Astro2020 Science White Paper

Far-Infrared studies of Galaxy Evolution

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation

☐Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics

☐Stars and Stellar Evolution ☐Resolved Stellar Populations and their Environments

☒Galaxy Evolution ☐Multi-Messenger Astronomy and Astrophysics

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Abstract:

Half of the energy in the universe is emitted at infrared wavelengths. Dust grains absorb starlight, making galaxy evolution impossible to study using redshifted starlight emission alone. The far-infrared thermal continuum from dust grains and fine structure lines from gas are prime tracers of galaxy conditions including their rate of star formation and extreme environments in starbursts and active nuclei. In this white paper we describe some of the scientific potential of measuring the polarized thermal emission of galaxies to trace their magnetic fields and using far-infrared fine structure emission to trace the inventory and physical of interstellar gas.

Galactic Center as a Template for Black Holes and Starbursts

Star formation in the early Universe and in luminous active galaxies occurs in extreme environments characterized by large magnetic field strengths, turbulent motions, gas densities, temperatures, and pressures relative to typical Galactic star-forming regions. The Galactic Center (GC) is the closest region with such extreme conditions. Moreover, with its $4x10^6$ $M_\odot$ central black hole and its massive star clusters (Central, Arches, and Pistol Clusters, and Sgr B2), the GC combines many aspects of the extreme environments of both starburst and active galactic nuclei. Yet the star formation rate predicted by current models overestimates that observed in the GC by an order of magnitude [Longmore et al. 2013]. Observations of the GC, therefore, can provide a local template to understand AGN and starburst nuclei, and produce the “ground truth” for models of high-redshift star formation and galaxy evolution.

Far-infrared observations of the GC provide direct templates for submm observations of redshifted galaxies, and only for the Mily Way can we obtain high enough spatial resolution to separate and relate the black hole, circumnuclear material, and star formation in the central several pc. In order to understand the GC, infrared observations to map the dust continuum, the dominant cooling lines, and the magnetic field directions in the central 2 pc CircumNuclear Ring (CNR) and throughout the central 200 pc “Central Molecular Zone” are required.

For the CNR, the warm, ~1 pc radius predominantly molecular structure of several x 10^4 $M_\odot$ that orbits the central black hole, SOFIA has imaged its warm dust emission in the mid-infrared [Lau et al. 2013]. The shorter wavelengths probe the hotter dust at the inside edge of the Ring while the longer wavelengths probe the cooler dust at larger radii. The data can be modeled as a clumpy, porous disk illuminated by intense UV radiation from the massive Central Star Cluster located well inside the Ring. SOFIA observations of high-J CO lines [Requena-Torres et al. 2012] show that the gas temperatures are ~300 K, far higher than in typical molecular clouds. Any star formation in such an environment will be quite different from that in the galactic disk.

Figure 1. SOFIA image of the CircumNuclear Ring on the Hubble star field. Streamlines of magnetic field direction from SOFIA/HAWC+ superposed, showing the field follows the shapes of the arcs and ring.

A new angle on galactic center observations is provided by polarized thermal dust emission. SOFIA measured the magnetic field directions in the CNR at ~10” (=0.4 pc) resolution (see Figure 1). The magnetic field aligns with two warm arcs (the so-called “mini-spiral,” blue-white in Fig. 1), one oriented east-west and the other north-south, resulting in remarkably perpendicular magnetic-field vectors where the bars intersect on the sky. At larger radii the magnetic field approximately aligns with the CNR.

Future far-infrared observations are required to map the [CII], [OI], high-J CO lines, and the star formation density (by including mid-infrared imaging) over several pc in the Galactic Center [e.g., Iserlohe et al. 2018]. [CII] probes the UV field strengths, the gas densities, and temperatures throughout this complex region. The rich structures in preliminary SOFIA [CII] GC map indicate dozens of clouds with distinct velocities throughout the region. In comparison, a kpc-scale observation of a distant galaxy would blend all of these clouds together. Far-infrared observations with SOFIA (in the coming decade), and SPICA or Origins (in the future) will provide a template for the nuclear regions of galaxies.

Magnetic Fields on Galaxy Scales

The origin of galactic magnetic fields remains poorly understood. Current theories suggest that a dynamo mechanism, combining the effects of differential rotation, turbulence, and large-scale circulation, operates on galactic scales. Magnetohydrodynamic (MHD) simulations explaining the production of and role of magnetic fields in galaxies have advanced to the point where new observational constraints are solely needed [Ruszkowski et al. 2017]._SOFIA can now provide the critical observations in the FIR without the confusing effects of scattering at shorter wavelengths or synchrotron emission at longer wavelengths to answer the open questions: How do magnetic fields align with spiral arms? How do starburst outflows drive magnetic fields into extragalactic environments? Do magnetic fields channel or just follow interstellar gas motions?

Figure 2 shows thermal dust polarization for the starburst galaxy M82. Unexpectedly, the magnetic field structure lies perpendicular to the plane of the galaxy on kpc scales, and co-spatial with the large-scale galactic outflow driven by the central nuclear starburst [Jones et al., 2019]. The vertical magnetic field in M82 illustrates how galaxies can possibly seed a magnetic field in the intergalactic medium, important for galaxy formation [Kronberg 1994]. By contrast, in spiral disk galaxies we expect the magnetic field in the plane of the galaxy and aligned with spiral arms. Initial observations of NGC 1068 and M 51 appear to support this view. This area of research is only in its infancy, but will experience significant growth as more galaxies are observed in thermal dust emission using SOFIA, balloon-borne instruments such as BLAST and PILOT, and ground-based instruments including SCUPOL and NIKA2 and (in the future) TolTEC. All of these instruments bridge a gap in technical capabilities that could be achieved with Planck (for which essentially all galaxies are unresolved) and cannot be readily done with ALMA (for which nearby galaxies are too large to map).

Is [CII] an Accurate Tracer of Star Formation?

The [CII] 157.7μm fine structure line is the single most luminous spectral line in normal gas-rich galaxies, typically containing ~0.01% to 1% of the total FIR luminosity. Since young high-mass stars dominate the production of the near-UV radiation that ionizes carbon, in normal galaxies the [CII] luminosity correlates linearly with the inferred star formation rate over six orders of magnitude, from the few pc scale of individual Galactic

Figure 2. Starburst galaxy M82 in starlight (blue), Ha (red, Kitt Peak), and FIR (yellow, SOFIA) emission, with streamlines of the magnetic field (SOFIA) superposed. Note how the magnetic field on the galaxy scale is perturbed by the starburst in the inner portion of the galaxy.

star-forming regions, to kpc scale regions in the Milky Way, and on to entire galaxies [Pineda, Langer & Goldsmith 2014]. Because the [CII] line from galaxies is so luminous, it is now commonly used to measure global star formation rates in both nearby galaxies [Stacey et al. 2010] and high-redshift galaxies [Kimball et al. 2015, Capak et al. 2015, Gullberg et al. 2015]. With ALMA's breakthrough in mm and submm sensitivity, [CII] measurements of high-redshift galaxies have become an important new tool to characterize star formation in the very early universe out to z~7 [Pentericci et al. 2016; Smit et al. 2018].

This simple interpretation of [CII] luminosity as a proxy for star formation rate, however, breaks down at both large and small scales. One longstanding problem is the observed deficit of [CII] emission from galactic nuclei compared to disks, and from luminous and ultra-luminous infrared galaxies (LIRGs and ULIRGs) compared with normal spiral galaxies [Ibar et al. 2015]. Large optical depths might explain this deficit, they would diminish the [CII] luminosities for a given star formation rate. SOFIA observations of the isotopic [^{13}CII] hyperfine lines require large optical depths for [^{12}CII], and high-resolution [CII] profiles often show optically thick self-absorption features toward certain star-forming regions [Graf et al. 2012]. Thus, the cavalier extrapolation of the local relation between [CII] and the star formation rate to global scales in galaxies must be treated with considerable caution. By measuring the [^{13}CII] hyperfine lines and velocity-resolved profiles of [CII] toward a larger sample of Galactic star forming regions, SOFIA will definitively address the question of the applicability of [CII] as an accurate star formation tracer. Further spectrally-resolved [CII] observations, in star-forming clouds in the Milky Way, in the Galactic Center, and for nearby galaxies, can be used as templates for understanding line profiles seen with ALMA for more distant galaxies.

[CII] observations of nearby galaxies can relate the observed [CII] brightness to other tracers of the star formation rate and determine its relationship to the various phases of the ISM, the proximity to stars, and the evolutionary state of the clumps and cores in significantly greater detail than is possible for distant galaxies. For example, [CII] can trace molecular gas that does not emit in CO, the usual tracer of molecular gas. Evidence from FIR dust emission, visible-light extinction, and gamma-ray brightness all indicate a significant amount of molecular interstellar gas that does not emit in CO lines. Models of the transition from C^+ to C^0 to CO suggest that in these "CO-dark" clouds, the hydrogen is molecular (H_2), but the carbon is either ionic (C^+) or atomic (C^0). Therefore, using CO to measure the total amount of molecular gas underestimates and misses much of the transitional, translucent "CO-dark" phase. This gas, however, can be traced by [CII]. Additional constraints on the physical conditions can be derived from the fine-structure lines from the atoms and ions of nitrogen and oxygen, particularly useful for examining the physics of low-metallicity systems. Thus, the "local template" can be obtained by studying nearby galaxies and the Milky Way.

Unlike past Herschel surveys of nearby galaxies that could cover only small regions of active star formation, SOFIA's unprecedented [CII] mapping speed enabled the entire spiral galaxy M51 to be mapped (Figure 3). The galaxy's spiral structure is clearly evident in [CII], reflecting the close association between star formation and spiral structure. Moreover, SOFIA's high-resolution spectroscopy is able to show velocity shifts between [CII] and CO that are consistent with the passage of the spiral arm shock.

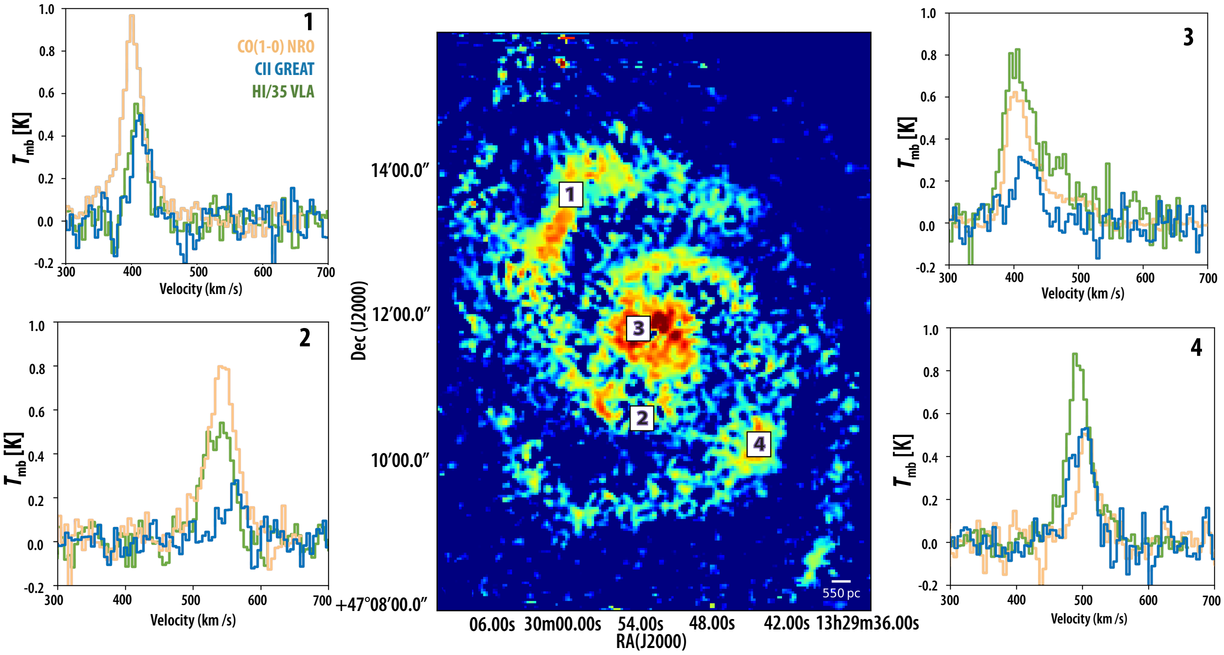

Figure 3. Image of spiral galaxy M51 in the [CII] line from SOFIA, together with 4 panels showing superposed spectra of CO, [CII], and HI for the labeled positions. [Image and supporting material provided by J. Stutzki (U. Cologne).]

These sensitive observations of [CII] can also be used to determine how the ISM evolves in spiral density waves. Pineda et al (2018) shows that the location of [CII] in an M51 spiral arm lies in between the CO emission tracing molecular gas and the ultraviolet emission tracing recently formed high-mass stars—meaning that [CII] traces the stage where star formation is incipient. Future [CII] research on nearby galaxies using SOFIA can be used spatially separate these arm/interarm regions. These same capabilities of the observatory also make it the optimal platform for studying dwarf galaxies—the templates for early-redshift galaxies with low metallicity—and galaxies with a range of star formation rates, diversifying the overall inventory of [CII] available to the community for broadening our understanding of the Universe.

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