Virtual Research Presentation Conference

Testing Theories of Spiral Arm Formation and Evolution of Galaxies

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Program: Spontaneous Concept

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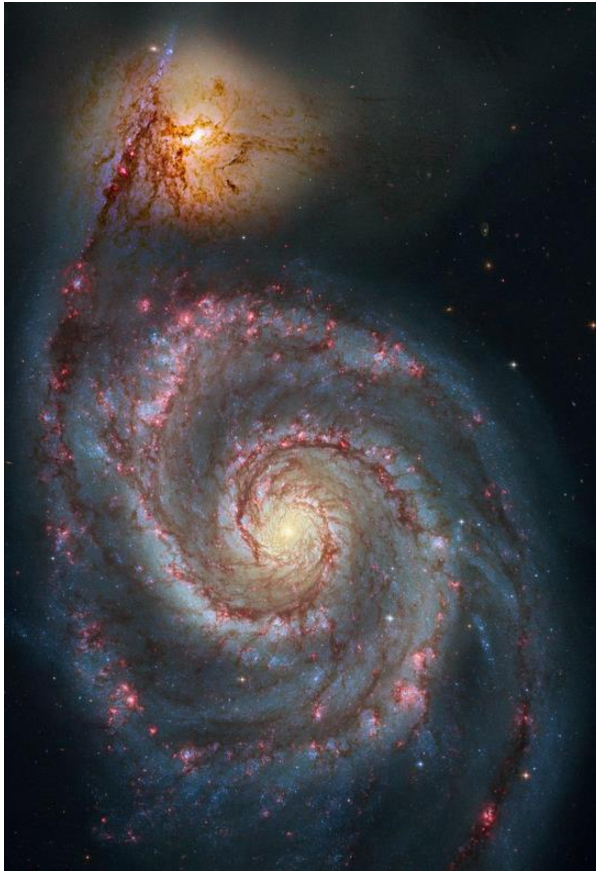
Tutorial Introduction

Abstract

Determining the nature of spiral arms in galaxies is fundamental for understanding the evolution of spiral galaxies and for testing theories of their formation. In spiral galaxies, spiral density waves play a fundamental role assembling the giant molecular clouds in which star formation takes place. How, and under what conditions, these dynamical mechanisms operate is a key problem in galaxy evolution and star formation models. There are two competing theories of the nature of spiral arms in isolated galaxies. In the quasi-stationary spiral structure (QSSS) hypothesis, spiral arms are thought to be rigidly rotating, long-lived patterns that persist over several galactic rotations (see Bertin & Lin 1996 for a review). Alternatively, the transient spiral hypothesis (Goldreich & Lynden-Bell 1965) suggests that each spiral arm is a transient feature generated by the swing-amplification mechanism. Discerning between these comparing theories of the nature of spiral arms in galaxies will have an important impact in the field of star formation and galaxy evolution.



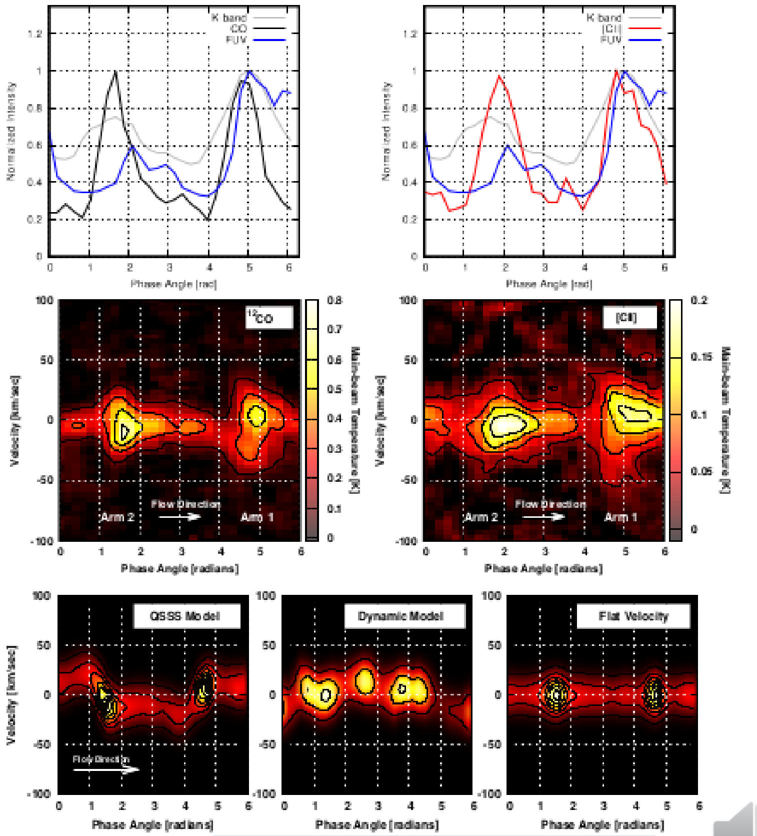
Problem Description

Recently we developed a novel method that uses spectrally resolved far-infrared [CII] and ground-based CO line observations to discern between these two competing theories by studying their position-velocity distribution across spiral arms in galaxies (Pineda et al. 2020).

These spectral lines trace two different evolutionary stages of the spiral arm, CO tracing the early stage dense molecular star forming clouds and [CII] tracing the subsequent formation of stars.

In this work we used a SOFIA [CII] map of galaxy M51 and ancillary CO archival data to determine that the quasi-stationary spiral structure theory is favored in this galaxy.

However, the spiral shocks that are observed in M51 might originate as a result of the interaction between M51 and its companion galaxy,M51b, and thus the velocity structure observed in comparing [CII] with CO would reflect the shocks and not the arm dynamics.



Pineda et al. 2020

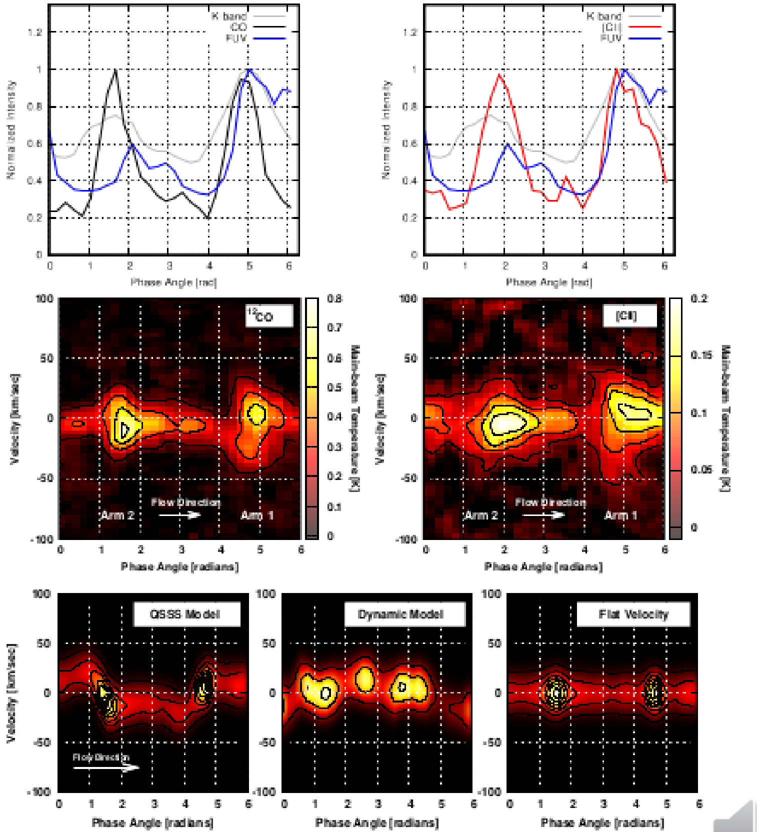
Problem Description

A better test for theories of spiral structure in galaxies would be to apply the techniques described in Pineda et al. (2020) to velocity resolved [CII] and CO observations of isolated galaxies that have not been influenced by tidal interactions.

We therefore submitted a large/legacy SOFIA proposal in Sept 2020, to follow up research proposed in this spontaneous concept to observe [CII] in an isolated galaxy. Such a project will require a large amount of SOFIA time, ~10-30h, which are typically difficult to schedule due to limited observing time of the SOFIA observatory.

This schedule constraint has resulted in cases in which highly rated proposals are not selected due to over subscription for certain locations of the sky (e.g. inner galaxy and Orion). However, projects that use SOFIA to observe locations complementary to these oversubscribed regions are favored and improve the likelihood of selection.

In this task we did preparatory work for a SOFIA proposal by searching the literature and data archives for an isolated galaxy that is in the complementary region of SOFIA's oversubscribed observing range. This galaxy needs to be close enough for clear separation between arm and inter-arm regions, have emission at velocities that are not affected by atmospheric absorption due to ozone and water in the upper atmosphere, and no tidal disruptions. It will also preferably have high spatial resolution CO, and other gas tracer, archival maps.



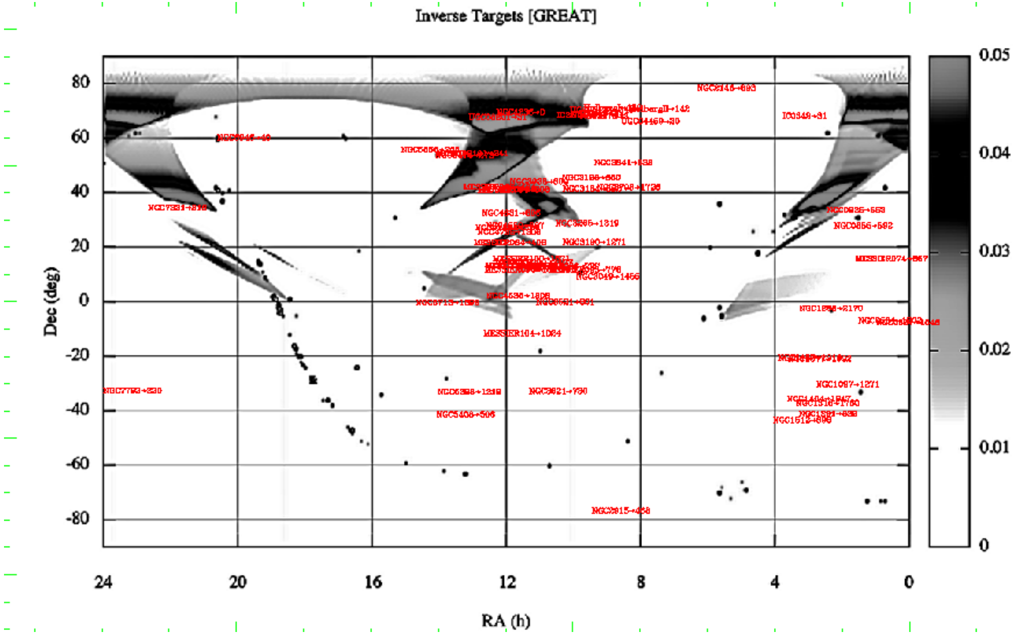
Pineda et al. 2020

Methodology

We searched the Herschel and ISO archives to find galaxies that have been detected in [CII] (typically at very low spectral resolution) that are located in the complementary region of the sky for SOFIA's oversubscribed observations. The SOFIA complementary position map with the positions of previous Herschel observations is shown here.

From this map we identified Galaxy M94 as a candidate galaxy that is in the complementary sky and has a detection of the [CII] line with the PACS instrument on Herschel at low spectral resolution. This detection of [CII] facilitated an accurate observing time estimate for SOFIA observations.

We run the AM atmospheric model to determine the spectral purity of this galaxy at SOFIA’s altitudes, finding that observations of this galaxy will not be affected by atmospheric absorption.

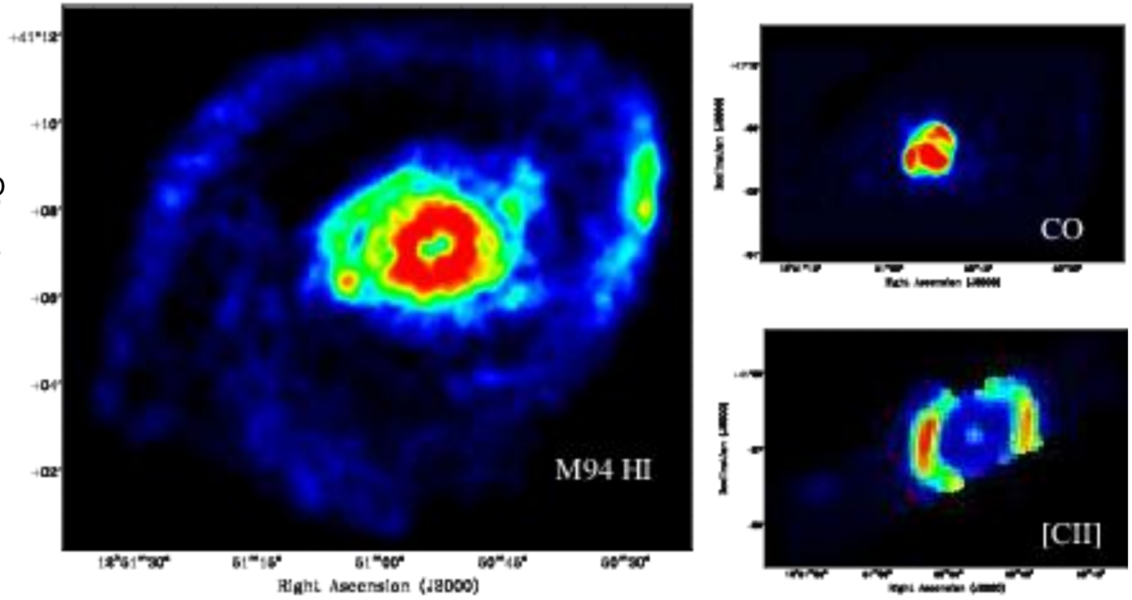


Methodology

We also performed a preliminary search and analysis of existing CO and HI data on M94 to determine whether these maps have the spectral and velocity structure favorable to applying our method to the candidate galaxy.

Here we show atomic hydrogen (HI), carbon monoxide (CO), and ionized carbon ([CII]) images of galaxy M94, representing different phases of the interstellar medium. CO and [CII] are concentrated in the inner parts of M94, and a clear displacement is seen between these tracers at the location of spiral arms, making this galaxy an important laboratory to test theories of the nature of spiral arms, using the high velocity resolution capability of the GREAT instrument on SOFIA.

We also used the spectral information in this data to determine the width of spectral lines, with the [CII] intensity information derived from the low spectral resolution Hershel maps, enabled an accurate estimation of the peak intensity of the spectraly resolved [CII] emission in this galaxy.



Results

We used this information to develop the scientific and technical case for SOFIA observations in this galaxy. We submitted a SOFIA observing proposal on this galaxy in September 2020.

The results of this task helped us to be in a much better position for obtaining SOFIA time to observe the M94 galaxy. These observations, and the analysis techniques we developed previously, will help solving a long standing problem in Astrophysics, which is the nature of spiral arms in galaxies, by providing strong tests to competing theoretical models.

Publications and References

Pineda J.L., Stutzki J., Buchbender C., Koda J., et al. 2020, ApJ, 900,2