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Towards a Theory for Star Formation on All Scales

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☐ 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: Investigations of the large-scale distribution of star formation in galaxies critically guide physically-motivated theories of galaxy formation and evolution over cosmic time. Yet, our current understanding of star formation on galactic scales remains highly incomplete due to our limited ability to precisely track the flow of energy from star formation into the interstellar medium (ISM) across the full range of appropriate scales. Observations of star formation and the ISM within nearby galaxies form a vital bridge between the physical scales probed by in-depth studies of Galactic star-forming regions and the globally integrated measurements of distant galaxies. Such investigations are critical to a host of larger astrophysical problems (e.g., the physical nature of the Hubble sequence, the structure and phase balance of the ISM, feedback processes such as the triggering of starbursts and quenching of star formation, etc.), and act as a linchpin for the physical understanding of galaxy formation and evolution. To fully understand the role of star formation and build a complete theory of galaxy evolution requires accurate measurements of the *current* (i.e., $\lesssim$ few Myr) star formation rate and available gas content within galaxies for a range of physical scales (i.e., $10 - 1000\,$pc). Current facilities have been able to deliver such investigations for the most nearby (i.e., $\lesssim 20\,$Mpc) galaxies and brightest regions within them. However, to sample the full range of physical conditions for star formation ultimately requires a combination of sensitivity, mapping speed, and angular resolution at wavelengths that do not involve complicated interpretations and/or corrections to spatially varying dust extinction. This demanding combination of requirements is not achievable with extant or planned facilities.

Introduction

A fundamental goal in extragalactic astrophysics is to provide a robust observational foundation for understanding the causal physics behind star formation in galaxies. To date, a purely theoretical understanding of the phase changes, and the complex recycling of gas into stars and back into gas again (i.e., a complete, predictive, and self-contained theory of star formation) has yet to be developed. While processes operating at small (pc to kpc) scales must ultimately be part of the equation, global relations (measured on galaxy-wide scales; e.g., Schmidt 1959; Kennicutt 1998) point to collective forces and large-scale physics that also contribute to the secular evolution of galaxies. Galaxy environment (cluster versus field; e.g. Dressler et al., 1997; Butcher & Oemler, 1978, 1984; Desai et al., 2007) and galaxy-galaxy interactions clearly play roles in a galaxy's rate of evolution. To fully address questions related to the rate of star formation in galaxies, data must be acquired over a wide range of physical scales for a variety of galaxy types, subjected to as wide a range of environmental conditions as possible. Not being able to bridge the many order-of-magnitude gap between star formation captured on galaxy-wide scales and studying the individual sites of current star formation has been a major impediment to real progress.

Nearby galaxies are among the best laboratories for understanding the detailed physics of star formation. They offer a much larger range of physical conditions than the Milky Way without complicated de-projection issues. This has made observations of nearby galaxies the workhorse for testing physical models of star formation and stellar feedback. These models underpin galaxy evolution models and are used to explain observations of large populations of galaxies across redshifts, including high redshift systems where it is extremely difficult to conduct detailed measurements.

Using nearby galaxies to understand star formation *requires* robust diagnostics of star formation activity. Combined with measures of gas, kinematics, and galaxy properties such measurements allow us to understand the physics of star formation. They are also needed to train the more indirect estimators for star formation that can be applied to observations of galaxies in the early universe. In practice, this means calibrating empirical radio, infrared, and UV/optical, and hybrid star formation rate (SFR) diagnostics against gold standard measurements. Perhaps even more important, it means developing a physical understanding of the basis and limitations of these tools (e.g., see review by Kennicutt and Evans 2012). But so far, the gold standard observations that anchor empirical SFR calibrations have been terribly expensive and limited to a small fraction of the local galaxy population. To make the next great leap in piecing together a self-consistent theory for star formation, we will require robust maps of star formation for large, heterogenous samples of nearby galaxies at $\lesssim 1''$ resolution.

Nearby Galaxies as Laboratories to Study Star Formation

Studies within the Milky Way and in nearby galaxies reveal a molecular Kennicutt-Schmidt law: a strong correlation between the abundance of molecular gas and the rate of star formation and a more complex relationship between star formation and HI (e.g., Kennicutt 1998, 2007 Bigiel et al. 2008; Schruba et al. 2011; Leroy et al. 2008, 2013, 2017a, Saintonge et al. 2011, 2017). But there remains considerable galaxy-to-galaxy scatter in these relationships and different studies find different second order correlations, e.g., with dynamical state, density, and host galaxy properties. Studies comparing denser gas to star formation add more complexity to this picture. Star formation activity correlates with dense gas mass, but some observations claim that the star formation efficiency per dense gas is constant (e.g., Lada et al. 2010, Evans et al. 2014) while others find

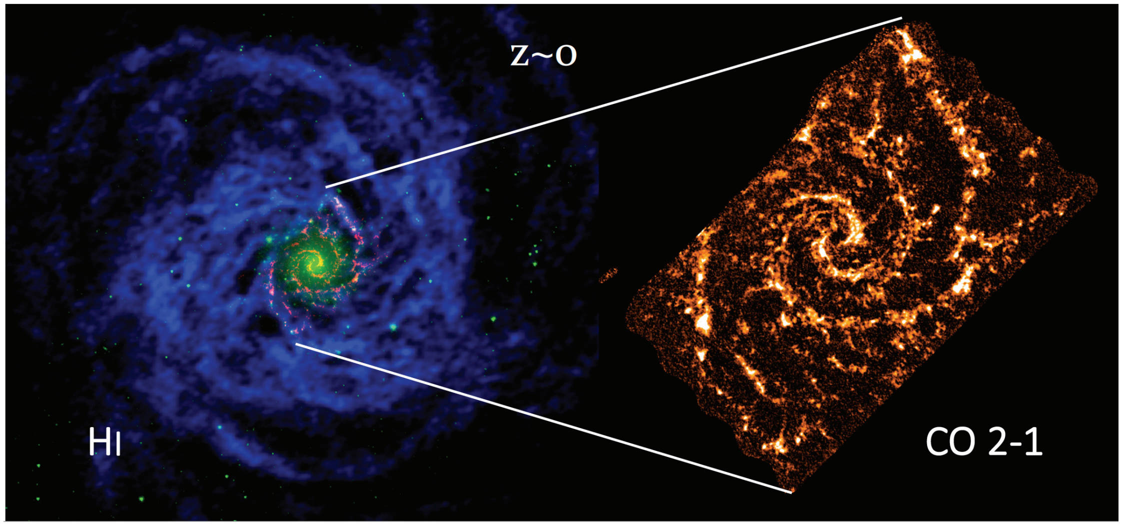

Figure 1: *Left:* The spiral galaxy M 74 illustrating the CO molecular disk imaged by ALMA (red; Sun et al. 2018; Kreckel et al. 2018), the stellar disk in near-infrared light imaged by *Spitzer* (green; Kennicutt et al. 2003) , and the atomic disk imaged in HI at $\approx$10$''$ by the VLA (blue; Walter et al. 2008), showing the relative distribution of the stars and the molecular and atomic gas phases. *Right:* A zoom in showing the CO $J = 2 \rightarrow 1$ map at 1$''$ resolution.

an anti-correlation between the star formation efficiency of dense gas and the dense gas fraction ($f_{dense} = M_{dense}/M_{gas}$; e.g., Longmore et al. 2013; Murphy et al. 2015; Usero et al. 2015; Gallagher et al. 2018b; Quereteja et al. 2019).

All of this work depends on SFR estimates, often indirect, empirically calibrated estimates. Improving these estimates represents a major path forward for the field. To do this, one ultimately would like to obtain unambiguous, short-timescale, extinction free SFR estimates on scales of ~ 10 pc (i.e., individual HII regions, clouds, or clusters) up to several kpc across large samples of nearby star-forming galaxies. We would like to combine these with observations full spectral energy distributions (SEDs) of stars, gas, and dust Such observations would allow one to measure the systematics and uncertainties associated with all widely used SFR estimators. Understanding how different SFR indicators behave will reveal how much of the scatter observed in the gas depletion time ($\tau_{gas} = M_{gas}$/SFR) is real. Better SFR calibrations will also highlight which trends represent key physics related to star formation and which reflect uncertainties in the chosen SFR estimator. *In short, precise SFR estimation is the key to measure depletion times, chemical evolution, positive/negative feedback, and many other physical parameters in an unbiased way.*

It is also worth stressing that getting around dust is the key to this science. Most stars form deep within molecular clouds. During the first few million years, only a small fraction of the photospheric UV radiation from young massive stars escapes. As a result, wavelengths that penetrate dust are critical for studying early phases of star formation and improved SFR estimates need to focus on infrared and radio wavelengths. Such extinction-free SFR estimations will ultimately allow calibration and cross comparison of complementary SFR estimates within and among galaxies. Unfortunately, this is simply beyond the sensitivities of current telescopes.

At the same time, measurements of gas need to improve. To take the next step in understanding star formation, these gold standard SFR measurements need to be compared to the kinematics and distributions of stars, atomic gas, and molecular gas. This will allow us to study the impact on star formation of changing stellar populations, metallicity, gas pressure, cloud-cloud collisions, barinduced shocks, galactic shear, and a host of other physical condition. In turn, this will improve simulations and inform our understanding of the morphological assembly of galaxies.

Figure 1 shows state-of-the-art multi-wavelength data are shown for the nearby spiral galaxy M 74. This map highlights the large atomic gas reservoir traced by HI (Walter et al. 2008) and the $J = 2 \rightarrow 1$ CO molecular gas towards the galaxy center (Sun et al. 2018; Kreckel et al. 2018). This beautiful image also highlights the shortcomings of current facilities. Even with the Very Large Array one can only image atomic gas with good sensitivity on $\approx$10$''$($\approx$500 pc) scales. Imaging CO over the inner part of the galaxy already takes ALMA, the best mm telescope in the world by far, several hours. Mapping the whole extended HI disk would be a major project. Meanwhile surveying the dense gas that is actively forming stars (e.g., traced by HCN, HCO^+, etc) takes dozens of hours for ALMA even over only the CO field. This renders both high resolution CO imaging and detailed spectroscopy major challenges, but also major opportunities for the next decade (e.g., see Astro2020 White Paper by Leroy et al.).

Robust Mapping of Star Formation in Galaxies on All Scales

Apart from a few nearby galaxies with resolved stellar populations, SFR estimates for normal galaxies are largely based on UV/optical measurements. These suffer from interstellar extinction that varies spatially within and among galaxies. The interpretation of infrared dust emission is also complex; variations in dust content and geometry affect the fraction of UV ionizing photons absorbed and a portion of the infrared emission arises from dust heated by older stars (e.g., Bendo et al. 2010, 2012; Li et al. 2013; Tomicic et al. 2019). Radio observations offer two powerful tools that are sensitive to both the birth and death of massive stars at levels that vary as a function of frequency; low frequencies ($\lesssim$5 GHz) are most sensitive to steep spectrum synchrotron emission associated with CR electrons accelerated by supernova remnants (SNRs), whereas higher frequencies ($\gtrsim$ 30 GHz) are dominated by free-free emission powered by HII regions.

To date, a variety of nearby galaxy surveys such as SINGS[1] and KINGFISH[2], have rendered a large number of diagnostic tools, including many SFR indicators typically used to characterize star formation activity at high z (e.g., UV, Hα, warm/cool dust emission, 20 cm radio continuum, [CII]; see reviews by Kennicutt & Evans 2012; Calzetti 2013). However, a key piece of data is desperately lacking from such studies: a highly accurate measure of the massive SFR measured across a large range of environments. This would allow us to properly interpret these other diagnostics, which are sensitive to metallicity, dust and gas content, and a range of timescales.

High-frequency radio observations offer an extremely promising direction. This emission is unaffected by extinction and can be related directly to ionizing photon production by newly-formed massive stars (e.g., Mezger & Henderson 1967). Over the last decade, case studies using the VLA and ALMA have shown that on $\sim$100 pc scales radio emission from individual star-forming regions in nearby galaxies is dominated ($\gtrsim$90%) by free-free emission (e.g., Murphy et al. 2011, 2012, 2018b; Bendo et al. 2015, 2016; S. Linden et al. 2019, in preparation). However, such studies have been limited to the brightest regions within galaxies and still require significant telescope time. Obtaining robust maps of star formation activity on the scale of individual HII region complexes for the entire disks of a large, diverse sample of nearby galaxies is beyond reach of current facilities.

[1] The *Spitzer* Infrared Nearby Galaxies Survey (Kennicutt et al. 2003)

[2] Key Insights on Nearby Galaxies: a Far-Infrared Survey with *Herschel*, (Kennicutt et al. 2011)

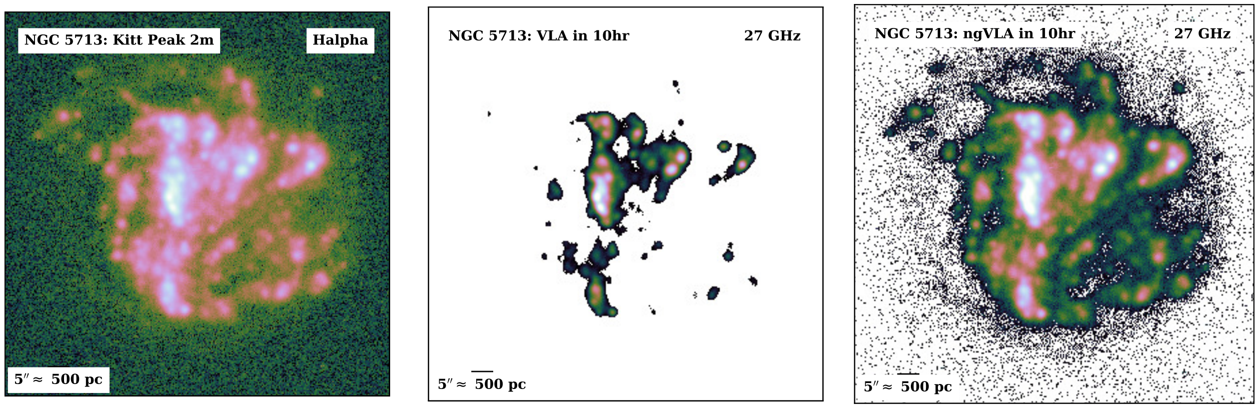

Figure 2: *Left:* An Hα image of NGC 5713 ($d_L \approx 21.4\,\mathrm{Mpc}, \mathrm{SFR} \approx 4\,M_\odot\,\mathrm{yr}^{-1}$) taken with the Kitt Peak 2 m as part of SINGS (Kennicutt et al. 2003). *Middle and Right:* Both panels show a model 27 GHz free-free emission image based on the existing Hα narrow band image at its native ($\approx 1''$) angular resolution, and illustrate the emission that would be detected at the 3σ level after a 10 hr on-source integration time using the current VLA in C-configuration ($1\sigma \approx 1.5\,\mu\mathrm{Jy\,bm}^{-1}$) and the ngVLA with a $1''$ sculpted beam ($1\sigma \approx 0.17\,\mu\mathrm{Jy\,bm}^{-1}$). With a modest integration, the ngVLA is easily able to recover a significant fraction of the star formation that is completely missed by the VLA.

A Plausible Way Forward

What is ultimately required to make the next great leap in piecing together a self-consistent theory for star formation are robust maps of star formation for large, heterogenous samples of nearby galaxies at $\lesssim 1''$ resolution. More specifically, what is needed are maps that directly trace the ionizing photon rate of massive stars on $\approx$100 pc scales and that are unbiased by dust. Such a dataset would critically improve upon the Hα images that astronomers have heavily relied on for decades by not having the additional complications of extinction corrections and contamination by wavelength-adjacent [N II] line emission, which make such images challenging (and in some cases nearly impossible) to interpret. They would further improve upon current IFU maps (e.g., CALIFA; Sanchez et al. 2012; MANGA; Bundy et al. 2015; ATLAS^{3D}; Capellari et al. 2011) that, even when able to extinction correct via the Balmer decrement, still miss the youngest, and most heavily enshrouded star formation activity in galaxies ($\approx 5-10\%$; e.g., Prescott et al. 2007; Murphy et al. 2018b). Looking toward the future, such maps will greatly complement the galaxies that *JWST* are able to map via NIR-recombination lines with MIRI. But, given the MIRI field of view, large overheads, and the finite lifetime of *JWST*, it is unlikely it will map $\approx$100 galaxies, and NIR-recombination lines will also suffer from significant extinction ($A_V \gtrsim 25$ mag) towards normal galaxy nuclei (e.g., Tsai et al. 2013) and local luminous infrared (starbursting) galaxies (e.g., Murphy et al. 2001).

ALMA is already laying the groundwork for such resolved studies of star formation by mapping the molecular gas content with $\approx 1''$ resolution towards the centers of nearly 100 galaxies (i.e., CO $J = 2 \rightarrow 1$ in 74 nearby galaxies as part of the Physics at High Angular-resolution in Nearby GalaxieS with ALMA, PHANGS: A.K. Leroy, E. Schinnerer et al., 2019, in preparation). However, we still lack corresponding maps of star formation to relate the molecular gas to the forming stars on the same physical scales *within* GMCs. A new set of robust maps of the current star formation activity to accurately quantify the energy input of young massive stars into the ISM of 100's of galaxies on all scales will illuminate the relation between complex interactions of star formation, gas cycling, and positive/negative feedback processes. Such maps will be highly synergistic with existing and forthcoming ancillary observations from shorter wavelength, ground- and space-based telescopes that have access to large numbers of other diagnostics (line and continuum imaging) that may be difficult to interpret due to extinction at both low and high redshift. The same can be said for synergy with longer wavelength, far-infrared telescopes (e.g., *Origins*) that will provide access to dust continuum and fine structure line emission that can be used to characterize the cold/warm neutral phase of the ISM, but lack the angular resolution necessary to study discrete ($\gtrsim 10 - 100$ pc) star-forming regions in large samples of galaxies.

One example of the types of observations required to break down this current barrier in observational studies of star formation is illustrated in Figure 2, where an existing Hα narrow band image taken from SINGS (Kennicutt et al. 2003) was used to create a model 27 GHz free-free emission map at $1''$ resolution for the nearby star-forming galaxy NGC 5713. By achieving arcsecond-like resolution, high-frequency (i.e., $\gtrsim$30 GHz) radio maps that are commensurate with ground-based optical facilities, one will be able to probe $\approx$100 pc scales out to the distance of Virgo (the nearest massive cluster at $d \approx 16.6$ Mpc), which are the typical sizes of GMCs and giant H II regions. For this case, nearly an order of magnitude improvement in surface brightness sensitivity is required over extant facilities to generate large area maps for samples of nearby galaxies that sample the full range of environmental conditions for star formation that is representative of both the low- and high-z populations. Quantitatively, for a transformational step to occur this will require a sensitivity, in terms of SFR surface density, of $\approx 0.005\,M_\odot\,\mathrm{yr}^{-1}\mathrm{kpc}^{-2}$. With an order of magnitude improvement over current facilities, something like a next-generation Very Large Array (ngVLA: Bolatto et al. 2017; Murphy et al. 2018c) could deliver such maps with a $\approx$10 hr integration (i.e., an rms of $\approx$0.15 μJy bm^{-1} $\approx$35 mK). A comparison of what can currently be delivered with the VLA for the same integration time is also shown, indicating that only the brightest star-forming peaks would be detected. To make a map to the same depth using the current VLA would take $\gtrsim$800 hr! *This is the same amount of time it would take to roughly survey $\gtrsim$80 galaxies with the ngVLA*. Full 1.2 - 116 GHz frequency coverage is also necessary due to the potential for a significant contribution from anomalous microwave emission peaking at frequencies $\sim 20 - 40$ GHz (e.g., Murphy et al. 2010, 2018a; Scaife et al. 2010; Hensley et al. 2015; Astro2020 White Paper by Murphy et al.), which by itself may be a powerful new tool for constraining ISM conditions.

Using the same data, but applying a different imaging weighing scheme to create finer resolution maps (i.e., $0\farcs1$, or even higher for brighter systems), similar multi-frequency radio continuum analyses can be performed for discrete H II regions and SNRs to complement high-resolution, space-based optical/NIR observations (e.g., *HST*, *JWST*, *WFIRST*, etc.). At an angular resolution of $0\farcs1$, such maps would sample $\approx$10 pc scales in galaxies out to the distance of Virgo to resolve and characterize (e.g., size, spectral shape, density, etc.) discrete H II regions and SNRs with a sensitivity to diffuse free-free emission corresponding to a SFR density of $\approx 0.5\,M_\odot\,\mathrm{yr}^{-1}\mathrm{kpc}^{-2}$. Coupling free-free continuum maps with large, spectroscopic maps of near-/mid-infrared H-recombination line maps (e.g., from *JWST*), which in the absence of significant dust extinction will deliver an equally robust estimate for the current star formation activity, can be used to estimate electron temperatures of the ionized gas. This is a critical ingredient when trying to assess metallicities from common gas metal-abundance measures that suffer from temperature uncertainty. Such observations are required to make the next transformational step for studies of star formation in the local universe.

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