Towards a complete understanding of the Magellanic Stream Formation

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Ferdinand Magellan
1519-1522
• In the context of Milky Way

ram pressure v.s. tidal model

• Wang et al. 2019 (MNRAS, 486, 5907)
• Hammer et al. 2018 (ApJ, 813, 110)
• Yang et al. 2014 (MNRAS, 422, 2419)

• In the context of Local Group

the origin of MCs & other dwarf galaxies

• Hammer et al. 2019 (ApJ, accepted; arXiv:1812.10714)
• Hammer et al. 2018 (ApJ, 860, 76)
• Hammer et al. 2018 (NRAS, 475, 2754)
• Hammer et al. 2013 (MNRAS, 431, 3543)
• Fouquet et al. 2012 (MNRAS, 427, 1769)
• Yang & Hammer 2010 (ApJ, 725, L24)
Increasing Evidences:

- Dichotomy distribution of dSph and dIrr about the virial radius of MW/M31 eg. Greveich, Putman 2010, $\rho_{\text{hot}} \sim 4 \times 10^{-4} \text{ cm}^{-3}$ out to 100 kpc

- Associated high velocity clouds are disrupted (head tail & multi-velocity components, Karlberla & Haud, 2006) $\rho_{\text{hot}} \sim 10^{-4} \text{ cm}^{-3}$ at 50 kpc

- X-ray observations (Gupta et al., 2012, Hodges-Kluck, Miller & Bregman, 2016)

- Warm CGM (Circum-Galactic Medium, Zheng et al. 2019)
An impasse has been reached after 37 years of hard work by many astronomers, and we are now no closer to reaching an understanding of the origin of the Magellanic Stream than when I was in the Control Room of the 210-ft Parkes Radio Telescope pumping air some 40 years ago! Perhaps there is something very fundamental about our Galaxy that we don’t know?
Mastropietro+2010, first infall

- Column density
- morphology
- no SMC modeled
- LA?? (possibly solved in Mayer 2010)
- not consistent with HST PM of LMC

Besla+2012

- Lack factor 10 in N(HI)
- MW hot gas is not modeled

Fox+2014, ionized gas in MS
2 x 10^9 Msun

Tepper-García+2019: hot gas will destroy “LA” in the tidal model

Yanbin YANG  A synoptic view of the Magellanic Clouds: VMC, Gaia and beyond, ESO,Garching, 09/2019
The nature of the MS
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Hammer+2015 using GASS data (Kalberla, 2009)
Putman 2003 : DNA structure
Transonic (Mach=1.5) flow with vortices?

ΔV_{max} = 36 \text{km s}^{-1} + 1 \times \Delta V_{max} = 27 \text{km s}^{-1} + 1

ΔV_{max} = 30 \text{km s}^{-1} + 1

ΔV_{max} = 46 \text{km s}^{-1} + 1

ΔV_{max} = 26 \text{km s}^{-1} + 1

ΔV_{max} = 17 \text{km s}^{-1} + 1
~ 200 Myr old collision between the Magellanic Clouds

Evidenced by:

- the Bridge
- same SFH peak of the Clouds (~200Myr, Weisz+2013)
- proper motions
- Relics in GASS data (anomalous HVCs)
Ram-pressure plus collision scenario

Yang+2014

van der Marel+2014

Fox +2014

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From vdM06
Right: RGB+AGB
Left: HI (Kim 98)
Images scaled

1° = 0.87 kpc for D=50.1 kpc

23.55 x 21.55 = 20.49 kpc x 18.75 kpc

δ > 1 deg

(2) MS-II-III-IV (GASS)
modelling

- Software: Gadget2 (Springel 2005), classical SPH
- MilkyWay model with hot gas in the halo ($\rho \sim 10^{-4}/\text{cm}^3$ at 50 kpc)
- Initial LMC: mass, $1.8 - 5 \times 10^9$ M$_\odot$; $f_{\text{gas}}$, 40-60%
- Initial SMC: mass $\sim 0.7$ LMC mass, $f_{\text{gas}}$, 40-70%
- Initial Orbits: Trace back 2 - 4Gyr (correcting energy dissipation)
- Reproduce present-day stellar and gas mass within 20% accuracy
The Magellanic Stream System: Ram-pressure tails and the relics of the collision between the Magellanic Clouds (Hammer+2015)

Observation hydrogen
Nidever+2010

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two more extraordinary discoveries are challenging the modelling:

Surprising 3D shape of the small Magellanic cloud (SMC)

hot, ionized gas in MS system (5-10 times massive than HI)

Ripepi+2017
Scowcroft+2016
see also Mathewson+1986!

Fox+2014
Richter+2017!
two more extraordinary discoveries are challenging the modelling:

- Surprising 3D shape of the small Magellanic cloud (SMC)
- hot, ionized gas in MS system (5 times massive than HI)

See also Mathewson+1986!
Modelling Magellanic Stream and Clouds: ram-pressure + collision

GIZMO Hopkins+2014, eg FIRE

Milky Way: hot gas density & rotation curve (12-16M particles) fitting observation data

Hot gas in hydrodynamic equilibrate and cold gas, stars disks within the analytic dark matter halo

- Initial LMC: mass, $5 \times 10^9 M_\odot$, $f_{\text{gas}}$, 50%
- Initial SMC: mass, $\sim 0.6$ LMC mass, $f_{\text{gas}}$, 40-70%

Prochaska et al. 2017
Results from simulations (Wang+2019, MNRS)
"Ram pressure + collision between Magellanic Clouds" is able to reproduce all Magellanic Stream & Clouds properties with great success!

| properties of MS          | ram pressure + collision |
|---------------------------|--------------------------|
| Bridoe                    | Y                        |
| Leading arm (4 arms!)     | Y(e.g., Yanq+2014, Mayer 2010) |
| no stars in main stream   | Y                        |
| Length (150 degree, main stream) | Y                      |
| N(HI) density             | Y                        |
| Tow filaments (MS I)      | Y                        |
| DNA-like filaments (MS II, III, IV) | Y (limited by simulations) |
| bifurcation (MS V, VI)    | Y                        |
| S0 filament               | Y                        |
| ionized gas (10^8 Msun)   | Y                        |
| life time of stream (a few 100Myr) | Y                      |
| Stream total HI mass      | Y                        |
| Stream location and velocity | Y                    |
| relics of shocks          | Y                        |

| properties of MW          | ram pressure + collision |
|---------------------------|--------------------------|
| MW hot gas (n ~ 10^-4/cm^3) | Y                        |

| properties of MCs         | ram pressure + collision |
|---------------------------|--------------------------|
| Shrunken LMC HI disk      | Y                        |
| LMC proper motion         | Y                        |
| LMC star and gas center offset by 1 kpc | Y |
| LMC rotation curve        | Y                        |
| SMC 3D morphology (30 kpc in depth) | Y |

Yindeer et al. 2010
Model

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Metallicity of MS sampled by observing 5 active galactic nuclei (Fox et al. 2013 and Richter et al. 2013)
The Bridge formation

- There is gap between Young stars and old star
- The OB stars are leaving SMC

Belokurov et al. 2017

Oey et al. 2018
Similar behaviour than hydrodynamical flows with similar \((\text{Re, Strouhal})\) numbers, including vortices (or hairpin shedding).

First wake instabilities on a flow, \(\text{Re}=400\), Wesfreid et al. 2014

Collaboration with ESPCI Paris
Simulated LMC proper motion

No Dark Matter in the Magellanic Clouds?

Gaia dr2 (H18)
Table 2  LMC and SMC Proper Motion Measurements

| Study Method                   | LMC | SMC | Refs. |
|-------------------------------|-----|-----|-------|
|                               | $\mu_W$ (mas/yr) | $\mu_N$ (mas/yr) | $\mu_W$ (mas/yr) | $\mu_N$ (mas/yr) |
| MS Model (G94)                | $-1.72$ | $0.12$ | $...$ | $...$ | (1,2) |
| MS Model (HR94)               | $-2.0$ | $0.16$ | $...$ | $...$ | (3) |
| Ground-based+Hipparcos$^a$    | $-1.68\pm0.16$ | $0.34\pm0.16$ | $-1.16\pm0.18$ | $-1.17\pm0.18$ | (4) |
| HST two-epoch (K1,K2)         | $-2.03\pm0.08$ | $0.44\pm0.05$ | $-0.754\pm0.061$ | $-1.252\pm0.058$ | (5) |
| HST two-epoch (P08)           | $-1.56\pm0.036$ | $0.435\pm0.036$ | $-0.93\pm0.14$ | $-1.25\pm0.11$ | (6) |
| 2.5m du Pont                  | $-1.72\pm0.13$ | $0.50\pm0.15$ | $-0.98\pm0.30$ | $-1.10\pm0.29$ | (7) |
| Southern Proper Motion        | $-1.89\pm0.27$ | $0.39\pm0.27$ | $-0.722\pm0.063$ | $-1.117\pm0.061$ | (8) |
| HST three-epoch (K3)          | $-1.910\pm0.02$ | $0.229\pm0.047$ | $...$ | $...$ | (9) |
| Helmi+2018, Gaia-Dr2          | $-1.89 +/- 0.03$ | $0.314 +/- 0.03$ | $...$ | $...$ | |
Increasing density of the hot gas

Putman 2003a

Kalberla & Haut 2006
The Magellanic Stream System: Ram-pressure tails and the relics of the collision between the Magellanic Clouds (Hammer+2015)

Observation hydrogen Nidever+2010

simulation "hydrogen" Hammer+2015

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| properties of MS | Tidal (ref. Besla et al.2012) | ram pressure + collision |
|-----------------|-------------------------------|-------------------------|
| Bridge          | Y                             | Y                       |
| Leading arm (4 arms!) | N                             | Y (e.g, Yang+2014, Mayer 2010) |
| no stars in main stream | N                             | Y                       |
| Length (150 degree, main stream) | Y                             | Y                       |
| N(HI) density   | N                             | Y                       |
| Tow filaments (MS I) | N                             | Y                       |
| DNA-like filaments (MS II, III, IV) | N                             | Y (limited by simulations) |
| bifurcation (MS V, VI) | ...                           | ...                     |
| S0 filament     | N                             | N (explained)           |
| ionized gas (10^9 Msun) | N/show-stopper               | N (Gadget cannot resolve K-H instability) |
| life time of stream (a few 100Myr) | N                             | Y                       |
| Stream total HI mass | N                             | Y                       |
| Sream location and velocity | Y                             | Y                       |
| relics of shocks | Y                             | Y                       |
| properties of MW |                               |                         |
| MW hot gas (n ~ 10^-4/cm^3) | N                             | Y                       |
| properties of MCs |                               |                         |
| Shrunken LMC HI disk | N                             | Y                       |
| LMC proper motion | Y                             | Y                       |
| LMC star and gas center offset by 1 kpc | Y                             | Y                       |
| LMC rotation curve | Y                             | Y                       |
| SMC 3D morphology (30 kpc in depth) | Y?                            |                         |
Feedback prescriptions: 5 times the median Cox+06 value