Astro2020 Science White Paper

Probing Galaxy Evolution through Far-Infrared Spectroscopy of the Interstellar Medium.

Thematic Areas: ☐ Planetary Systems x Star and Planet Formation
☐Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☐Stars and Stellar Evolution **x** Resolved Stellar Populations and their Environments
x Galaxy Evolution ☐Multi-Messenger Astronomy and Astrophysics

Principal Author:
Name: Jorge L. Pineda
Institution: Jet Propulsion Laboratory, California Institute of Technology
Email: Jorge.Pineda@jpl.nasa.gov
Phone: 818-354-33477

Co-authors:
Paul F. Goldsmith, Jet Propulsion Laboratory, California Institute of Technology

William D. Langer, Jet Propulsion Laboratory, California Institute of Technology

Abstract (optional):

Executive Summary

A primary goal of astronomy is to reveal the history of our universe by determining the evolution of galaxies and the rate of star formation as a function of cosmic time. To this end it is essential to study the physical processes governing the evolution of the interstellar medium (ISM) from which stars form, and to explore the processes regulating star formation in galaxies, which is a key driver of galaxy evolution. Key stages in the formation of stars include formation of molecular clouds, their evolution into stars and stellar clusters, and the mechanical and radiative feedback from massive stars to their progenitor gas that can both halt and trigger further star formation. These processes are mediated by the impact of dynamical factors, such as spiral density waves, galaxy-galaxy interactions and mergers, and the influence of active galactic nuclei. During its evolution, the ISM transitions through ionized, atomic, and diffuse and dense molecular phases. Unique tracers of these phases of the interstellar medium are the fine structure spectral lines, including [CII] 158μm, [NII] 122μm and 205μm, [NIII] 57μm, [OI] 63μm and 146μm, and [OIII] 88μm. While ground-based facilities can observe these lines at red-shifts $z > 3$, covering only the first quarter of cosmic time. Observing the remaining three quarters of cosmic evolution, including the peak of star formation at $z \sim 2$, requires orbital and suborbital facilities because atmospheric absorption limits observation of the far-IR tracers. In this white paper we lay out a roadmap that builds on the use of multi-scale, high-spectral resolution observations of far-infrared fine-structure lines, to study the physical processes governing the evolution of the interstellar medium in galaxies, and how they impact the regulation of star formation in galaxies. We also summarize what type of suborbital and space-based missions are needed to advance our understanding of the evolution of the ISM, ranging from detailed large scale spectral images of star forming regions in the Milky Way, to high spatial and spectral resolution images of a large number of nearby galaxies. Finally, we discuss how these space-based investigations merge with ground-based observations of high-*z* redshifted far-IR lines to complete our picture of the cosmic time line of galactic evolution.

Galaxy Evolution through Cosmic Time:

A fundamental goal in modern astrophysics is to understand galaxy formation and evolution from early cosmological times to the present day (Fig 1.). Galaxy evolution is fundamentally mediated by stellar birth and death. On large scales, star formation is regulated by the inflow and outflow of gas from their halos to their disks, by galaxy-galaxy interactions/mergers, by dynamical effects within their disk such as spiral density waves and bars, and the energy sources present in active galactic nuclei (AGN). At smaller scales the physical processes at play include the formation of molecular clouds, their collapse to form stars, and the mechanical and radiative feedback from massive stars in their placental gas that impacts nearby clouds both potentially halting and triggering further star formation. A complete observational understanding about these physical processes is an important goal for understanding galaxy evolution over cosmic time and for testing cosmological models.

Why Far-Infrared Spectral Lines are Ideal Probes for Understanding Galaxy Evolution:

Far infrared fine structure lines (FSLs) trace nearly all phases of the interstellar gas, and indirectly the rate of star formation. Along with mm and submm observations, they allow a nearly complete picture of the lifecycle of star formation in galaxies. They are the signatures of the radiative and mechanical feedback from star formation into the interstellar medium of galaxies. They characterize the conditions of HII regions resulting from massive star formation and photon dominated regions (PDRs) surrounding molecular clouds. They play a fundamental role regulating the thermal balance of the gas, which controls the star formation rate. Furthermore, FSLs provide an unobscured view of the galactic ISM (in contrast to visual and UV observations which are heavily affected by extinction), revealing its density structure, and the physical and dynamical conditions of the star forming gas.

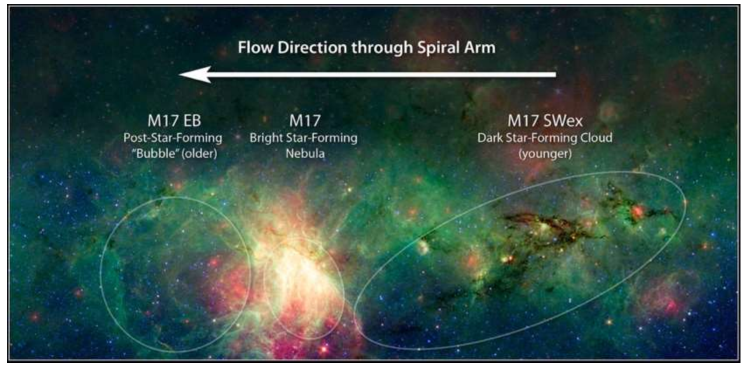

Figure 1: The regulation of star formation in galaxies is mediated by processes occurring over a wide range of physical scales. This infrared Spitzer figure shows the evolution of star forming regions as a function of position within a spiral arm in the Milky Way. FIR fine structure lines observed over a wide range of scales can be used to determine the impact that star formation has in the evolution of galaxies. Credit NASA/IPAC.

For example, [NII] FSLs are excellent tracers of the density structure of ionized gas regions (Goldsmith et al. 2015, Herrera-Camus et al. 2016), and can be used to trace the radiative and mechanical impact of star formation in galaxies. The two [OI] lines are excellent tracers of warm neutral gas close to massive young stars, and thus offer unique insight into their interaction with their immediate surroundings, while [NIII] traces the radiation environment of massive star forming regions. [CII] is a widely studied key tracer of diffuse atomic and molecular gas, and Photon Dominated regions and is also an important tracer of the formation of molecular clouds as described in the white paper by Heyer et al. Thus, far-infrared fine structure lines are fundamental astrophysical tools to understanding the impact and regulation of star formation in galaxies.

The Need for Observations of FSL in the Nearby Universe.

FIR lines, such as the bright [CII] and [OIII], lines can be detected at high red-shifts and have been used to trace star formation (Carilli and Walter 2013). These redshifted lines can be detected at mm to submm wavelengths from the ground, which is an advantage as the large collecting area of facilities such as ALMA, allow a detailed study of their ISM and star formation at $z > 3$. However, to get a complete picture of galaxy evolution and star formation throughout cosmic time we need to observe local galaxies out to $z = 3$, keeping in mind that for z greater than 3, ALMA is only exploring the first quarter of galactic evolution in cosmic time.

The observational challenge to these studies is the absorption of most FIR lines by atmospheric water vapor, requiring orbital and suborbital platforms. Here we briefly review the capability of recent and current facilities for studying galactic evolution, followed by advocacy for future missions. We also outline the need for such platforms dedicated to mapping local galaxies, including the Milky Way, utilizing high spectral resolution arrays.

The Infrared Space Observatory (ISO) and Herschel Space Observatory (*Herschel*) surveyed a large number of nearby galaxies ($z << 1$) in FSLs at angular resolution 10 to 30 arcsec, mostly with low spectral resolution incoherent detector arrays. (Malhotra et al. 1997, Kennicutt et al. 2011, Diaz-Santos et al. 2017) ALMA, with angular resolution of order milli-arcsec and large collecting area, has been able to study these FSL in distant galaxies with redshifts $z > 3$, and with spectrally resolved features. The ISO and *Herschel* observations have provided important insights in the properties of the ISM in galaxies, but due to the low spatial and spectral resolution they provide only a global view of the interstellar medium properties and star formation in these galaxies. More detailed mapping of regions with sufficient spatial and spectral resolution is needed for a precise quantification of the impact of radiative and mechanical feedback from stars into the interstellar medium, and how larger scale dynamical effects regulate star formation in galaxies

FSLs are also powerful tools to study radiative and mechanical feedback at small scales in galaxies. For example, SOFIA [CII] observations recently revealed an expanding bubble driven by the most massive young star in Orion, and allowed accurate measurement of its previously unknown energy and momentum (Fig. 2).

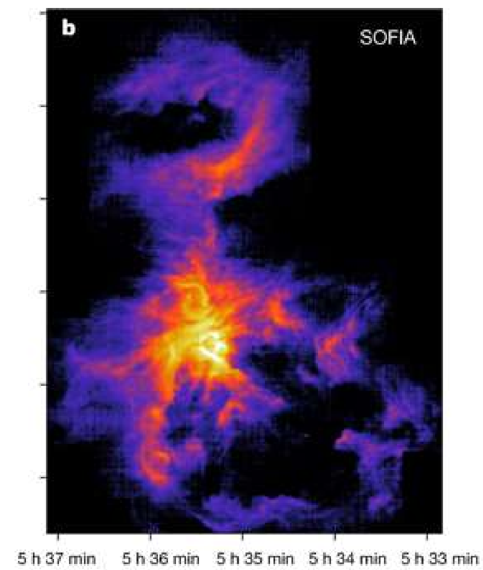

Figure 2: Detailed high spatial and spectral resolution spectral maps of far-infrared spectral lines in star forming regions over large scales provide unique information of the stellar feedback acting at small scales. This SOFIA high spectral resolution map of [CII] in the Orion star forming region shows its influence on the gas structure (Pabst et al. 2019). Future SOFIA instrumentation and 2 meter class sub-orbital balloons can provide comparable maps of other important far-infrared spectral lines in a large number of Galactic regions.

FSL Observational Roadmap for Galaxy Evolution

1) **Tracing physical processes at small scales: High spatial/spectral resolution, high dynamic range images of Galactic star forming regions.**

It is well-established that star formation is an inefficient process in which only a few percent of the interstellar gas mass is converted into stars. Numerical simulations of galaxy formation and evolution show that in the absence of stellar feedback the gas in galaxies cools efficiently and collapses on time-scales that are much shorter than observed, with nearly 100% of the gravitationally bound gas being converted into stars (Bournaud et al. 2010, Hopkins et al. 2014). Stellar feedback is therefore predicted to play a fundamental role in the regulation of star formation in galaxies. The main stellar feedback mechanisms are radiation pressure, stellar winds, gas photo-ionization, and Supernovae (SNe) explosions. These processes disperse molecular clouds or by compressing gas trigger further star formation (the "Collect & Collapse" process; Elmegreen 2012), by replenishing turbulence in the interstellar medium, and by transporting material from the disk of galaxies to their halos. The energy and momentum injected by stellar feedback processes into the ISM determine the structure and kinematics of the ionized/neutral gas. Ionized regions are highly inhomogeneous, showing features such as bubbles, shock fronts, filaments, pillars, globules, and clumps, all of which are the result of stellar feedback acting over a wide range of spatial scales. Dust continuum maps from *Herschel* have also revealed the presence of filamentary structures in the neutral gas in star forming regions (Andre et al. 2010, Molinari et al. 2010).

The goal of understanding stellar feedback is therefore to quantify the impact of various feedback mechanisms acting in star forming gas. This impact can be quantified by measuring the energy input from different stellar feedback mechanisms and by observing a phase transition from ionized gas to the cold and dense gas that is suitable for further star formation. Achieving this goal requires large-scale maps of a large number of star-forming regions experiencing different degrees of feedback (e.g. with or without SNe). These observations would provide information that can be

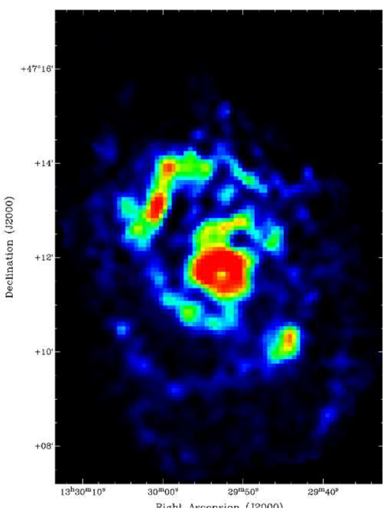

Figure 3: Building upon the knowledge gained at small scales in Galactic star forming regions, the next step in our understanding of the role of star formation in galaxy evolution are observations of FSLs over wide range of environmental conditions and scales in nearby galaxies and the Milky Way. SOFIA observed the M51 galaxy in [CII] (Pineda et al. 2018) at high spectral resolution. These observations provide important kinematic information of the flows of gas in and out of spiral arms.

used to test models of star formation and cloud evolution (Franeck et al. 2018, Clark et al. 2018). FSL observations can be used to determine the electron density structure of star forming regions (via [NII] 122 μm and 205μm observations), which can be used trace the distribution of shocked gas. Bubbles produced by stellar feedback can also be traced by the [CII] line, as shown by SOFIA observations of Orion (Pabst et al. 2019). The transition from ionized to neutral gas, can be traced by a combination of the [CII] 158μm, and CO lines.

Because stellar feedback processes occur on scales ranging from less than a parsec to ~100's of parsecs, the typical size of star forming regions, they can only be characterized in sufficient detail by mapping Galactic star forming regions at high angular resolution over large scales. At high angular resolution, the three dimensional structure of these clouds is revealed by velocity changes among gas components, and thus high spectral resolution is also required to separate different gas components in these regions. Therefore, we need large format arrays, of order 100 pixels, that can produce high spectral resolution spectral maps. SOFIA currently only has the capability to map the [CII] line with the 14-pixel upGREAT array. However, no current capabilities are available for the [NII] 205μm, 122μm, [OIII] 88μm, [NIII] 57μm, and other key FSLs. While the ability to observe some of these lines can be incorporated into future SOFIA instrumentation, many lines, including the important [NII] 122μm line, are obscured by telluric atmospheric absorption, and require balloon-borne or space-based observations.

Facilities Required: Large heterodyne arrays: SOFIA, balloons with 2-m telescopes, and orbital platforms.

2) **Tracing physical processes at the scale of galaxy disks: High-Moderate spatial/spectral resolution FSL maps of nearby galactic disks and large scale FSL maps of the Milky Way.**

While stellar feedback effects initially impact sub-parsec scales in star forming regions, over time they impact the properties of the ISM gas over scales of kilo-parsecs. Stellar feedback produces large scales outflows and super-bubbles observed in the disks of galaxies, which can bring gas from the disk of a galaxy to its halo, thus removing the availability of the gas required for star formation. Also, at these scales, dynamical effects such as spiral density waves, bars, AGN radiation and flows, and galaxy-galaxy interactions and mergers become important and play a fundamental role in the agglomeration and compression of gas that can trigger star formation.

Building on our understanding of stellar feedback at the scales of star forming regions, the next step is to use FSLs to characterize ISM properties at the scale of galactic disks with the aim to study how large scale dynamical effects and stellar feedback affect their properties. This goal requires complete maps of nearby galaxies (Fig. 3), with the advantage of studying a wide range of environmental conditions (galaxy interactions, metallicities, radiation environments, etc.). The Milky Way can be studied at these scales, with large (degree-scale) maps of FSLs, using balloon-borne observatories or small satellites. At moderate velocity resolution (5 km/sec), the kinematics of the gas across spiral arms can be studied adding an important constraint to models of the nature of spiral structure in galaxies. This spectral resolution is sufficient to trace large scale gas shocks that are manifested in density enhancements, which result in locally enhanced star formation, and by velocity discontinuities observed in different ISM tracers (Baba et al. 2016). The [CII] can be used to trace CO-dark H_2 gas, which is predicted by models to represent the bulk of the molecular gas reservoir in the inter-arm regions of galaxies (Smith et al. 2014). The CO-dark-H_2 is even more important in low metallicity environments, in which [CII] can trace a much larger fraction of the molecular gas reservoir needed for star formation (Cormier et al. 2015).

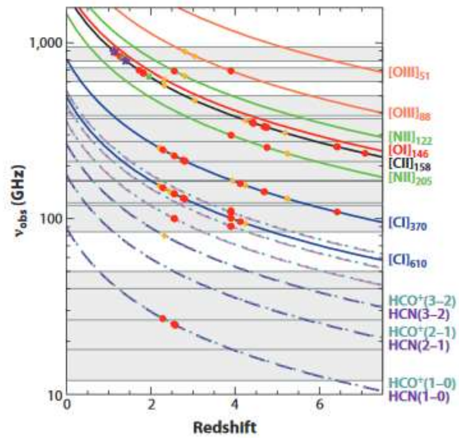

Figure 4: While ALMA revolutionized the observations of FSLs at high redshift combining high angular and spectral resolution, atmospheric absorption present it to observe galaxies at z-2-3, which when the peak of star formation occured in the Universe. While these galaxies will be targeted with observatories like SPICA or OST at low angular and spectral resolution, detailied images of these galaxy will be only attainable with a far-infrared space telescope. Image from Carilli & Walter et al. (2013). ALMA/VLA bands shown in grey.

To reduce observing time, multipixel heterodyne arrays are needed to make such maps. Also, high resolution Fabry-Perot-interferometer based instruments such as HIRMES on SOFIA, can be used to observe and map shorter wavelength FSLs. A 2-m class balloon-borne instrument would enable access to FSLs that are obscured by the atmosphere at SOFIA's altitudes. For large-scale mapping the Milky Way, balloon-borne observatories or small-satellites with small telescopes can be used to map our galaxy at large scales.

Facilities Required: Multi-pixel heterodyne arrays. SOFIA, 2m class balloons for nearby galaxies. Ultra-long duration balloons, small satellites for mapping the Milky Way.

3) **Tracing entire distant galaxies at the peak of star formation: High spatial/spectral resolution FSL images of galaxies at the peak of star formation in our Universe.**

With detailed knowledge of the effect of stellar feedback in small scales in Galactic clouds and its large scale effects coupled with dynamical processes occurring at kilo-parsec scales in the disk of galaxies, we will obtain important information on the regulation of star formation in the nearby Universe. While this information will be invaluable for understanding the regulation of star formation across the Universe, it is still important to study the environments of galaxies during the peak of star formation at redshift z ~2-3. ALMA has revolutionized the use of FSLs for studying distant galaxies at high spatial and spectral resolution, as several of the key FSLs are shifted to the millimeter and submillimeter wavelengths. But, due to atmospheric absorption in the submillimeter, galaxies at redshift 2-3 and below cannot be observed with ALMA in [CII] or [NII], as well as many other key galactic tracers (Fig. 4). Such observations will become available in the 2020s with missions like SPICA and the Origins Space Telescope (OST). However, beyond the 2030s observational capabilities similar to ALMA will become necessary for understanding the evolution of galaxies at the peak of star formation. Such observations will require a far-infrared space interferometer, which will require important technological advances in low-cost space telescopes, possibly derived from increasingly capable small satellites. Long term investments in technologies that could make such space interferometer possible need to be started in the 2020s.

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