Virgo Cluster spiral galaxies and their Mach cones

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Over the years many observations have shown the environmental influence on Virgo Cluster spiral galaxies:

- *Radially truncated gas disks (Cayatte et al. 1990, AJ, 100, 604; Chung et al. 2009, AJ, 139, 2716)*
- *Long HI tails (Chung et al. 2007, A&A, 659, 115)*
- *Asymmetric polarized radio ridges marking gas compressions and shear motions (Weżgowiec et al. 2007, A&A, 471, 93; Vollmer et al. 2007, A&A, 464, L37)*

The model.

Recently, Vollmer (2009, A&A, 502, 427) established a model-based ram pressure stripping time sequence of Virgo spiral galaxies:

- Snapshots of three-dimensional models including ram pressure are compared to the observed HI gas distributions and velocity fields
- The 3D velocity vector and the timestep are matched with the observed projected position and radial velocity of the galaxy

Expectations.

- The ram pressure stripping heats the gas to X-ray temperatures via bow shocks, heat conduction, and the mixing of the stripped ISM into the hot intracluster medium (e.g. Stevens et al. 1999, MNRAS, 310, 663; Roediger et al. 2006, MNRAS, 371, 609).
- Supersonic velocities of cluster galaxies causes bow shocks with associated Mach cones

Aims.

- **We look for signs of Mach cones in XMM-Newton X-ray observations of Virgo Cluster spirals.**

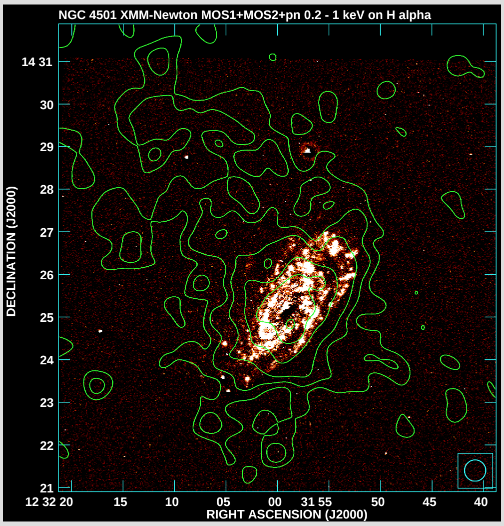

FIG. 1: X-ray emission (0.2-1 keV) of NGC 4501 overlaid onto the Hα image from Goldmine. The map resolution is 30″. The X-ray contours are 3, 5, 8, 16, 25 times the rms noise level.

NGC 4501 (Fig. 1)

- A strong compression of the magnetic field in the southwest (Weżgowiec et al. 2007, Vollmer et al. 2007)
- A sharply truncated HI disk at the same position
- A moderately extended hot gas halo
- A hot gas tail at ~ 0.7 keV
- **The observed characteristics fits the ram pressure stripping model by Vollmer et al. (2008, A&A, 483, 89).**
- **The X-ray emission beyond the HI disk might be due to stripped gas mixed with the intracluster medium and/or a galactic wind due to star formation in the prominent northwestern spiral arm.**

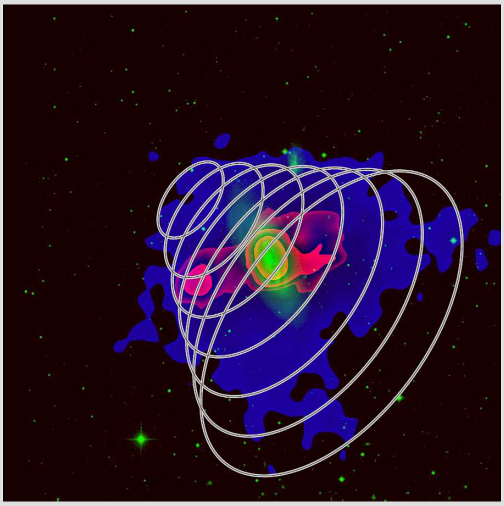

FIG. 2: An RGB image of NGC 4569 constructed from DSS optical B band image (green), X-ray emission (0.2-1 keV; blue), and 1.4 GHz total radio emission (red). The lower cut for both X-ray and radio emission is 3σ and the resolution is 1'. Overlaid is the Mach cone geometry fitting the X-ray large-scale emission.

The Mach cones.

- Mach cones fitted to the X-ray emission (Figs. 2 and 3).
- The direction based on the dynamical model
- The opening angle fitted by eye
- The Mach cone angle depends on the angle β between the 3D velocity vector and the plane of the sky
- **We suggest that the magnetic field plays a role and that the magnetosonic velocity is relevant for the determination of the Mach number**
- **This allows to estimate the intracluster magnetic field strength**

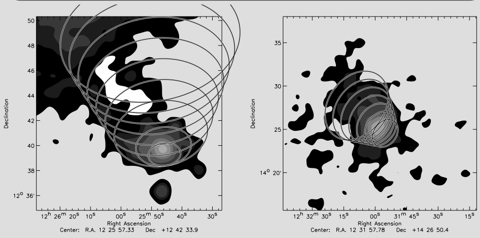

FIG. 3: X-ray emission (0.2-1 keV) of NGC 4388 (left) and NGC 4501 (right) together with the Mach cone whose direction is based on the dynamical model and whose opening angle is adjusted to the X-ray distribution. The greyscale is cut at 7σ for NGC 4388 and 3σ for NGC 4501.

Conclusions:

All extraplanar X-ray emitting hot gas is found within the Mach cones of the three galaxies.

- In NGC 4569 it is associated with the galactic outflow observed in Hα and radio continuum (Chyży et al. 2006). The diffuse X-ray emission has a triangular shape.
- In NGC 4388 it follows the beginning of the HI tail discovered by Oosterloo & van Gorkom (2005).
- In NGC 4501 it is located opposite to the side of the galactic disk where the gas is compressed by ram pressure (Vollmer et al. 2008) and may be stripped gas heated to X-ray temperatures.

NGC 4569 (Fig. 2)

- One of the largest and most HI deficient galaxies in the Virgo cluster (Solanes et al. 2001, ApJ, 548, 97)
- A giant hot gas diffuse halo of $20' \times 20'$ (100 × 100 kpc)
- Large radio lobes (Chyży et al. 2006, A&A, 447, 465).
- The hot phase at ~ 0.5 keV (Fig. 5 right) has a pressure 2 times lower that that of the cosmic rays and magnetic fields
- **The radio lobes and the hot gas halo most likely origin from galactic superwind driven by cosmic rays**
- **The magnetic field strength estimated from the Mach cone angle is $\sim$ 3-6 μG for an intracluster medium density of $n \sim 10^{-4}$ cm^{-3}**

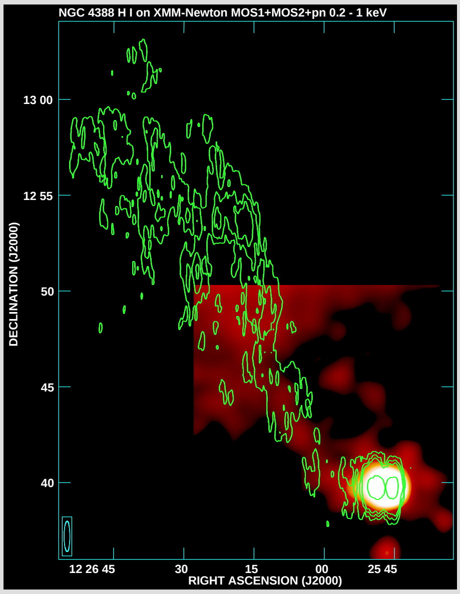

FIG. 4: X-ray emission (0.2-1 keV) of NGC 4388 together with the HI map from Oosterloo & van Gorkom (2005). The X-ray map was cut at the position, where contribution from the M 86 halo starts to dominate. The first greyscale corresponds to 7 times the rms noise level.

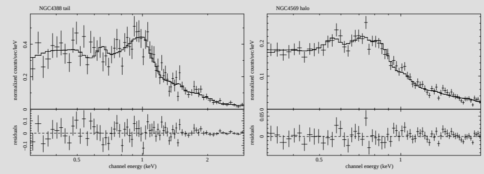

FIG. 5: Spectra of the hot gas tail of NGC 4388 (left) and of the inner hot gas halo of NGC 4569 (right) with the fitted models. "Double-peaked" model fits show that we can trace different gas components (i.e. ISM/ICM) in the X-ray emission.

NGC 4388 (Fig. 4)

- An impressive hot gas tail associated with the Hα plume (Yoshida et al. 2002, ApJ, 567, 118) and the huge HI tail discovered by Oosterloo & van Gorkom (2005, A&A, 437, L19)
- The spectrum (Fig. 5 left) traces the hot ISM (~ 0.9 keV) and the ICM (~ 2.3 keV)
- The thermal pressure in the tail is a few times lower than the estimated ram pressure
- **The estimated total gas mass of the tail ($\sim 6\times10^8$ M$_\odot$) is much lower than the expected stripped gas mass based on the HI deficiency (2×10^9M$_\odot$; Vollmer & Huchtmeier 2007, A&A, 462, 93)**
- **This could be due to a strong ISM-ICM mixing, as well as initial stripping of the outer gas disk, as proposed by Vollmer & Huchtmeier (2007)**

Acknowledgements This work was supported by DLR Verbundforschung "Extraterrestrische Physik" at Ruhr-University Bochum through grant 50 OR 0801 and based on observations obtained with XMM-Newton, an ESA science mission with instruments and contributions directly funded by ESA Member States and NASA.

More in: **2011, A&A, 531, 44**.