NEW RESULTS ON COUNTER-ROTATING GALAXIES FROM 3D SPECTROSCOPIC PROJECTS

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OUTLINE

Topics
- Definition
- Classification
- Size
- Components
- Morphological signatures
- Kinematic signatures
- Statistics
- Stellar populations
- Formation scenarios

Focus on
- Normal and bright galaxies
  (interacting galaxies = Barrera-Ballesteros, dwarfs = Ryś)
- Main-plane decoupled components
  (off-plane components = Coccato, Sil’chenko)
Counter-rotation is observed when two galactic components have their angular momenta projected antiparallel onto the sky plane.

- **intrinsic**: the components rotate around the same axis
- **apparent**: the components rotate around skewed axes and the line of sight lies between them (multi-slit/IFU spectroscopy)
NGC 4365 – E3
isolated core

Surma & Bender (1995)
NGC 4365 – E3
isolated core

Davies et al. (2001)

Surma & Bender (1995)
CLASSIFICATION

Counter-rotation occurs in a variety of forms

✧ **gas vs stars**: the gaseous disk counter-rotates with respect to the stellar body (e.g., NGC 4546)

✧ **stars vs stars**: two stellar components counter-rotate (e.g., NGC 4550)

✧ **gas vs gas**: two gaseous disks counter-rotate (e.g., NGC 7332)
NGC 4546 – SB0
gas vs stars counter-rotation

Galletta (1987)
NGC 4546 – SB0

gas vs stars counter-rotation

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NGC 4550 – SB0
stars vs stars counter-rotation

Rubin (1992)
NGC 4550 – SB0
stars vs stars counter-rotation

Rubin (1992)
Johnston et al. (2013)

- galaxy + fit
- stars #1
- stars #2
- gas
- residuals

Hβ region

Wavelength (Å)

Primary Disc
Secondary Disc
Hy and Hβ emission
OIII emission

V_{LOS} [km/s]

V_{LOS-V_0} [km/s]

Radius (arcseconds)
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NGC 7332 – S0 pec
gas vs gas counter-rotation

Fisher et al. (1994)
NGC 7332 – S0 pec
gas vs gas counter-rotation

Fisher et al. (1994)
NGC 7332 – S0 pec
gas vs gas counter-rotation

Plana & Boulesteix (1996)
NGC 7332 – S0 pec
gas vs gas counter-rotation

Plana & Boulesteix (1996)
Counter-rotation is observed in

- **inner regions** of the galaxy (cores, small-scale disks, bulges, bars) (e.g., NGC 3593)
- **outer regions of the galaxy** (nested disks) (e.g., NGC 4826)
- **overall the galaxy** (large-scale disks) (e.g., NGC 3626)
NGC 3593 – S0/a
inner counter-rotation

Bertola et al. (1996)
NGC 3593 – S0/a
inner counter-rotation

Bertola et al. (1996)
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- **overall the galaxy** (large-scale disks) (e.g., NGC 3626)
NGC 4826 (M64) – Sab
outer counter-rotation

Braun et al. (1992): HI
Rubin (1994): ionized gas
Rix et al. (1995): stars
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NGC 3626 – S0/a
overall counter-rotation

Ciri et al. (1995)
## COUNTER-ROTATING COMPONENTS

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>HOST</th>
<th>TYPE</th>
<th>REGION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core</td>
<td>E</td>
<td>stars vs. stars</td>
<td>inner</td>
</tr>
<tr>
<td>Bulge (?)</td>
<td>S0</td>
<td>stars vs. stars</td>
<td>inner</td>
</tr>
<tr>
<td>Disk</td>
<td>E, S0, S</td>
<td>gas vs. stars stars vs. stars gas vs. gas</td>
<td>inner outer overall</td>
</tr>
<tr>
<td>Secondary bar</td>
<td>SB0</td>
<td>stars vs. stars</td>
<td>inner</td>
</tr>
<tr>
<td>Stars in bar</td>
<td>SB0, SB</td>
<td>stars vs. stars</td>
<td>inner</td>
</tr>
</tbody>
</table>
MORPHOLOGICAL SIGNATURES

�� Early-type galaxies harboring KDCs
  • do not differ from galaxies without KDCs (Krajnovic et al. 2011)

뱅 No late-type spirals with counter-rotation
  • most of spirals are early (S0/a-Sab) with smooth arms
  • arm suppression is predicted by simulations of multi-armed spirals triggered by density inhomogeneities (D’Onghia et al. 2013)

뱅 No evidence of interaction
  • same environment of galaxies with no counter-rotation (Bettoni et al. 2001)
  • need for deep optical imaging (e.g., Duc et al. 2011) since fine structures due to accretion events have low surface brightness (~27 mag arcsec\(^{-2}\))
The detection of a counter-rotating gaseous disk is straightforward

- opposite inclination of emission/absorption lines

The detection of a counter-rotating stellar component

- depends on the fraction of retrograde stars, their velocity with respect to prograde stars, and instrumental setup
- requires a bimodal LOSVD
- can be suggested by a double-peaked velocity dispersion
Bureau & Chung (2006)

NGC128
S0 pec

NGC3203
S0

NGC0128

NGC 0128

stars

gas

NGC 3203

stars

gas

Position (arcsec)
KINEMATIC SIGNATURES

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The detection of a **counter-rotating stellar component**

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IC 719 – S0  
counter-rotating stellar disks  
Katkov et al. (2013)  

LOSVD  
\[ \text{fit} = \text{stars #1} + \text{stars #2} \]  
Gauss-Hermite fit
KINEMATIC SIGNATURES

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Vergani et al. (2007)

NGC 5719 – Sab
counter-rotating stellar disks

Vergani et al. (2007)
double $\sigma$-peak galaxies

Krajnovic et al. (2011)
STATISTICS – EARLY-TYPE GALAXIES

long-slit data/IFU data

✧ Early-type galaxies - gas vs stars
  • Bertola et al. (1990): 3/6 dust-lane Es = 50%
  • Bertola et al. (1992): 9/26 S0s with gas = 35%
  • Pizzella et al. (2004): 17/53 S0s with gas = 32%
  • Davis et al. (2011): 9/133 E/S0s with gas = 7% (40% decoupled)

✧ Early-type galaxies - stars vs stars
  • cores: Mehlert et al. (2000): 1/35 Coma E/S0s = 3%
    Krajnovic et al. (2011): 8/260 E/S0s = 4%
  • disks: Kuijken et al. (1996): 0/17 S0s with gas = <10% (with 10% stars on retrograde orbits)
STATISTICS – SPIRALS

long-slit data/IFU data

✧ Spirals - gas vs stars
  • Kannappan et al. (2001): 0/38 Sa-Sbc = <8%
  • Pizzella et al. (2004): 2/50 S0/a-Sd = 4%
  • Falcon-Barroso et al. (2006): 1/24 Sa = 4%
  • Ganda et al. (2006): 0/18 Sb-Sd = 0%
  • Barrera-Ballesteros et al. (2014): 0/77 Sa-Sc = 0%

✧ Spirals - stars vs stars
  • Pizzella et al. (2004): 1/50 S0/a-Sd = 2%
  • Falcon-Barroso et al. (2006): 1/24 Sa = 4%
  • Ganda et al. (2006): 0/18 Sb-Sd = 0%
FORMATION SCENARIOS

Different scenarios for building counter-rotating components

✧ external origin
  • gas accretion: retrograde acquisition of gas and subsequent star formation (e.g., Thakar & Ryden 1996, 1998)
  • minor merging: retrograde capture of a (gas-rich) dwarf companion (e.g., Balcells & Quinn 1990, Thakar et al. 1997)
  • major merging: gas for cores (e.g., Hoffman et al. 2010) tuned initial conditions for disks (e.g., Crocker et al. 2009)

✧ internal origin
  • bar structure: retrograde orbits trapped around $x_4$ family (Wozniak & Pfenniger 1997)
  • bar dissolution: box-orbit stars are scattered onto clockwise/counter-clockwise-streaming tube orbits (Ewans & Collett 1994)
Thakar & Ryden (1998)

rotating stars

$t = 6.0$

counter-rotating gas

t = 6.0

infalling gas

stars

$t = 2.0$

face-on view

$t = 2.5$

$t = 3.0$ (x2)

$t = 4.0$ (x2)

$t = 4.5$ (x2)

$t = 5.0$ (x4)

$t = 5.5$ (x4)

$t = 6.0$ (x4)

edge-on view

$t = 2.0$

$t = 2.5$

$t = 3.0$ (x2)

$t = 4.0$ (x2)

$t = 4.5$ (x2)

$t = 5.0$ (x4)

$t = 5.5$ (x4)

$t = 6.0$ (x4)

face-on view

edge-on view

rotating stars

$t = 1.5$

$t = 6.0$

counter-rotating gas

$t = 6.0$

Thakar & Ryden (1998)
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gas-rich dwarf

face-on view

stars

edge-on view

Thakar et al. (1997)
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Crocker et al. (2009)

gas

stars

prograde

retrograde

tar density            star velocity            gas velocity

T=250 Myr

prograde

T=500 Myr

retrograde

T=750 Myr

prograde

T=1250 Myr

star density

star velocity

gas velocity
FORMATION SCENARIOS

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SB0s - local stellar counter-rotation

data

self-consistent models

Bettoni (1989)

Wozniak & Pfenniger (1997)
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STELLAR POPULATIONS

The properties of the stellar populations are a key to disentangle between the different formation scenarios

✧ external origin
  • gas accretion: counter-rotating stars are associated with gas and younger than the host galaxy
  
  • minor/major merging: counter-rotating stars are not always associated with gas and younger than the host galaxy

✧ internal origin
  • bar dissolution: the two counter-rotating components have the same stellar population
NGC 5719 – Sab
counter-rotating disks

Vergani et al. (2007)
Coccato et al. (2011)

stars #1
- older
- more metal-rich

stars #2
- younger
- less metal-rich
NGC 5813 – E1-2
counter-rotating core

Kuntschner et al. (2010)
Krajnovic et al. (2015)

stars host
- old
- less metal-rich

stars core
- old
- more metal-rich
COUNTER-ROTATION: STATUS

✧ It shows a variety of forms (gas vs gas, stars vs stars, gas vs gas)

✧ It is observed in different regions (inner, outer, overall)

✧ No obvious morphological signatures (but not in late-type spirals)

✧ Obvious kinematic signatures (but LOSVD issue for detecting stars vs stars)

✧ It is not so rare (4% Es with stars vs stars; 30% S0s with gas vs stars; <10% S0s with stars vs stars; <10% spirals with gas/stars vs stars; most of SB0s)

✧ Both external (accretion) and internal (bar) processes explain the formation of counter-rotation

✧ Stellar populations promise to nail down the formation mechanism
COUNTER-ROTATION: FUTURE

✧ **Photometry**: deep imaging survey to look for fingerprints of accretion/merging events

✧ **Kinematics**: detailed analysis of LOSVD to look for undetected retrograde stars

✧ **Statistics**: volume/luminosity-limited samples to drive unbiased conclusions

✧ **Simulations**: not limited to few cases but exploring a wider parameter-space

✧ **Stellar populations**: to test predictions of the formation scenarios