Inflows or Outflows: Tracing the Path of Gaseous Arms in the LMC

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Background

The Large Magellanic Cloud (LMC) galaxy interacts with its smaller companion galaxy as they revolve around the Milky Way. Imprints from these interactions are two gaseous filaments, arm B and arm E [1], flowing in and around the LMC's disk. These arms connect to a starburst region [2], 30 Doradus, making it difficult to determine their formation. They could be flowing into the region or flowing out of it. **This project analyzes the velocity and spatial distribution of the two arms to better understand their origin.**

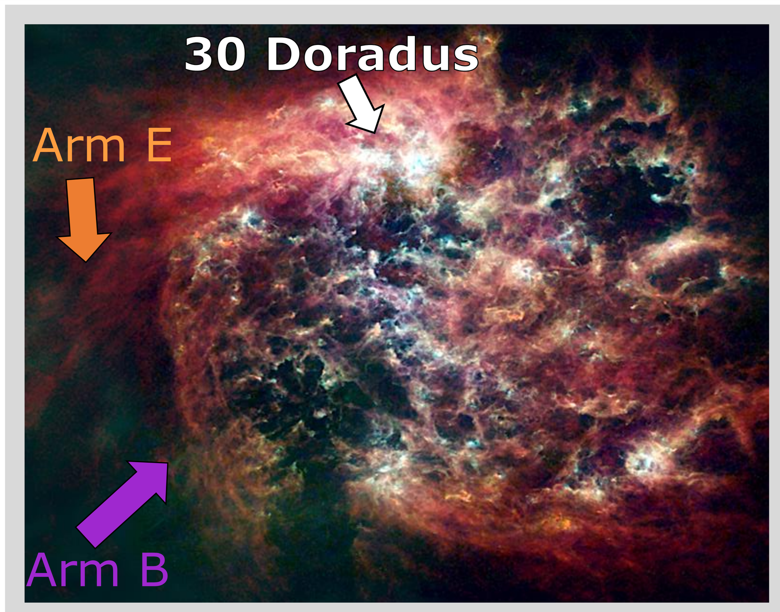

Figure 1: The LMC galaxy with the hydrogen gas in red, cold dust in green, and warm dust in blue. Credit: ESA/NASA/JPL-Caltech/CSIRO/C. Clark (STScI)

Data & Observations

We complimented radio observations from the Galactic Sky Survey (GASS; [4]) and Galactic Australian Square Kilometer Array Pathfinder (GASKAP; [5]) with data from Hubble [6]. Observations from GASS and GASKAP help explore small-scale gaseous structures, while Hubble data constrains the arms' orientation. We search for the arms near 30 Doradus along 8 background stars.

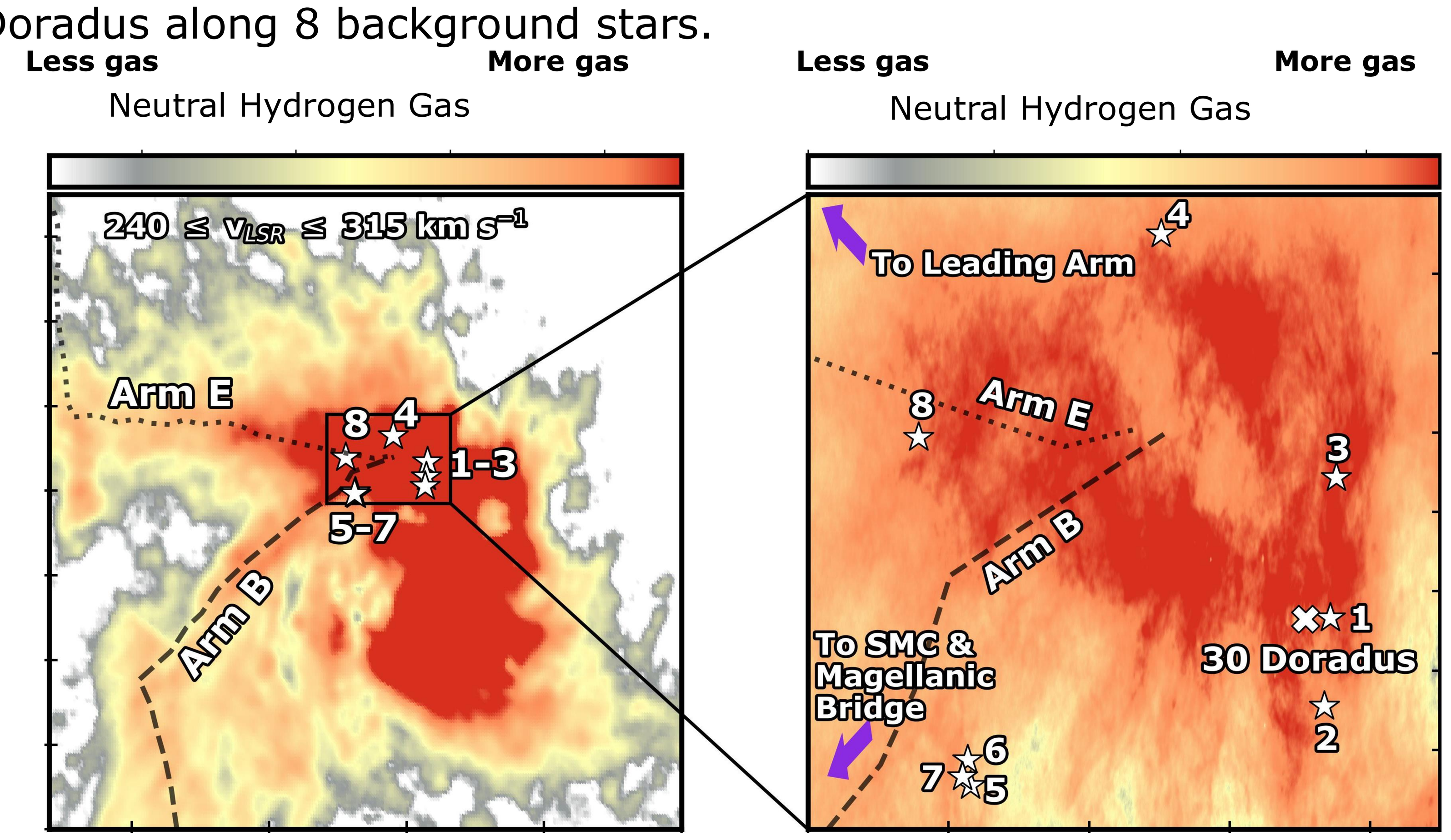

Figure 2: Neutral hydrogen emission maps. Left: GASS. Right: GASKAP. Sightlines in our study are marked with a star and are numbered.

Gas flowing in and around galaxies can reveal how a galaxy evolves over time. Our neighboring galaxy, the Large Magellanic Cloud (LMC), is perfect for studying gas flows because it has two long gas "arms" that connect to a region where stars are born. Our findings indicate that the arms move at a high-velocity and partially cross in front of the LMC. These properties provide clues to their formation: they could fuel new star formation or could contain exploded star debris. Understanding gas flows helps us learn more about the forces that shape galaxies and drive their evolution.

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Properties of the Arms

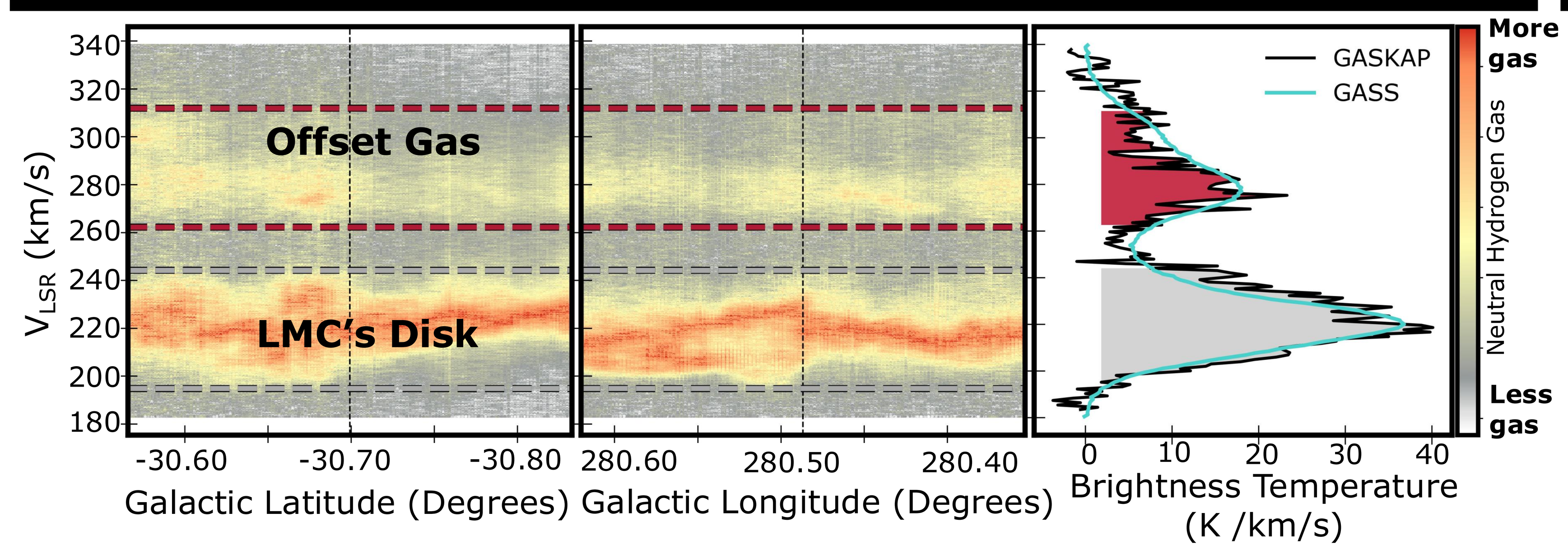
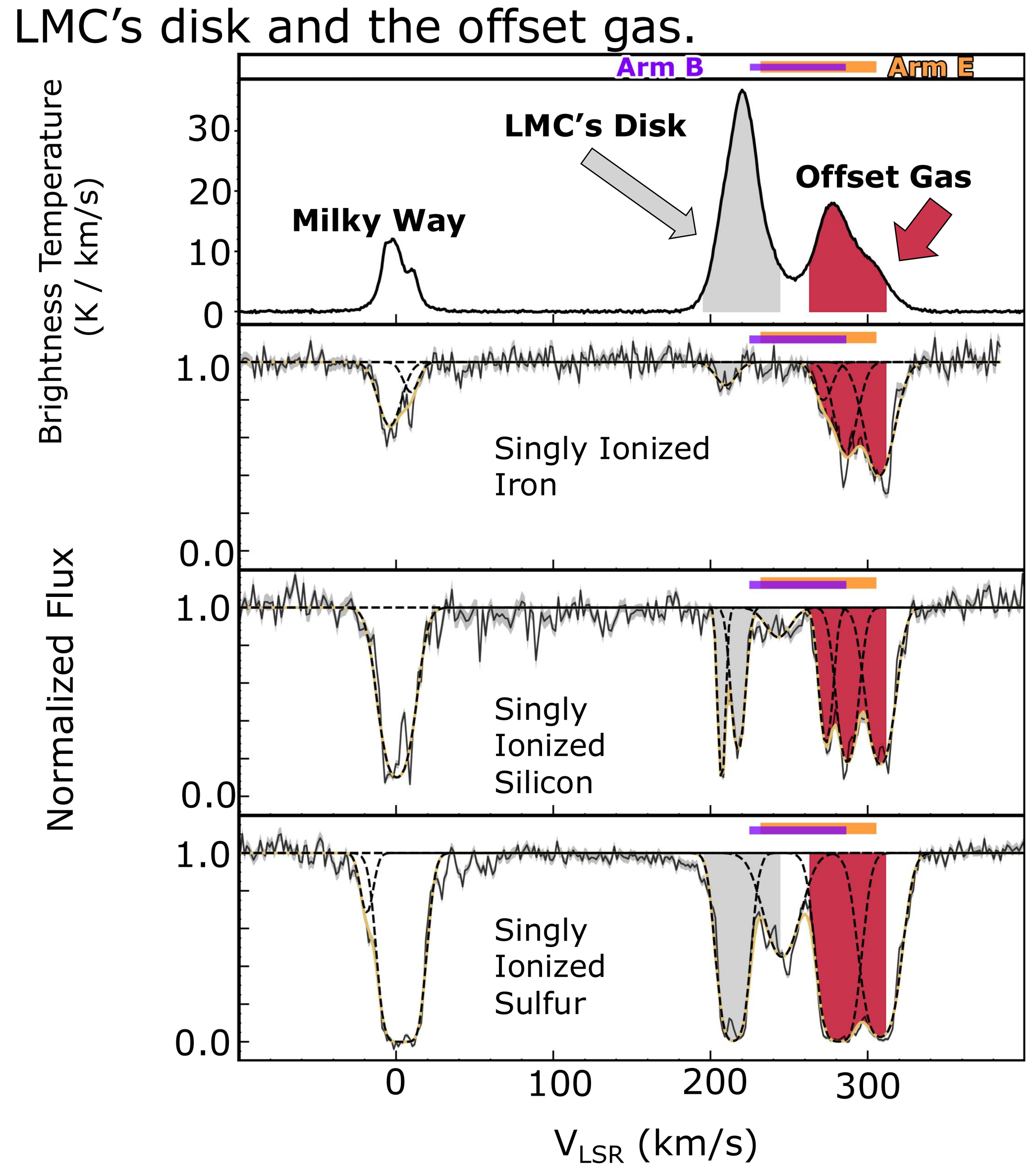


Figure 3: Left and Middle: Position-velocity maps for sightline 4. Right: GASS and GASKAP neutral hydrogen emission profiles.

We created position-velocity maps to observe how the neutral hydrogen gas varies kinematically inside and outside the disk along each sightline. We fit the emission profiles with Gaussians to find the boundaries of the LMC's disk and the offset gas.



We find high-velocity absorbers (red) in the Hubble spectra likely belonging to arm B and/or arm e. We note two key features:

1) The gas has to be in front of the LMC

2) The gas is at a higher velocity relative to the LMC's disk.

Figure 4: Neutral hydrogen emission and three ion transitions for sightline 4, with line fits (dashed lines) and predicted arm velocities highlighted (purple and orange bars).

We estimate how ionized the offset gas is by comparing how much doubly ionized aluminum gas is along our line-of-sight.

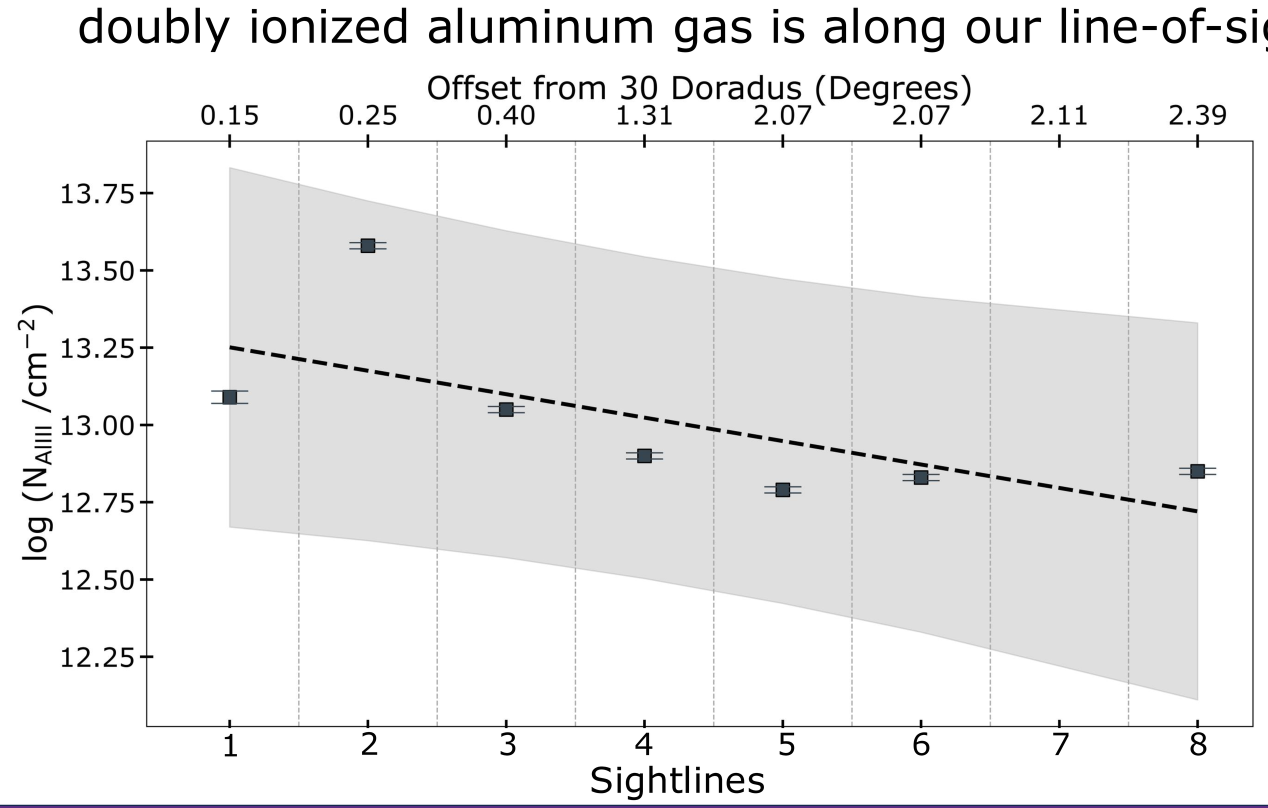


Figure 5: Total integrated column density of the doubly ionized aluminum gas. The sightlines are arranged in order of increasing angular offset from 30 Doradus from left to right. We fit the data points with a best fit line and estimate the range of the total possible line fits with the gray envelope.

Ongoing Debate

There is an ongoing debate about the origin of the high-velocity absorbers: 1) Is the gas inflowing and fueling new star formation, or 2) Is gas from exploded stars flowing out into these arms?

Inflows

- Inflows found throughout the LMC [e.g. 7,8]
- Group of stars with line-of-sight velocities counter-rotating to LMC's disk [9]
- Young star clusters in the LMC have on average a lower metallicity than intermediate-age clusters [e.g. 10]

Outflows

- Wide spread outflows detected across the entire LMC [e.g. 11]
- Arms are kinematically traceable near 30 Doradus [2]
- Simulated supernova explosions can form extended gaseous structures through environmental forces [12]

Simulation of the LMC

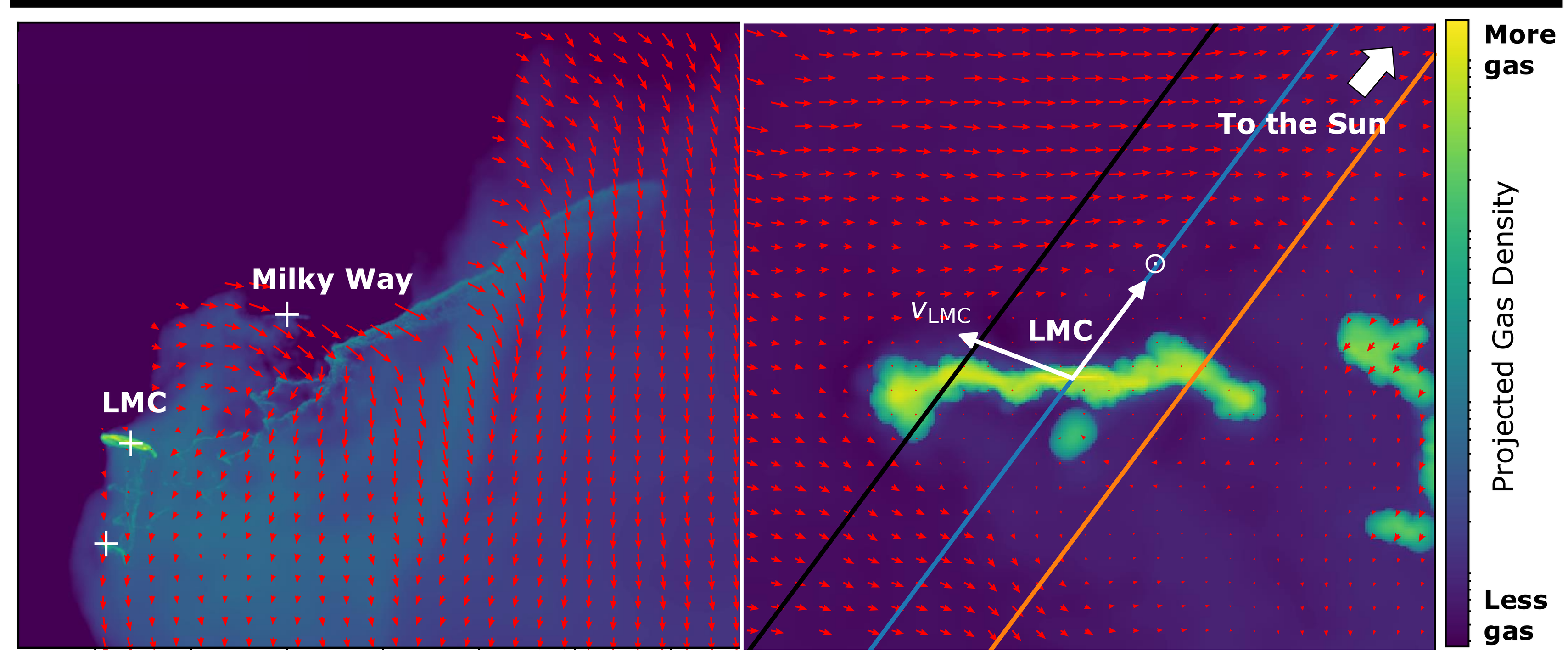


Figure 7: Projected gas density of the LMC with the velocity field overlaid in red arrows. The velocities are shown with respect to the LMC's motion. Right : Zoomed-in region around the LMC. The three lines are the sightlines from which we measure the gas velocities.

We performed simulations [13] to study the formation of high-velocity gas in front of the LMC due to outflows. We generate mock spectra of the gas velocities along three sightlines that pass through the LMC's disk. We find that outflows from a starburst region can be swept away in front of the LMC while remaining redshifted relative to the disk.

Conclusion

1) There are gaseous absorbers in front of the LMC which could be the material of arm B and/or arm E. These absorbers are found at a higher-velocity beyond the extent of the LMC's disk.

2) The amount of doubly ionized aluminum gas decreases with distance from 30 Doradus.

3) While our results support either inflows or outflows, future UV and deeper radio observations could reconstruct the arms' formation.

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