Ram Pressure Stripping as an Agent of Galaxy Evolution

Jeff Kenney (Yale)

GALEX UV of IC3418 (10x) on ROSAT X-Ray of Virgo Cluster
3D Ram Pressure Stripping as a 3D Agent of Galaxy Evolution in 3D

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GALEX UV of IC3418 (10x) on ROSAT X-Ray of Virgo Cluster
Ram Pressure Stripping does these things:

- completely strips dwarf galaxies in Virgo-like clusters
- partially strips large spirals in Virgo-like \((M \approx 10^{14} \, M_{\text{sun}})\) clusters
- completely strips massive galaxies during first infall into Coma-like \((M \approx 10^{15} \, M_{\text{sun}})\) clusters
- completely strips (small) dwarf satellite galaxies close enough to their (large) host galaxy

must be **important starvation mechanism** in high and medium density environments—gas removed from outer galaxy or halo by r.p. will not settle to inner disk & form stars
Hα on optical Subaru

Yagi+10

RPS Hα tails in Coma galaxies

peak ram pressure ~100x stronger than Virgo

Yoshida+08

RB199 merger remnant now being r.p.s.
RPS of massive spirals in massive clusters at \( z=0.3-0.4 \)

HST

F606+F814

Ebeling+2014
Diagnostic of active ram pressure stripping: Gas vs. Stars

Virgo Cluster
VIVA survey
~50 spirals

Truncated gas disks with normal stellar disks
& one-sided extraplanar gas features;
outside-in gas removal

Abramson+11
Kenney+04
Chung+09
Time Sequence of Stripping

XP HI: 40%

older <5%

intermediate 25%

recent

HI on R

100 Myr

NGC 4522

HI on R

300 Myr

NGC 4569

outer disk

500 Myr

IC 3392

SDSS Optical image

WIYN Optical spectra

N4522

N4569

I3392

XP HI:
Ram pressure stripping & color evolution

Contours: general SDSS galaxies
Points: ram pressure stripped Virgo spirals

+ Virgo cluster VIVA sample
~50 spirals

$\nu > 400$ Myr
$\nu = 200 - 350$ Myr
$\nu < 100$ Myr

Galaxies with good evidence for RPS:

- Quenching times from spectra
- No spectra

Ram pressure stripping (>partly) responsible for cluster spirals in “green valley” & “red sequence”
Anemic galaxies: gas lost thru “starvation”? 
Gas accretion to inner disk cut off by tidal forces or gas stripping
Starvation
removal of gas from outer galaxy disk or halo
so that it can’t accrete to inner galaxy
can be caused by either tidal or rp stripping

starvation naturally accompanies incomplete rps
rps removes gas directly from outer galaxy, causing:
• immediate outer galaxy quenching
• gradual inner galaxy quenching by starvation

Virgo spiral NGC 4216
Weak star formation throughout disk (anemic)
On red sequence
No HI beyond optical diameter
Inner disk probably starved by past rps of outer galaxy
How does the universe turn dwarf irregular galaxies into dwarf elliptical galaxies?

I Zwicky 18: a dwarf irregular with lots of gas and star formation

NGC 185, a dwarf elliptical with no gas or star formation
Virgo Cluster Dwarfs

Binggeli Sandage & Tammann 1987

dl’ s least concentrated

dE’ s most concentrated

→ Something transforms dwarfs from dl->dE in the cluster center
Local Group Dwarfs: HI content vs. distance from MW or M31

~ All dwarfs D>300 kpc are gas-rich
~ All dwarfs D<300 kpc are gas-poor

Dwarfs (spirals) get their gas r.p. stripped by the gaseous halo of their host galaxy (cluster) – just as spirals get their gas r.p. stripped by the gaseous halo of their host cluster.
No isolated quenched dwarfs

There are no isolated quenched dwarf galaxies in mass range $10^7 M_{\text{sun}} < M_{\text{star}} < 10^9 M_{\text{sun}}$

Quenching mechanism works only near a massive central galaxy

SDSS galaxies

Geha+12
We are probably witnessing the transformation of a dwarf irregular galaxy into a dwarf elliptical galaxy by complete ram pressure stripping.
Main body of IC3418

inner $R<30'' = 2$ kpc
Morphology: substructure
  => recent star formation

outer $R=30'' - 1' = 2-4$ kpc
Morphology: spiral structure,
  “Plume” of extra blue light on tail side

Radial light profile: exponential, just like
nearly all other dIs and dEs
Smoothed “Deep” R-band image

- Outer isophotes fairly regular => not (strongly) tidally disturbed
- Tail has no old smooth stellar component (to $\mu_R = 26.5$ mag arcsec$^{-2}$) only gas & young stars!

IC3418 WIYN Smoothed R on NUV

Kenney+2014
How we know tail is formed by ram pressure and not tidal interaction or starburst outflow

• Stellar body of galaxy appears undisturbed

• Tail is straight, one-sided, centered on galaxy center, composed of gas & young stars but not old stars

• “Fireball” phenomenon requires ram pressure
HI and H\(\alpha\): none in body, a little in outer tail

VLA VIVA survey data
HI detected (5\(\sigma\)) in only one 10 km/s channel
Peak \(\Sigma_{\text{HI}} = 3 \times 10^{19}\) cm\(^{-2}\)
\(M_{\text{HI}} = 4 \times 10^7 M_{\odot}\)

WIYN H\(\alpha\) image
8 HII regions in outer half of tail
\(L_{H\alpha} = 2 \times 10^{38}\) erg/s
SFR \(~ 0.002 M_{\odot}/yr\)

Kenney+2014
Velocities of HII regions in tail from Keck DEIMOS spectroscopy

Tail HII regions V=+40-115 km/s wrt galaxy

Redshifted, toward ICM velocity, as expected for ram pressure

Tail HII regions close to galaxy velocity of 170 km/s, do not extend to cluster velocity of 1070 km/s

In simulations tail extends to ICM velocity – tail in IC3418 may be much longer but only inner part has star formation

Kenney+2014
Velocities modestly (by 40-115 km/s) offset toward cluster velocity
Modest velocity gradient with significant scatter
Kinematics of gas in simulated tail

Gas density & velocity vs. distance from galaxy

Contours: gas density
Points: stars

250 Myr after ICM wind hits disk (constant ram pressure)

Tonnesen & Bryan 2012

Velocity gradient & scatter similar in IC3418 & simulations
But detected tail much shorter in IC3418 → True tail
probably much longer but conditions unsuitable for star formation
“Fireballs” in Tail of IC3418

- 3 brightest outer tail UV sources have head-tail morphology with HII region at head ("fireballs")
- Gas and newly-formed stars (HII regions) at outermost head of linear stellar streams
- Hα peaks offset outwards from UV peaks by 1-2” = 75-150pc
- Ram pressure continues to accelerate gas outwards, leaving behind trails of newly formed stars which decouple from the gas since they don’t feel ram pressure
Fireball model

- newly-formed stars
decoupled from
outwardly
accelerating
gas cloud

- ram pressure
accelerates
gas outwards
gas cloud
with ongoing
star formation

- slightly
older stars

- youngest &
brightest stars
“Fireballs” in Coma cluster galaxy RB199 (massive merger remnant)

Inner tail: B only
Outer tail: B+Hα

Gas closer to galaxy has been stripped downstream

Yoshida+08; Yagi+10
When smaller things fall into bigger things….

...expect BOTH a mass-mass (i.e. tidal) AND a gas-gas (e.g. r.p.s.) interaction

...small thing loses its gas to big thing by r.p.s.

...small thing loses outermost stars and gets remaining stars dynamically heated by tidal interaction

BOTH MUST happen to some degree, but relative strength of 2 effects varies, and timing of 2 effects generally very different
Spectacular ram-pressure stripped 70–kpc X-Ray tail in ESO137-001 (Norma cluster $M \sim 10^{15} M_{\text{sun}}$)

Blue: Chandra X-Ray 0.6-2 keV
Red: SOAR H$\alpha$ (Sun+10)
Inset: Optical (Woudt+08)
CO in Stripped Gas Tail of ESO137-001

Blue: Chandra X-Ray
Red: SOAR Hα (Sun+10)

Circles: APEX CO(2-1) (Jachym+14)

Tail has:
~$10^9$ M$_{\text{sun}}$ hot gas (X-Ray)
~$10^9$ M$_{\text{sun}}$ cold gas (CO)

Jachym+2014

molecular
atomic
ionized
Star formation timescale \( (=1/SFE) = T_{\text{gas}} = \frac{M(\text{HI}+\text{H}_2)}{\text{SFR}} \) is 2-50x longer in stripped extraplanar gas than in disks.

Most stripped gas doesn’t form stars but joins the ICM.

- Similar results: Vollmer et al. (2012)
- Jachym et al. (2014)
Inefficient star formation in stripped gas

Star formation timescale (=1/SFE) =

\[ T_{\text{gas}} = \frac{M(\text{HI}+\text{H}_2)}{\text{SFR(}\text{UV}+\text{FIR)}} \]

is 2-5x longer in stripped extraplanar gas than in disks

→ Most stripped gas doesn’t form stars but joins the ICM
Complexity of ESO137-001 tail

Double tail in x-rays
Due to magnetic fields? Ruszkowski+2014 simulations

Sun+2010

Broad tail of “orphan HII regions”
from earlier stage of stripping the outer disk?
dense star-forming clouds decouple from lower density gas
which gets accelerated downstream
Gunn & Gott (1972) criterion for rps

Galaxies moving through gas (from ICM/IGM/ISM) will experience a ram pressure which will push the ISM gas if:

\[ \rho_{\text{ICM}} v^2 > \Sigma_{\text{ISM}} \frac{d\Phi}{dz} \]

- **Ram pressure**
- **Gravitational Restoring force (per area)**

This is criterion for *accelerating* gas not *removing* it!
Efficiency of rps relative to GG72 depends on

- Duration of ram pressure
- Disk-wind angle
- Galaxy rotation
- ISM substructure
- Magnetic fields
Stripping efficiency duration effect

~Radial orbits in cluster

Gunn & Gott (long duration pressure)

Ram pressure vs. time over 1 orbit
Stripping efficiency inclination effect

Jachym+09 simulations galaxies falling on radial orbits thru simple cluster

Face-on stripping most efficient

Highly inclined stripping least efficient

Bigger inclination effect for weaker peak ram pressure and shorter duration ram pressure
Stripping the most massive Coma spiral

HST data obtained by K. Cook for Cepheid program
“Dust front”
Swept-up ISM along leading edge of ICM-ISM interaction

Coma spiral
NGC 4921

Kenney & Abramson 2014
Linear & V-shaped head-tail filaments protruding from dust front

young star complexes at heads
Dense gas clouds too dense to strip are decoupling from lower density gas which is accelerated downstream by rp
BUT decoupling inhibited by magnetic(?) binding
C-shaped filaments along dust front

Lower density gas pushed by ram pressure remains connected by magnetic fields to decoupling higher density gas clouds

Kenney & Abramson 2014
Ridge of strong radio polarization at leading edge magnetic fields aligned with edge
r.p. compresses gas & magnetic fields
Decoupling dense clouds during rps

Filament morphology not consistent with ablation or shadowing but is consistent with magnetic binding

Head-tail dust filaments:
- Length ~ 1000 pc
- Width ~ 100 pc
- $M_{\text{gas}} \sim 10^7 M_{\odot}$

Abramson & Kenney 2014
Summary: Ram Pressure Stripping does these things:

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