National Aeronautics and Space Administration

FY23 Innovative Spontaneous Concepts Research and Technology Development (ISC)

Evolution of Molecular Gas in the Spiral Galaxy M51 Traced with SOFIA [CII] Maps

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Objectives and Background: The regulation of star formation in galaxies drives galaxy evolution by determining their stellar mass growth and chemical enrichment. Star formation is an inefficient process in which a small percentage of the mass in galaxies is converted into stars at any given time. There are two competing theories that attempt to explain the star formation inefficiency. The slow star formation hypothesis argues that molecular clouds are long lived and due to a variety of physical support processes (e.g., magnetic fields, turbulence, and galactic differential rotation) only a small fraction of the gas becomes gravitationally bound and collapses to form stars. In contrast, the fast star formation hypothesis argues that clouds arise in converging flows that form gas overdensities at short timescales in which star formation takes place. In this case, stellar feedback in the form of radiation, stellar winds, and supernovae explosions play the dominant role slowing down star formation and dispersing and destroying molecular clouds. The ionized carbon [CII] and neutral CO lines can be combined to trace the relative fraction of the different phases of the the interstellar medium across the disk of galaxies. This information, in turn, can be used to determine the timescales of cloud and star formation and test competing star-formation theories. The objective of this task was to demonstrate and validate a new method to use the ratio of [CII] to CO lines to determine timescales and to test theories of star formation in the disk of galaxy M51. We successfully demonstrated our approach, together with a robust understanding of the associated uncertainties, and used the results to write an improved ADAP proposal (submitted May 2023) for a full analysis of the M51 data set.

Approach and Results: We first searched the Herschel and SOFIA data archives for [CII] observations in nearby galaxies, and found four galaxies also observed by SOFIA in which the coverage is sufficient for tracing the evolution of gas from arm to inter-arm regions in a large number of samples. These galaxies are M51, NGC 6946, NGC 4321, and NGC3627 (Figure 1).

A sample of the derived procedure is illustrated in Figure 2, where we show the azimuthal distribution of the [CII]/CO ratio at a given radius (3 kpc from the center) observed in galaxy M51. We show this distribution twice, over 4π phase angle range, so that the spiral arms are better visualized. The black line represents the distribution of stellar mass as traced by K–band NIR emission. We can see a systematic variation on the [CII]/CO ratio showing a minimum in the upstream side of the spiral arms and a peak in the inter–arm region, downstream side of the spiral arms.

Measuring the distance between peak and minimum in the [CII]/CO distribution, as described above, we derive a time scale for CO dense cloud formation of about 23–29 Myr, which is similar to that of cloud destruction. The rapid variation of the [CII]/CO ratio in this region supports the fast star formation hypothesis, and its correlation with the location of spiral arms suggest that spiral density waves are playing an important role in the transition between phases of the ISM.

Significance/Benefits to JPL and NASA: The proposed work will provide a demonstration and validation of the use of the [CII] and CO distribution in M51 to test theories of star formation in its impact on galaxy evolution. The results from this task was included in, and will substantially increased the chances of winning, an ADAP proposal submitted in May 2023 with a potential award of ~$400K over a two year period. Additionally, this technique will enhance the science justification of future flights of the JPL-ASTHROS balloon for nearby galaxies, and of the JPL-led PRIMA probe-class mission for distant galaxies.

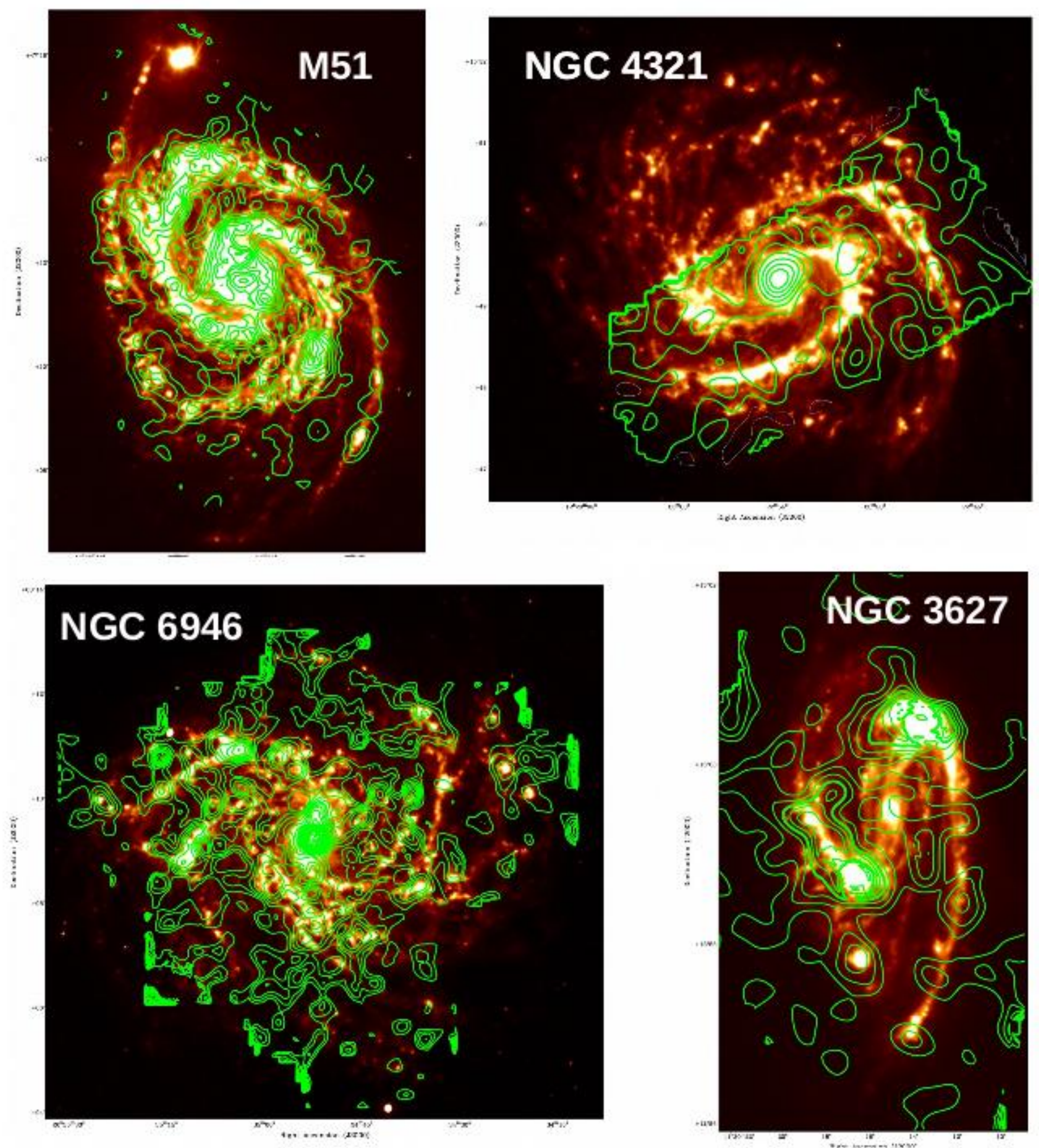

Figure 1: SOFIA observed [CII] maps of the entire disk of four nearby galaxies enabling a clean separation of arm and inter-arm regions which enable us to study the evolution of the ISM phases under the influence of spiral density waves. Here we show Spitzer/IRAC 8μm images of M51, NGC 4321, NGC 6946, and NGC 3627 overlaid with green contours denoting the SOFIA [CII] in units of signal–to–noise ratio.

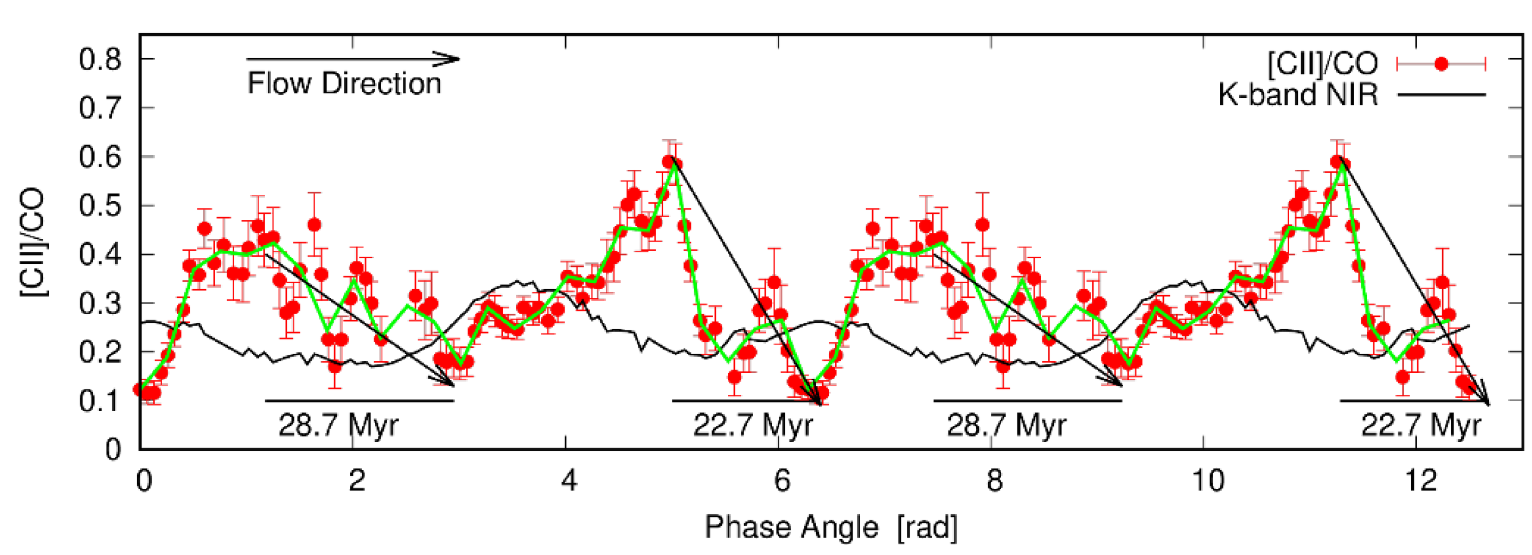

Figure 2: Preliminary analysis of the azimuthal distribution of the [CII]/CO ratio at a given radius (3 kpc from the center) derived from the data set available for galaxy M51. This plot demonstrates the method used to derive the timescales for CO dense cloud formation and destruction by measuring the distances between the peak and minimum values in the [CII]/CO distribution and knowing the rotation velocity. The rapid variation of the [CII]/CO ratio in this region supports the fast star formation hypothesis.

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