analysis of the data has already brought to very interesting and new results: it has indeed shown for the first time that cluster galaxies are stripped of their dust content because of both gravitational interactions and ram pressure stripping (Cortese et al. (2010a), Cortese et al. (2010b)). It has also shown the existence of dust in metal poor BCD (Grossi et al. (2010)) and dwarf elliptical galaxies (de Looze et al. (2010)), as well as the existence of massive ellipticals with a far infrared emission dominated by synchrotron (Baes et al. (2010); Boselli et al. (2010a)). Other works were focused on the study of the relation between the gas and the dust content and the metallicity of resolved and unresolved objects (Smith et al. (2010); Magrini et al. (2011); Corbelli et al. (2012)), while the study of the far infrared colours of late-type systems is presented in Boselli et al. (2012).

[i] http://egg.astro.cornell.edu/alfalfa/
[ii] http://www.hevics.org/

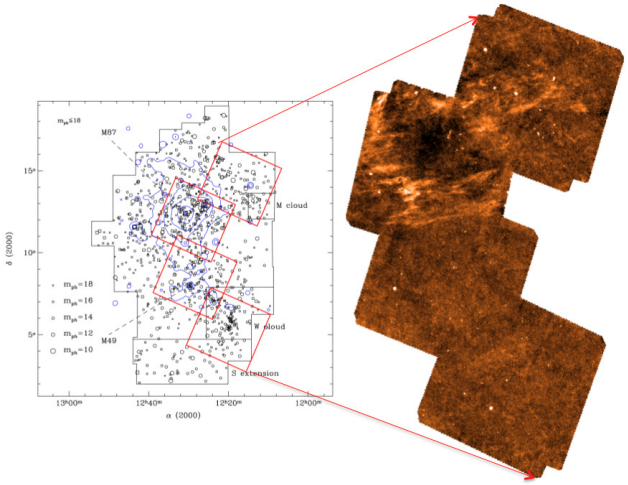


**Fig. 1.** The Virgo region observed by Herschel (red solid squares) compared to that observed by Binggeli et al. (1985) (black solid) (left). The *Herschel* PACS image at 250 $\mu$m (right) (adapted from Davies et al. (2012)).

### *2.3 SMAKCED: the Stellar content, MAss and Kinematics of Cluster Early-type Dwarfs*

The Stellar content, MAss and Kinematics of Cluster Early-type Dwarfs (SMAKCED)[iii] is a pointed near infrared photometric and optical high resolution spectroscopic survey of selected dwarf elliptical galaxies in the Virgo cluster (see Janz et al. (2012)). Near infrared data are necessary to trace the distribution of the bulk of the stellar component within galaxies, and thus determine different structural parameters. High resolution spectroscopy is used to measure the kinematical properties of the observed galaxies, including velocity dispersion and rotational velocity. Combined, these data will be used to study and compare the main scaling relations of dwarf ellipticals to those of massive systems or spiral galaxies with the aim of understanding whether this particular category of objects might result from the transformation of gas rich, late-type systems recently perturbed by the interaction with the hostile cluster environment. The first results indeed confirm this scenario: a large fraction of early-type dwarf galaxies are supported by rotation. These dE are characterised by relatively young stellar populations and are located at the peryphery of the Virgo cluster. Their rotation curve is similar to that of late-type systems of similar mass (Toloba et al. (2009); Toloba et al. (2011)).

### *2.4 NGVS: the Next Generation Virgo Survey*

The Next Generation Virgo Survey (NGVS)[iv] (Ferrarese et al. (2012)) is an optical (*ugriz*) survey covering 104 deg$^2$ of the Virgo cluster with MegaPrime on the CFHT to a point-source depth of $g \sim 25.7$ mag and a corresponding surface brightness of $\mu_g \sim 29$ mag arcsec$^{-2}$. The survey has detect $\sim 3\ 10^7$ sources, including low surface brightness Virgo cluster members, globular clusters associated to the massive galaxies and background objects. Due to a dome failure in the spring 2012 semester, the survey still has to be completed in the $u$ and $r$ bands (123 hours required). Figure 2 illustrates the sky region covered by the NGVS survey (solid red line) and the overlap with several other programs that have targeted the Virgo cluster.

The goals of the NGVS are the study of faint end slope of the galaxy luminosity function, the characterization of galaxy scaling relations over a dynamic range of 7 orders of magnitude in mass, and the study of the diffuse and discrete intracluster population.

[iii] `http://smakced.ned/`
[iv] `https://www.astrosci.ca/NGVS/The_Next_Generation_Virgo_Cluster_Survey/Home.html`

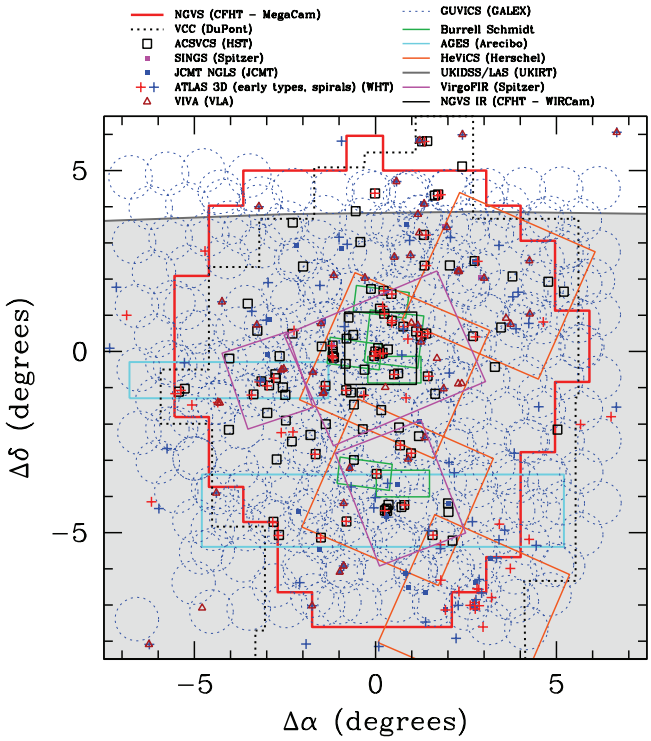


**Fig. 2.** NGVS survey area, shown in heavy red, compared to the regions covered by a number of multi-wavelength surveys of the Virgo cluster (primarily at non-optical wavelengths), taken from Ferrarese et al. (2012). The different surveys are indicated in the legend at the top of the figure.

### *2.5 GUViCS: the GALEX UV Virgo Cluster Survey*

The GALEX UV Virgo Cluster Survey (GUViCS)[v] Boselli et al. (2011) is an ultraviolet survey of the Virgo cluster in the NUV (2316 Å) and FUV (1539 Å) bands. The data were obtained as part of the mission surveys on one hand, during GI open time proposals (Boselli et al. (2005b)), and especially during a cycle 6 proposal that will extend the coverage to the whole area of the cluster with 94 new pointings, for a total of 121.5 ksec. The surveyed region, as depicted in Fig. 3, covers $\sim$ 40 sq. deg. in the FUV and $\sim$ 120 sq. deg. in the NUV at a sensitivity of $\simeq$ 27.5-28 mag arcsec$^{-2}$ in surface brightness and a detection limit for point sources of $\sim$ 21.5 AB mag. This survey detected $\sim$ 1.4 $10^6$ sources in the NUV band, and $\sim$ 2 $10^5$ in the FUV.

The UV observations are of paramount importance for a large number of studies. In star forming galaxies, the present day star formation activity can be measured from the UV flux emitted by the youngest stellar population (Kennicutt (1998); Boselli et al. (2001), Boselli et al. (2009)), provided that dust extinction can be accurately determined (e.g. using the far-IR to UV flux ratio, Cortese et al. (2006), Cortese et al. (2008)). In quiescent galaxies, the level emission can help to date the last generation of stars (on a few 100 Myr timescale) or be related to very old populations (UV upturn; Boselli et al. (2005a)).

The analysis of these GALEX data allowed us to detect low surface brightness features associated with tidally perturbed galaxies (Boselli et al. (2005a); Arrigoni Battaia et al. (2012)) or study the star formation history at galactic scales in NGC 4569, a prototypical massive spiral undergoing a ram pressure stripping event (Boselli et al. (2006)). We also determined the UV luminosity function of galaxies in the core of the cluster in the NUV and FUV bands and separately for early- and late-type systems (Boselli et al. (2011)). Among the works done so far, however, the most important is probably the study of the origin of dwarf elliptical galaxies in Virgo. Our analysis has convincingly shown that this population of objects probably results from the transformation of low luminosity, star forming systems which recently entered the hostile cluster environment and rapidly ($\leq$ 100 Myr) lost their gasous content, quenching their star formation activity (Boselli et al. (2008a), Boselli et al. (2008b)).

[v] `http://galex.oamp.fr/guvics/index.html`

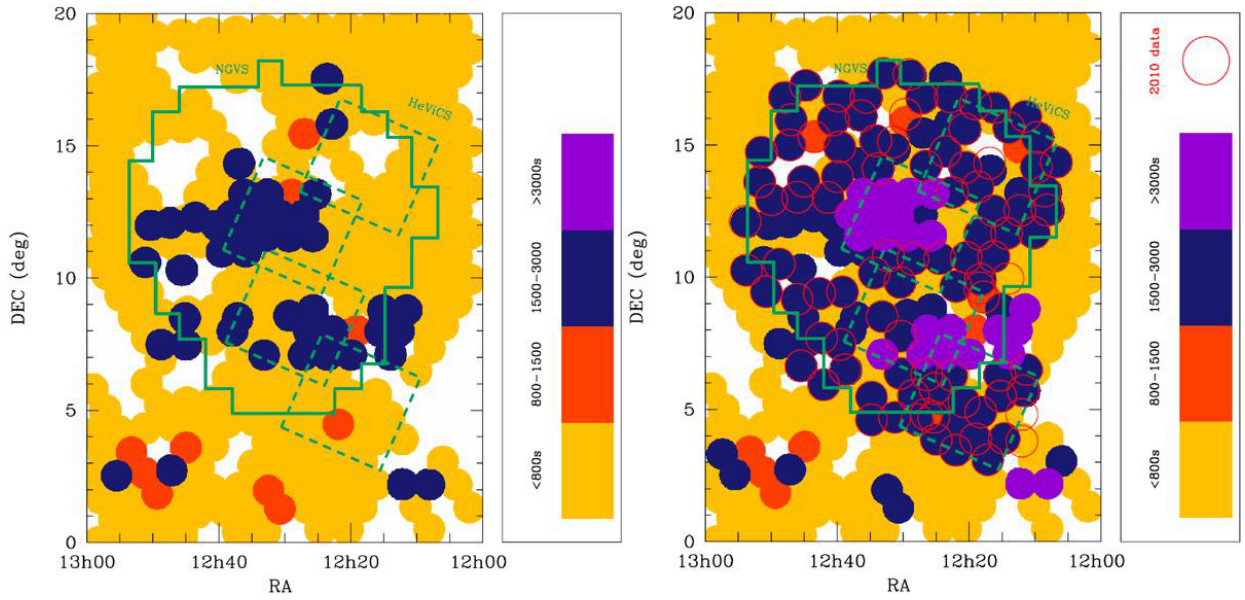


**Fig. 3.** The Virgo cluster region observed by GALEX in the FUV (**left**) and NUV (**right**) bands, from Boselli et al. (2011).

I also take the opportunity to advertise the long term effort that our team has done during these last years to obtain, reduce and homogeneise imaging and spectroscopic data for galaxies in the Virgo cluster at almost all frequencies, all made available to the community through our dedicated database GOLDMine [vi] (Gavazzi et al. (2003)). This includes H$\alpha$ narrow band (Boselli & Gavazzi (2002), Boselli et al. (2002a), Gavazzi et al. (2002), Gavazzi et al. (2006)), optical (Boselli et al. (2003a), Gavazzi et al. (2005b)), near infrared (Boselli et al. (1997), Boselli et al. (2000), Gavazzi et al. (2000b), Gavazzi et al. (2001)) and mid infrared imaging (Boselli et al. (2003b)), 2.6 mm CO (Boselli et al. (1995), Boselli et al. (2002b)) and 21 cm HI data (Gavazzi et al. (2005a)), radio continuum data (Gavazzi & Boselli (1999)), as well as optical spectroscopy (Gavazzi et al. (2000a), Gavazzi et al. (2004)). This unique set of data is at the origin of the review paper on the effects of the environment on galaxy evolution that we published a few years ago (Boselli & Gavazzi (2006)) as well as of many others publicarions.

This publication is done on behalf of the ALFALFA, HeViCS, NGVS, SMAKCED and GUViCS teams. I am greateful to the PI of the different projects, R. Giovanelli, J. Davies, L. Ferrarese and T. Lisker, for providing me with all the information necessary to write this communication.

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[vi] http://goldmine.mib.infn.it/

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