Gas and Stellar Spiral Arms and Their Offsets in the Grand-Design Spiral Galaxy M51

Fumi Egusa (National Astronomical Observatory of Japan)  
江草芙実（国立天文台）

Erin Mentuch Cooper (Texas), Jin Koda (Stony Brook),  
and Junichi Baba (NAOJ)

**Key Question**

- “What is a lifetime of spiral arms?”
- “Are they long-lived or short-lived?”
- this is related to an evolution of spiral galaxies
- z=0: ~70% of galaxies are spiral
- z=0.65 (6 Gyr ago): only ~30% of galaxies are spiral (Delgado-Serrano+2010)
Theories of Spiral Structure

- The winding problem
  - if spiral arms rotate differentially, they become too tightly wound within a few rotations, i.e. ~Gyr
  - this is against the current predominance of spiral galaxies

http://ircamera.as.arizona.edu/astr_250/Lectures/Lecture_23.htm
Density Wave Hypothesis

- Spiral arm is a quasi-stationary density wave (Lin & Shu 1964)
- based on an idea that “spiral arms should be long-lived”
- linear and local analysis assuming tightly-winding spiral arms
- spiral pattern is a rigid body for > a few Gyr

Galactic Shock

Gas response to **fixed** stellar spiral arms

- Fujimoto (1968), Roberts (1969)
- super-sonic gas flow experience a shock around potential minima
- increased gas density has been regarded as a trigger of star formation

reproduced from Roberts (1969), http://ned.ipac.caltech.edu/level5/Sept04/Pasha2/Pasha2_3.html
Tidal Arms

- Indication from simulations
  - isolated two-armed spiral structure w/o bar is difficult to form
- Interaction with a companion galaxy can drive m=2 spiral
  - tidal arms are still transient but live ~1 Gyr

Top: amplitude of mode for stellar and gas disk
Bottom: stellar disk for 800 Myr (Pettitt+2016)
Spiral arm becomes stronger when it changes from leading to trailing.
- has been regarded as a model for multi-arm and/or flocculent galaxies

High-res. N-body simulations
- stellar disk can maintain spiral structure w/o cooling (Fujii+2011)

From leading to trailing (left to right), arm density becomes higher due to epicyclic motion (Toomre 1981)

Transitory but recurrent multi-arm structure (Fujii+2011)
steady (fixed) spiral models

- shock location moves from downstream to upstream with increasing radius (i.e. different pitch angles for stellar and gas arms)
- same trend for all models with different parameters

dynamic spiral models: shock almost coincides with potential minima

Baba, Morokuma-Matsui, & FE (2015)

location of stellar spiral

color: gas density

steady spiral model:

- shock location moves from downstream to upstream with increasing radius (i.e. different pitch angles for stellar and gas arms)
- same trend for all models with different parameters
Gas-Star Offsets in M51

- M51 (NGC 5194)
  - nearby grand-design spiral galaxy
  - one of the best studied galaxies

Data
- $\Sigma_H$: from HI + CO
- $\Sigma_{\text{star}}$: from SED fitting

Gas and stellar surface density in the sky (RA, DEC) and in the polar coordinates $(r, \theta)$. Solid contours are the arm definition.
Gas-Star Offsets in M51

- Gas and stellar peak positions from azimuthal profiles
- peak (by arrow)
- gauss-fit (red dashed curve)

Gas-star offsets vs radius from the peak-finding method. Two arms separated by colors. “matched” means peaks from both methods consistent. Green-dashed line represent a prediction of fixed spiral (i.e. galactic shock) model by Baba+2015.

In the inner region (r<150”), two arms behave differently.
Gas-Star Offsets in M51

- Inner region (r<150")
  - arm1: inconsistent with galactic shock
    - short-lived (< 0.5 Gyr), dynamic spiral
  - arm2: consistent with galactic shock
    - long-lived (> 0.5 Gyr), steady spiral

CO-Hα offsets (Egusa+2009):
- arm1: consistent with density waves
  - 10 Myr < lifetime < 0.5 Gyr
- arm2: inconsistent with density waves
  - why??
## Lifetime by Two Offset Methods

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>NO</td>
<td>“slowly-winding”</td>
</tr>
<tr>
<td>YES</td>
<td>“long-lived”</td>
</tr>
<tr>
<td>M51 arm1</td>
<td>long</td>
</tr>
<tr>
<td>lifetime</td>
<td>noncircular motion?</td>
</tr>
<tr>
<td>M51 arm2</td>
<td>$t_{\text{SF}}$ not constant?</td>
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- $t \lesssim 500$ Myr
- $t \gtrsim 500$ Myr
“What is a lifetime of spiral arms?”

Numerical simulations suggest that gas-star offset can tell if spiral arms are long-lived or short-lived.

Gas-star offsets in M51
- different behaviors for two arms
- arm1: short-lived, consistent with slowly winding tidal arm?
- arm2: long-lived, but not consistent with CO-H\(\alpha\) offset result?