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Far Infrared Spectroscopic Imaging of the Neutral Interstellar Medium in Galaxies

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: We describe the importance of obtaining velocity-resolved far-infrared emission lines to investigate the physics of the neutral interstellar medium of galaxies, star formation and galaxy evolution. The [CII] 158μm fine structure line is emphasized owing to its ability to trace multiple ISM phases including the critical regime at which hydrogen is primarily molecular but is not effectively traced by CO due to a low CO abundance. We describe four fundamental topics (thermodynamics of the neutral ISM, the assembly of giant molecular clouds, interstellar turbulence, and radiative feedback) that can be addressed with far-infrared spectroscopy.

The formation of stars is a fundamental process that drives the evolution of galaxies over cosmic time. Newborn stars emerge from clouds of molecular gas that are embedded within a dynamic, multiphase interstellar medium (ISM) driven by the large-scale Galactic gravitational potential, rotational shear, magnetic fields, turbulence, and mechanical and radiative feedback from supernovae and massive stars. Understanding these processes, how they interact and to what degree they regulate star formation activity both locally and globally are essential to obtain a comprehensive understanding of star formation and galaxy evolution.

Significant progress in this area of research requires imaging of spectral line emission from well-defined tracers of the neutral atomic and molecular gas phases of the ISM. Such spectral maps define the distribution of gas and establish spatial and kinematic relationships between different phases as these relate to turbulence and streaming motions induced by gravity and feedback processes. To follow the sequence of the formation of molecular clouds, dense clumps and finally stars within them, we have to start by tracing the transition from atomic to molecular material, not only as a chemical transition, but also in terms of the velocity perturbations injected into the molecular clouds that in turn, creates the density enhancements providing the seeds of star formation. Conventionally, the warm neutral medium (WNM) and cold, neutral medium (CNM) are spectroscopically probed with the HI 21cm line. However, the HI 21cm line in emission cannot distinguish between WNM and CNM so that the HI emission observations provide no reliable spatial and kinematic boundary to the denser, molecular gas component. The CNM is more directly studied through HI 21cm absorption profiles towards background continuum sources but such sources with sufficient brightness are sparsely distributed precluding the construction of even a moderate resolution map of a CNM cloud and an evaluation of its key physical properties. The molecular gas is examined with various molecular lines that trace different density regimes. The millimeter and submillimeter rotational lines of CO are the primary spectral line tracer of the molecular hydrogen in galaxies. However, CO is not sensitive to the regime where hydrogen is mostly molecular but the CO abundance remains very low due to photodissociation. This CO-dark H_2 gas may comprise a significant fraction (20-80%) of the molecular mass of galaxies (Pineda et al. 2014; Grenier, Black, & Strong 2015). Figure 1 shows a schematic of the multi-phase ISM and the key atomic and molecular constituents.

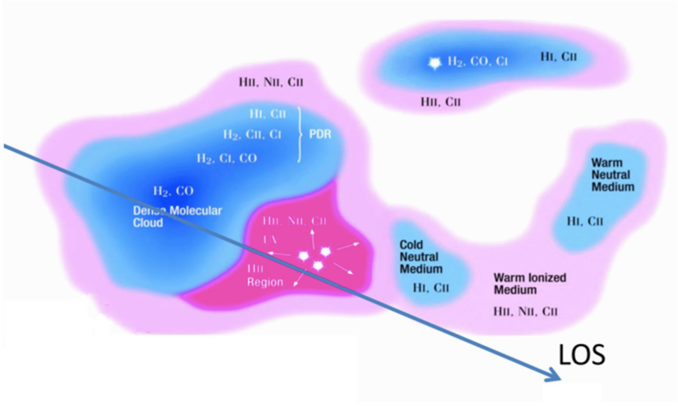

Figure 1: *Schematic view of the multi-phase interstellar medium and the key atomic and molecular species to probe each phase with spectroscopy (based on Langer 2009). High spectral resolution is needed to decompose the emission into each phase. Under realistic conditions the situation is even more complex than depicted here due to fractal boundaries between the different phases.*

Herschel and SOFIA observations have shown that far-IR fine structure lines of ionized carbon,

[CII], oxygen, [OI], atomic carbon, [CI], and ground-state rotational transitions of simple hydrides like CH, HF, CH^+, and OH can overcome the limitations of these conventional spectroscopic tracers of neutral gas (Gerin et al. 2015). Their diagnostic value depends on the main formation mechanism, the upper level energy and the critical density for their excitation. The [CII] 158μm line arises in multiple environments with varying emissivity: from regions of ionized gas, the WNM and CNM, CO-dark H_2 gas, and photodissociation regions (PDR) – the dense surfaces of molecular clouds illuminated by UV radiation from nearby recently formed OB stars or the ambient UV radiation field (see Figure 1). To decompose the emission into each type of region, velocity-resolved measurements of the [CII] emission are necessary to compare with similarly velocity-resolved line profiles of CO and HI 21cm line emission (Pineda et al. 2013). [CII] emission associated with CO line emission at a given velocity can be confidently assigned to molecular cloud surfaces. Such regions are intrinsically bright in [CII] emission. As its intensity depends on the UV radiation field, the [CII] line offers a spectroscopic measure of the local star formation rate. [CII] emission from the atomic medium can be linked to HI 21cm line emission over a common velocity interval. Because of the subthermal excitation at low densities (Goldsmith et al. 2012) the emissivity per H nucleon of [CII] is 10-20x higher in the CNM environment than in the WNM (Wolfire et al. 1995) so that [CII] emission coincident with HI 21cm line but not linked to CO, is strongly biased towards the CNM. [CII] signal correlated with spectral line ionized gas tracers such as [NII] (λ205μm, λ122μm) originates mainly from denser HII regions. Finally, any [CII] not associated with ionized gas, HI 21cm and CO emission is assigned to the CO-dark H_2 regime. Simple hydrides may form proxies for H_2 allowing one to trace the CO-dark H_2 gas in emission and absorption (Gerin, Neufeld, & Goicoechea 2016). With excitation energies corresponding to 26 and 40 K, the ground-state transitions of CH and CH^+ are often traceable in emission. In contrast HF and OH are observed in absorption against background sources. A fraction of the CO-dark H_2 gas may also be visible in the fine structure lines of atomic carbon. The [OI] 63μm line is a strong coolant in denser (3000 cm^{-3}) regions but is optically thick under most conditions. The [OI] 145μm line is optically thin providing an important tracer of mass and column density in the dense PDR regions if sufficiently high temperatures are reached.

Fundamental Topics Addressed by Far Infrared Spectroscopy

As a tracer of gas in many types of interstellar environments, far-infrared emission lines are valuable tools to investigate key processes related to the formation of stars and the impact of star formation on the ISM. In the following sections, we describe several topics that are fundamental to a broader understanding of the star formation process and galaxy evolution.

Thermodynamics of the Diffuse ISM

Local and global thermal pressure variations regulate the amount of cold, dense material that is available for star formation in galaxies. Pressure disturbances from shocks of expanding shells and spiral density waves can redistribute material from the WNM regime to the CNM component, where it is generally assumed that molecular gas develops. More globally, the weight of stars, gas, and dark matter imposes a mid-plane gas pressure required to maintain disk hydrostatic equilibrium. This pressure in galaxies modulates the CNM/WNM ratio and in turn, the molecular gas fraction (Elmegreen & Parravano 1994). Blitz & Rosolowsky (2006) have demonstrated that the ratio of molecular to atomic gas in galaxies does indeed depend on the hydrostatic pressure imposed by the overlying weight of stars and gas. Together with the tight correlation between molecular gas and the star-formation rate on galaxy scales this suggests that the gas pressure is a dominant parameter for star-formation. However, Lada et al. (2013) have shown that these relations break down on the scale of giant molecular clouds and the observations in the central region of the Milky Way reveals low star-formation activity at high pressure (Kruijssen et al. 2014). To understand the evolution of the disk and the star formation within it we need to measure this pressure and decompose it into thermal, turbulent and magnetic components.

In a dynamic ISM, it is necessary to measure the relationships between gas kinematics, gas and stellar surface density, thermal pressure, and ultimately, the rate of star production. High spectral and angular resolution observations of the [CII] 158μm fine structure line can characterize gas kinematics in the CNM and dark H_2 regimes. Its emissivity, I_{CII}/N_H, is proportional to the thermal pressure (Kulkarni & Heiles 1987). Herrera-Camus et al. (2017) recently examined a sample of 31 galaxies using Herschel-PACS instrument to compile [CII] images to derive thermal pressure. For selected regions with the molecular gas fraction less than 1, they found gas pressures consistent with other independent measures and a well-defined correlation between pressure and surface density of star formation. However, without adequate spectral resolution, they could not decompose the [CII] emission into each gas phase so their results rely on assumptions of phase fractions of the gas and their contribution to the measured [CII] emission. More direct and accurate estimates of the thermal pressure require velocity-resolved observations. To distinguish ionized and neutral gas a resolution of 2 km/s is sufficient, but to study the boundaries between the regions a resolution better than 1 km/s is required (Draine 2011).

The Assembly of Star-Forming Molecular Clouds
Giant molecular clouds (GMCs) are the near-exclusive sites of massive star and stellar cluster formation. The assembly and destruction of such massive ($M_{GMC} > 10^5$ $M_\odot$) structures are critical steps in the star formation process and impact the gas depletion time that is encapsulated in the Kennicutt-Schmidt scaling relationship. Gravity is an essential component to cloud formation as it acts to accumulate gas over large scales. Perturbations to the local gravitational potential conducive to cloud formation are generated by spiral density waves, the interface of large-scale ($\sim 10^2$ pc) converging flows, and shells of interstellar material swept up by feedback processes. An important clue is the preferential location of the most massive GMCs in spiral arms of disk galaxies (Koda et al. 2009), which points to two competing descriptions of GMC formation: 1) a top-down process in which a compressed, atomic layer of gas becomes gravitationally unstable – forming denser, self-shielded regions that allow the formation of molecules (Elmegreen 1989); 2) a bottom-up sequence in which pre-existing, small molecular clouds agglomerate into larger structures due to the action of the spiral potential (Scoville & Hersh 1979; Dobbs & Pringle 2013). In the first case, one expects a large change in the molecular-to-total gas fraction between the arm and interarm regions while no change is expected for the bottom-up agglomeration model. However, the pre-existing, small interarm molecular clouds could be comprised of dark H_2 gas that does not produce CO emission. Without a full accounting of the CNM and dark H_2 gas in both arm and interarm regions, it is not possible to accurately assess either description.

Recent synthetic [CII] emission studies on the scales of GMCs show its potential as a superior tracer of the physical properties of the H_2 gas and the total gas of the cloud, relative to CO and its isotopologues (Smith et al. 2014, Bisbas et al. 2017, Franeck et al. 2018). [CII] emission in these simulations coherently extends beyond the CO and [CI] emission. Velocity-resolved imaging of [CII] 158μm line emission from entire galaxies or galaxy segments with complementary CO and HI 21cm line emission allows one to evaluate the amount of material in each phase, including dark H_2, with respect to kpc scale structures such as spiral arms and stellar bar potentials. This requires velocity-resolved line profiles of [CII] emission, which can also define the kinematic relationships between various neutral gas phases that are predicted by spiral density wave theory (Roberts 1969, 1972; Dobbs et al. 2014).

Injection and dissipation of turbulence

A closely related aspect of cloud assembly is how the cloud inherits high levels of internal turbulence from the large scale diffuse ISM. Statistical studies of GMCs have shown that clouds have highly non-thermal motions (Heyer at al. 2009) and the main physical process that drives such supersonic motions operates on size scales comparable or larger than the GMCs themselves (Brunt et al. 2009). Since turbulence should decay over roughly a crossing time, it is a puzzle in cloud formation studies as to how intermittent sources of energy in the ISM sustain the observed supersonic turbulence. Various solutions have been proposed that range from multi-scale gravitational collapse, to externally driven, and internally-driven (via stellar feedback) turbulence (see Dobbs et al. 2014). Distinguishing between these scenarios requires a simultaneous study of the clouds and their diffuse environment to measure the flows and turbulence injection generated from accretion and feedback (Vázquez-Semadeni 2015). To do this demands detailed mapping with a tracer such as [CII] of the overall mass reservoir of cloud and the diffuse ISM around it to determine velocities and their degree of spatial correlation with varying displacements. Simulations predict the [CII] signal from the diffuse medium to be very weak (Clark et al. 2018), below the detection limit of current instruments. This explains why the [CII] emission maps obtained with Herschel and now with SOFIA, which are limited in sensitivity and mapping area, have not been able to address the issue of gas flows and turbulence. Large scale mapping of [CII] (over several 10 pcs) at high spectral resolution ($\sim$0.1 km/s) is thus required to understand an important aspect of GMC formation and evolution.

Due to the intermittent nature of turbulence the main regions of dissipation are not volume-filling but cover only a small fraction of the overall phase-space. To quantify the scales of turbulent dissipation these "turbulent dissipation regions" (TDRs, Godard et al. 2009) need to be understood. The locally enhanced dissipation may heat the gas to temperatures that allows for the formation of species with a significant reaction barrier or endothermicity such as CH^+ or SH^+. Pon et al. (2014) also showed that high-J CO transitions can be used to study the heating through turbulence dissipation. However the details of intermittency in interstellar turbulence are still not understood. The models can be parameterized but there is no ab initio derivation of the time scales, sizes and relative velocities in the TDRs (Godard et al. 2014). To understand the dissipation problem, searches for TDR tracers have to be combined with detailed mapping of the velocity structure at sub-km/s resolution.

Radiative Feedback and the Quenching of Star Formation

Radiative feedback from massive stars in dense clusters regulates the dynamics, thermal balance, and chemistry of the ISM. It is a multi-scale process influencing the star-forming regions of our own Galaxy, the ISM of starburst galaxies and those in the early universe. The [CII] emission from bright PDRs is one of the best tracers of massive, deeply embedded star formation (Goicoechea et al. 2015). If spectrally resolved, it can measure the dynamics of radiative feedback in terms of the expansion velocity of HII regions and associated shells (Pilleri et al. 2014; Pabst et al. 2019). However, for inhomogeneous, clumpy structures, the effective kinetic energy input through the different feedback processes (protostellar outflows, radiation pressure, photoionization pressure, stellar winds and supernova explosions), is still very uncertain (Krumholz et al. 2014). Together with the thermal structure, interstellar turbulence and magnetic fields regulate star formation but the relative contribution of the different processes is debated. Galaxy evolution models critically depend on an observational calibration of this kinetic feedback input through observations of the velocity structure within the disturbed volume. Significant momentum impact occurs for regions with densities above 100 cm^{-3} at velocities above a few km/s (Haid et al. 2018) and this interaction is best traced through [CII] large-scale mapping observations. The measurement of the momentum feedback enables one to estimate time scales and physical conditions over which star-formation is suppressed by the removal of molecular material. This is essential to interpret the fraction of starburst galaxies in terms of a global star formation history in the universe. Moreover, [CII] observations provide a tool to quantify the thermal feedback of star formation on the surrounding interstellar gas by measuring the gas heating efficiency (Okada et al. 2013) that governs the distribution of the phases of the interstellar medium.

Executive Summary

Far-infrared spectroscopy is a valuable tool to investigate the physics and chemistry of the diffuse interstellar medium and more broadly, galactic ecosystems maintained, in part, by star formation. The measured intensity of key spectral lines and PDR models constrain gas properties such as density and pressure, and the local ultraviolet radiation field from which we can assess the role of radiative feedback from massive stars. Velocity resolved observations can also reveal the amount and relative motions of dark-H_2 gas with respect to the atomic gas reservoir and CO-emitting molecular clouds that may be the key to understanding cloud assembly and the cascade of turbulent energy from the diffuse gas component to star-forming molecular clouds. To gain a more complete understanding of the diffuse ISM and star formation in galaxies, it is necessary to build upon the scientific foundation laid by Herschel Space Observatory and SOFIA heterodyne spectroscopy with innovative observations, PDR models, and analyses that leverage the rich information within the data.

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