Test of the density-wave theory based on VLBI astrometry results

Sakai et al. 2015

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July 8, 2015@EAVN workshop in Hokkaido univ.
Density wave theory (Lin & Shu 1964)

Recurrent transient spiral (e.g., Miller+1970; many papers)

Fujii et al. 2011: N-body simulation

- Spiral arm is the most prominent structure in a disk galaxy.

- However, the nature, origin and evolution are still unknown.
Context: 1-D observation

(Burton 1973)
● Distribution of line-of-sight velocity is **asymmetry** in the MW.
→ **Effect of spiral arm?**

● The observed velocity field might be explained by a gravitational perturbation (i.e., **spiral arm**) in the context of the **density-wave theory**.

**Systematic non-circular motion** might be explained by the **density-wave theory**!
3D non-circular motion \((U, V, W)\) in Reid+09

Averaged non-circular motions with 8 sources in the Perseus arm
\((U_{\text{mean}}, V_{\text{mean}}) = (9.8\pm2.6, -17.8\pm2.5)\) km/s in Sakai et al. (2012)

\(\rightarrow\) Systematic inward motion and slower Gal. rotation
3D non-circular motion \((U, V, W)\) in Reid+09

Right-handed coordinate system

Choi et al. (2014) found the same tendency with 25 sources!

Averaged non-circular motions with 8 sources in the Perseus arm
\((U_{\text{mean}}, V_{\text{mean}}) = (9.8+/-2.6, -17.8+/-2.5) \text{ km/s} \) in Sakai et al. (2012)

→ Systematic inward motion and slower Gal. rotation
1. Cont. & Goals

Goals of this research

① We compare astrometry (3D) results for the Perseus arm with an analytic gas dynamics model for testing the density-wave theory.

② Using the results, we make a suggestion toward an incoming astrometry (e.g., Gaia).

Ultimate Goal

- We understand the nature, origin and evolution of the spiral arm especially for the Milky Way Galaxy.
The least squares fit

Observables $(U, V)$ for 27 sources in the Perseus arm

$\chi^2_U$ was minimized.

Spiral model (density wave)
- Pinol-Ferrer+12 & 14 (analytic)
- Equations of motion with gas friction term were solved using the linear approximation.

(Zanmer Sanchez+08)
Gas distribution model

\[ (U_{\text{mean}}, V_{\text{mean}}) = (8{\pm}3, -9{\pm}2) \text{ km/s} \]

\[ (\Delta U_{\text{mean}}, \Delta V_{\text{mean}}) = (-2{\pm}2, -2{\pm}2) \text{ km/s} \]
Results

(U_{mean}, V_{mean}) = (8+/−3, −9+/−2) km/s

(ΔU_{mean}, ΔV_{mean}) = (−2+/−2, −2+/−2) km/s

Gas distribution model

Spiral potential model
M51 vs. The model of the Milky Way

\[12\text{CO} \text{ intensity map (Koda+09)}\]

\[\text{The model of the Milky Way (Sakai et al. 2015)}\]
M51 vs. The model of the Milky Way

12CO intensity map (Koda+09)

Massive clumps were traced by bright HII regions.

Egusa+10

Massive clumps

Gal. rotation

Upstream

Downstream

The model of the Milky Way (Sakai et al. 2015)

Gray: 12CO intensity

Circle: Molecular clump
Revised kinematic distance

\[ \frac{D_{\text{kin}}}{D_{\pi}} = 1.45 \pm 0.35 \]

- Impact on astrophysics, e.g., Luminosity \( \propto D^2 \)

Shadow region: \( | \frac{D_{\text{kin}}}{D_{\pi}} | = 1.45 \pm 0.35 \)

-----> Impact on astrophysics, e.g., Luminosity \( \propto D^2 \)
Revised kinematic distance

\[ \frac{|D_{\text{kin}} / D_\pi|}{1.45 \pm 0.35} \]

\[ \frac{|D_{\text{revis-kin}} / D_\pi|}{1.03 \pm 0.20} \]

Impact on astrophysics, e.g., $L \propto D^2$

- Shadow region: $|D_{\text{kin}} / D_\pi| = 1.45 \pm 0.35$

- Shadow region: $|D_{\text{revis-kin}} / D_\pi| = 1.03 \pm 0.20$
We tested the density-wave theory using VLBI astrometry results. Then, we found

① A dense gas region at the downstream of the spiral potential (model) ———> Identical to M51 (Egusa+2011)

② Revised kinematic distance

③ Gas (VLBI) + Stellar (Gaia) astrometry