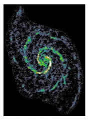
Geometrical offsets between gas compression and star formation across spiral arms - A case study in M51



Melissa Louie[1], Jin Koda[1], and Fumi Egusa[2]

[1]Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY; melissa.louie@stonybrook.edu

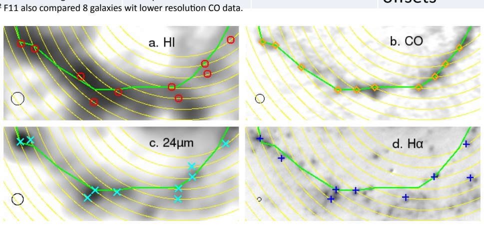
[2]Department of Infrared Astrophysics, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Japan

Geometrical offsets between gas spiral arms and associated star formation are a suggested measure of the star formation timescale and test of the density wave theory. There is a discrepancy between recently reported offsets measured in nearby spiral galaxies. Large and ordered offsets are found between CO and Hα, where as small and non-ordered offsets are found between HI 21 cm and 24 µm emissions. The latter is evidence against gas flow through spiral arms and could be evidence against the conventional density wave theory. We report measurements of geometrical offsets in grand-design spiral galaxy M51 and investigate potential causes. We find consistent offsets with previous measurements and find the difference in gas tracer, HI verse CO, to be the primary cause for the discrepancy. The HI emission is contaminated by the gas photodissociated by recently formed stars and can coincide spatially with the star forming regions, leading to small offsets. We find mostly positive offsets with substantial scatter between CO and Hα, suggesting that gas is flowing through the spiral arms but the spiral pattern may not be constant or stationary.

Offset Between Gas and SF

	Tamburro et al. 2008 (T08)	Egusa et al 2009 (E09)	Foyle et al. 2011 (F11)
Gas Tracer	HI 21 cm (atomic gas)	CO (molecular gas)	HI 21 cm[2]
SF Tracer	24µm	Hα	24µm
Method	Cross-correlation	Peak Tracing	Cross-correlation
SF timescale[1]	~1 Myr	~10Myr	No systematic offsets

[1] Based on ~10 galxies from each study
[2] F11 also compared 8 galaxies wit lower resolution CO data.

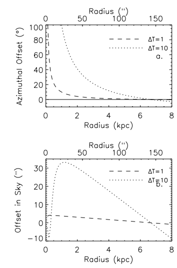


Above: : Locations of the maximum peaks for a section of the Arm 1. The green line traces the maximum points in CO. HI appear along or downstream the spiral arm traced by CO.
HI (Walter et al. 2008), CO (Koda et al. 2009. 2011), 24µm and Hα (Kennicutt et al. 2003).
•24µm appears downstream of CO, no visual offset seen between HI & 24µm
•Hα is leading CO emission in offset , while offset between HI and Hα is small or zero. When offset is seen, Hα is downstream HI

The offset and circular velocity can be measured as a function of radius observationally and can be described by

$$\Delta\theta(r)_{G\rightarrow SF} = \left(\Omega(r) - \Omega_p\right)\Delta t$$

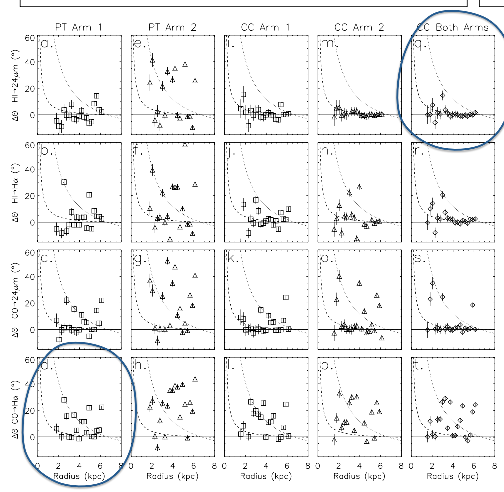
Δθ is the azimuthal offset angle between spiral arm of the gas (G) and star forming regions (SF) and Δt is the time that gas takes to evolve from spiral arm entry into young massive stars (Egusa et al. 2004; E04).



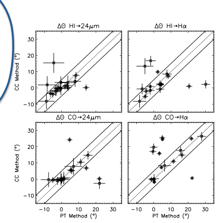
Measuring Offsets

Peak Tracing Method
- Developed by E04, updated in E09
- Offsets are measured by taking the difference in the azimuthal location of peaks between gas and SF tracers at radial bins of 5"
- Emission peaks are determined separately by eye for each tracer

Cross-Correlation Method:
- T08 defined a normalized cross-correlation, $cc_{x,y}(l) = \frac{\sum_k [(x_k - \bar{x})(y_{k-l} - \bar{y})]}{\sqrt{\sum_k (x_k - \bar{x})^2 \sum_k (y_k - \bar{y})^2}}$
- 5" radially binned azimuthal profiles of gas tracers are cross-correlated with SF tracers
- The offset is the maximum of a fourth degree polynomial fit to the peak of $cc_{x,y}$



Azimuthal offsets between gas and SF tracers as a function of radius. The model predictions of offset are overplotted for star formation timescales of 1 and 10 Myr. The circled panels shows the offsets using methods and main tracers used in T08, E09, F11. Arm 1 is the spiral arm furthest from the companion.

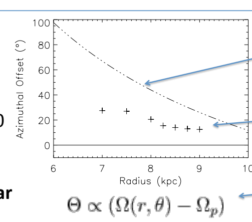


Comparison between the offsets using the CC and PT methods for Arm 1. Neither method appears to bias offsets in any systematic way.

- Reproduced E09 and T08 measurements with their methods and tracers
- Identified the source of the discrepancy as the tracers
- **HI is not only tracing dense gas that will form stars but also gas photodissosicated by young stars**
- **Positive offsets suggest spiral arm is a density wave (though is does not need to be stationary)**

Offset Measurement Model Limitations

- Comparison of two models – circular rotation model and realistic numerical simulation.
- Offsets are measured between gas and 100 Myr old stellar population
- **Numerical simulations are lower by a factor of ~ 2 than those predicted by circular rotation model**



$$\Theta \propto (\Omega(r,\theta) - \Omega_p)$$

Analytical circular rotation model adopted in offset studies prediction after 100 Myrs

Realistic numerical simulations using stationary spiral pattern by Dobbs & Pringle (2010) and F11

Along spiral arms, the velocity of the gas is closer to that of the pattern for non-circular motion

References:
Dobbs, C.& Pringle, J., 2010, MNRAS, 409, 396
Egusa, F., Sofue, Y., & Nakanishi, H. 2004, PASJ, 56, L45
Egusa, F. et al. 2009,ApJ, 697, 1870
Foyle, K. et al. 2011,ApJ,735,101F
Kennicutt, R. C., Jr., et al. 2003, PASP, 115, 928
Koda, J. et al. 2009, ApJ, 700, L132
Koda J. et al. 2011, ApJS, 193, 19
Louie, Koda, & Egusa, 2013 ApJ, 763, 94
Tamburro, D. et al. 2008, ApJ 136, 2872

This work is supported in part by the NSF under grant AST-1211680. JK also acknowledges support from NASA through grant NNX09AF40G, a Hubble Space Telescope grant, and a Herschel Space Observatory grant.