Galaxy evolution in the Virgo Cluster

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Tout d’abord: un grand merci à

Galaxy evolution in the Virgo Cluster

- Introduction
- Interactions of a cluster spiral with its environment
- The data
- The model
- NGC 4522 – a case study
- Ram pressure stripping time sequence
- HI tailed Virgo spiral galaxies
- Stripping of multiple gas phases
- Independent confirmation of stripping ages
Atomic gas: the HI view

(Cayatte et al. 1990)  (Bravo-Alfaro et al. 2000)

HI deficiency = \log((\text{expected HI mass})/(\text{observed HI mass}))

Cluster spirals are HI deficient and show truncated gas disks
Molecular gas: the CO view

(Kenney & Young 1989) (Boselli et al. 1994)

Cluster spirals are NOT CO deficient
Star formation: the Hα view

« normal » Hα disks (Koopmann & Kenney 2001, 2004)
Star formation: the H\(\alpha\) view

anemic H\(\alpha\) disks          anemic truncated H\(\alpha\) disks
(Koopmann & Kenney 2001, 2004)
Star formation: the Hα view

truncated Hα disks
(Koopmann & Kenney 2001, 2004)

cluster radial profiles

52 Virgo galaxies: 37% normal, 6% anemic, 6% enhanced, 52% truncated
The Virgo Cluster

- **Distance:** ~17 Mpc
- 1' = 5 kpc
- **Velocity dispersion:** ~700 km/s
- **Dynamically young cluster**
- **Mass:** \(~10^{14} \, M_{\text{solar}}\) at R=1 Mpc
- **\(M_{\text{gas}}/M_{\text{tot}}\)** \sim 14%
- **\(M_{\text{gal}}/M_{\text{tot}}\)** \sim 4%
- **\(M/L\)** \sim 500

(Schindler et al. 1999)
Virgo - Coma

- D=17 Mpc
- Mass: $\sim 1.1 \times 10^{14} M_{\text{solar}}$
  at R=1 Mpc
- Velocity dispersion: $\sim 700$ km/s
- Large spiral fraction
- One central galaxy
- Asymmetric overall ICM distribution
- Dynamical young cluster

- D=100 Mpc
- Mass: $\sim 2.6 \times 10^{14} M_{\text{solar}}$ at R=1 Mpc
- Velocity dispersion: $\sim 1100$ km/s
- Small spiral fraction
- Two central galaxies
- Symmetric overall ICM distribution
- « relaxed » cluster
Interaction of a spiral galaxy with its environment

- Gravitational interaction galaxy - cluster

- Gravitational interaction galaxy - galaxy

- Ram pressure galaxy ISM – intracluster medium (ICM)

(Kenney et al. 1995)

(Böhringer et al. 1994)

(Kenney et al. 2004)
Interaction diagnostics

- Which interaction is responsible for the observed distortions/perturbations?
- Determination of the interaction parameters
- Means: HI maps and velocity fields, dynamical simulations, polarized radio continuum emission, photometry+ spectroscopy + stellar population synthesis
Polarized radio continuum emission – a new diagnostic tool for interactions

- Polarized radio continuum emission is proportional to the density of relativistic electrons and the strength of the large-scale regular magnetic field: $P_l \propto n_e B^{2-4}$

- Polarized radio continuum emission is sensitive to shear and compression motions

NGC 4522 (Kenney et al. 2004)
Grey: optical
Contour: HI

(Vollmer et al. 2004)
Grey: HI
Contour: polarized radio continuum emission
Mini-survey of 8 Virgo cluster spiral galaxies in polarized radio continuum emission


• 8 bright Virgo spiral galaxies
• 90h of VLA observations
• 20cm C array; 6cm D array
• Resolution: ~20”
• Sensitivity: 10mJy/beam at 6cm
VLA 6cm polarized radio continuum emission

Greyscale: optical B band; contour: 4.85GHz polarized radio continuum emission

Vollmer et al. (2007)
MHD simulations
(with M. Soida and K. Otmianowska-Mazur)

- Solve the induction equation on the velocity fields of the sticky particle simulations
- Assume relativistic electron distribution

evolution of the large scale regular magnetic field
evolution of the polarized radio continuum emission

grey: HI, contours: PI
(Vollmer et al. 2006)
HI Effelsberg 100m data

- **Why?** Large scale, low surface density gas might be missed by interferometers
- **Example:** 

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NGC 4388
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(Oosterloo & van Gorkom 2005)
HI Effelsberg 100m data
(Vollmer & Huchtmeier 2007)

- Sample of 6 carefully chosen Virgo spirals
- Only one detection of HI far away (>10kpc) from the galactic disk (NGC 4388)
- Suggestion: outer HI disks ($R>R_{25}$) are removed much earlier than expected by the classical ram pressure criterion
- Detection of up to 70% of the stripped gas mass assuming an initial HI deficiency of def=0.4
VIVA = VLA Imaging of Virgo in Atomic Gas
(A. Chung, J. van Gorkom, J. Kenney, H. Crowl, B. Vollmer)
Numerical simulations

- ISM-ICM interaction + gravitational interaction
- turbulent/viscous stripping (Nulsen 1982; timescale ~1Gyr)
- ram pressure stripping (momentum transfer; timescale ~10Myr)
- constant ↔ time dependent ram pressure
- Models: (i) Eulerian hydro (2D, 3D),
  (ii) SPH,
  (Abadi et al. 1999, Schulz & Struck 2001)
  (iii) sticky particles
  (Vollmer et al. 2001)
Comparison between the different codes

face-on stripping

Conclusion: models are consistent within a factor 2: Gunn & Gott works
Simulations with time dependent ram pressure

- depends on galaxy orbits within the cluster
- simulations of galaxy orbits in the Virgo cluster and determination of temporal ram pressure profiles

\[ \rho v^2 \]
Normalization of the code

boxes: Cayatte et al. (1994); stars: simulations

Conclusion: whatever you do with the disk, you will end up with a truncated gas disk

Vollmer et al. (2001)
Comparison between the models and the observations

- **Known**: systemic velocity, distance from cluster center, i, PA, gas distribution and velocity field
- **Unknown**: maximum ram pressure, time to maximum, angle between galactic disk and ram pressure wind

Ram pressure stripping criterion: 
Gunn & Gott (1972): \[ \Sigma_{\text{gas}} v_{\text{rot}}^2/R = \rho_{\text{ICM}} v_{\text{gal}}^2 \]
A case study: NGC 4522

- Distance from M87: 3.3° ~ 1 Mpc
- Radial velocity: +1000 km/s w.r.t. M87
- View: edge-on

(Kenney et al. 2004)

(Vollmer et al. 2004)
NGC 4522: the « best fit » model
NGC 4522: final result

Greyscale: gas; Contours: polarized radio continuum emission

(Vollmer et al. 2007)

→ near peak ram pressure stripping
NGC 4522: peak ram pressure stripping + projected distance of ~1 Mpc moving intracluster medium due to infall of the M49 group of galaxies
Observational gas characteristics

• Asymmetric ridge of polarized radio continuum emission at the outer disk (all)

• Gas disk truncated near the optical radius, asymmetric outer disk with tail structure (NGC 4501, NGC 4330)

• Truncated gas disk + extraplanar, high surface brightness gas (NGC 4522, NGC 4438)

• Truncated gas disk + extraplanar, very low surface brightness gas (NGC 4388)

• Truncated gas disk + perturbed, low surface brightness arms (NGC 4548, NGC 4569)
Observational gas characteristics

• Asymmetric ridge of polarized radio continuum emission at the outer disk (all)

• Gas disk truncated near the optical radius, asymmetric outer disk with tail structure (NGC 4501, NGC 4330)

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• Truncated gas disk + extraplanar, very low surface brightness gas (NGC 4388)

• Truncated gas disk + perturbed, low surface brightness arms (NGC 4548, NGC 4569)
Virgo, A Laboratory for Studying Galaxy Evolution

- \( V < 500 \) km/s
- \( 600 \) km/s \(< V < 1300 \) km/s
- \( 1400 \) km/s \(< V < 2000 \) km/s
- \( V > 2000 \) km/s
Gas disk truncated near the optical radius, asymmetric outer disk with tail structure → pre-peak stripping

NGC 4501 observations

HI

grey: HI, contours: PI

Vollmer et al. (2008)

NGC 4330 observations

NGC 4330

HI

model

model
Virgo, A Laboratory for Studying Galaxy Evolution

- $\mathcal{V} > 500 \text{ km/s}$
- $800 \text{ km/s} < \mathcal{V} < 1300 \text{ km/s}$
- $1400 \text{ km/s} < \mathcal{V} < 2000 \text{ km/s}$
- $\mathcal{V} > 2000 \text{ km/s}$
Strongly truncated gas disk + extraplanar, high surface brightness gas

$\rightarrow$ near peak stripping

NGC 4522 \cite{Vollmer2006}  
\textbf{model}  
\textbf{observations}

NGC 4438 \cite{Vollmer2005}

\textbf{CO(1-0) IRAM30m} $\rightarrow$

\textbf{model:}
Gravitational interaction  
+ ram pressure
Virgo, A Laboratory for Studying Galaxy Evolution

- $V < 500 \text{ km/s}$
- $800 \text{ km/s} < V < 1200 \text{ km/s}$
- $1400 \text{ km/s} < V < 2000 \text{ km/s}$
- $V > 2000 \text{ km/s}$
Truncated gas disk + extraplanar, very low surface brightness gas

\[ \sim 100 \text{Myr after ram pressure peak} \]

(Oosterloo & van Gorkom 2005)
Virgo, A Laboratory for Studying Galaxy Evolution
Truncated gas disk + perturbed, low surface brightness arms

~300Myr after ram pressure peak

NGC 4569

(Vollmer et al. 2004)
Ram pressure stripping time sequence

Vollmer (2009)

NGC 4501

NGC 4438

NGC 4330

NGC 4522

NGC 4388

NGC 4569

pre-peak

near peak

~150Myr after peak

~300Myr after peak
The 3D view

Vollmer (2009)
Ram pressure efficiency
Tidally enhanced ram pressure stripping

NGC4654

NGC4639

HI gas distribution

HI velocity field

(Phookun & Mundy 1995)
NGC 4654

(Vollmer 2003)

model I:
ram pressure

model II:
ram pressure + tidal interaction

HI observations
(Phookun & Mundy 1995)
HI tailed Virgo spiral galaxies

- from **VIVA** (Chung et al. 2007)
- out of 50 Virgo spirals <10 show extended HI tails
- distances to M87: 0.6-1 Mpc
- all tails probably involve ram pressure stripping
Ram pressure stripping of the multiphase ISM

Vollmer et al. (2008 subm.)

- IRAM 30m HERA CO(2-1) observations

Dashed: HI (Kenney et al. 2004)
Solid: CO(2-1)
Greyscale: CO(2-1)
Contours: Hα (Kenney et al. 2004)

Vollmer et al. (2008 subm.)

Greyscale: Hα
Contours: HI from Kenney et al. (2004)

model
Greyscale: Hα
Contours: HI
Ram pressure stripping of the multiphase ISM

- NGC 4438: decoupled molecular clouds
- NGC 4402 (Crowl et al. 2005)

Contour: 20cm radio continuum emission; Greyscale: B band

(Vollmer et al. 2005)
Ram pressure stripping of the multiphase ISM
Vollmer et al. (2008 subm.)

- NGC 4438: ionized gas stripped more efficiently than neutral gas

Update of Kenney et al. (1995)
Independent confirmation of stripping ages

- **NGC 4522** (Crowl & Kenney 2007, 2008)
  - WIYN SparsePack & GALEX UV

- **NGC4569** (Boselli et al. 2007)
  - GALEX UV
Conclusions

• Efficiency of ram pressure stripping is ~1 (Gunn & Gott works)
• For NGC 4522 a moving ICM is needed
• Temporal ram pressure sequence in the Virgo cluster
• Stellar population synthesis models confirm model stripping ages (NGC 4388, NGC 4569, NGC 4522; PhD thesis of H. Crowl, Yale)
• Indication of different stripping efficiencies of ionized and neutral ISM
• Ram pressure stripping plays an important role in the evolution of Virgo cluster spirals