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The Physics at High Angular resolution in Nearby GalaxieS (PHANGS) Surveys

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A major advance in understanding the process of star formation will come from charting the connections between cold (molecular) gas and young stars on the scale of individual molecular clouds, HII regions, and star clusters. For the first time, the ESO facilities ALMA and MUSE, in combination with HST, offer the opportunity to survey the properties of these regions and clusters across a large sample of galaxies, capturing the range of diverse galactic environments found in the local universe. Guided by theoretical models and simulations, the PHANGS collaboration has begun an endeavour which aims to reveal the physical processes controlling the process of star formation in galaxies.

Understanding the physics of star formation from detailed studies of nearby galaxies

For more than 10 Gyr, most stars have been formed in galactic disc-like systems in a secular mode. Star formation in galactic discs, including in our own Milky Way, is thus intimately linked to the formation of structure. As far as we know, the overwhelming bulk of star formation in these galaxy discs occurs in cold, well-shielded giant molecular clouds (GMCs). Therefore, the birth of stars in GMCs is connected to the structural and chemical evolution of galaxies, and the build-up of their stellar mass. Understanding this process — its triggers, efficiency, key timescales and dependence on environment — is a crucial goal of modern astrophysics.

Despite decades of intense observational and theoretical studies (for example, see the review by Kennicutt & Evans, 2012), major questions remain. How do the properties of these GMCs depend on their parent galaxy and on their location within the galaxy? How do the efficiency, duration and output of star formation depend on the hosting GMC, the dynamical environment in the galaxy, and the properties of the host galaxy? Do different clouds and different environments produce different cluster or stellar populations? How do clouds evolve? Does star formation accelerate over time or proceed at a steady pace? Which feedback mechanisms dominate the destruction of clouds in which environments? How does stellar feedback shape the larger structures of gas, metals, and eventually stars inside a galaxy?

These remain open questions because addressing them requires surveys that combine high resolution and high sensitivity. GMCs are the fundamental units of the cold interstellar medium (ISM). They sit at the interface between the large-scale physics of galactic discs and the small-scale physics of star formation. With sizes of ~ 100 pc, studying these clouds requires high physical resolution. Over the last decade, observations of individual galaxies, including the Milky Way, have replaced the old idea of a universal population of GMCs with a more diverse, dynamical view of clouds. But these previous-generation studies have been confined to individual galaxies, and often to small regions inside those galaxies. Before now it has simply been too expensive to survey molecular clouds across the whole galaxy population, and as a result, we still lack a rigorous statistical characterisation of GMC populations and properties across a representative sample of star-forming galaxy discs. Consequently, our understanding of the link between GMC properties and star formation is also in its infancy.

Our understanding of the time evolution of star formation regions has been similarly constrained by observations. Over time, an individual star formation region evolves from a GMC to an exposed stellar cluster, with turbulence, gravitational contraction, and stellar feedback all playing key but weakly constrained roles. Again, the key physics is accessible only from highly resolved observations. Here, a multi-wavelength approach is required. Observations of optical line emission from ionised gas are indispensable to probe the HII regions created by young stars, optical and ultraviolet observations probe the young stellar populations themselves, while longer wavelength observations measure the cold gas. To capture the violent cycling between ISM phases, all of these observations must at least isolate individual star-forming regions. Again, these requirements have been so strict that most key work on this topic has so far been restricted to case studies, mostly focused on the Milky Way or Local Group targets.

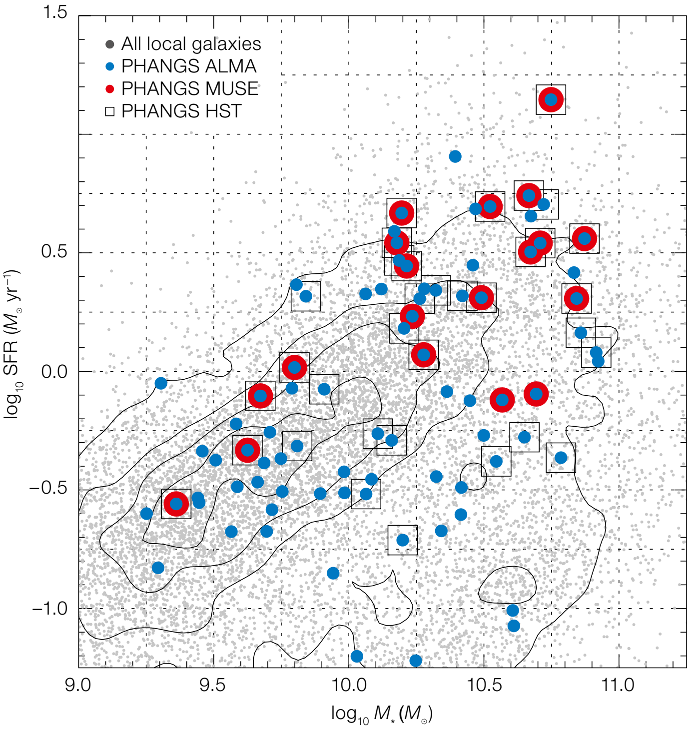

Figure 1. The PHANGS ALMA and PHANGS MUSE samples. PHANGS ALMA targets all of the closest massive, star-forming galaxies and PHANGS MUSE focuses on a key subset of these targets. Both samples achieve good coverage in the M-SFR* plane, covering the kinds of systems where most stars form. The galaxies targeted by ALMA (blue filled circles), MUSE (red circles), and HST (black squares) are shown with respect to the distribution of local galaxies.

The transformational power of ALMA and MUSE

The advent of two ESO flagship facilities dramatically changed the observational landscape in this field. The Atacama Large Millimeter/submillimeter Array (ALMA) can map cloud-scale CO (2–1) emission — a key tracer of molecular gas mass and kinematics — over the entire disc of a nearby (*d* ~ 15 Mpc) galaxy in about two hours of main array time. This is an improvement of roughly two orders of magnitude in survey speed compared to previous instruments, opening the transformational opportunity to survey GMCs across the whole nearby galaxy population.

Meanwhile the Multi Unit Spectroscopic Explorer (MUSE) at the VLT can capture the full optical spectrum with the same resolution and field of view as ALMA. MUSE spectral maps reveal the location, kinematics, and physical properties of HII regions, supernova remnants (SNe), and planetary nebulae (PNe). At the same time, MUSE captures the underlying stellar structures (spirals, bars, clusters) and populations that represent the dynamical drivers and outputs of the star formation process. With its large field of view, fantastic sensitivity, wavelength coverage, and sampling of the other stages of the star formation process, MUSE represents the perfect complement to ALMA.

PHANGS ALMA and PHANGS MUSE observations

Recognising this opportunity, the PHANGS collaboration proposed ambitious observational campaigns that aimed to use ALMA and MUSE to address the open questions in this field. The PHANGS ALMA and PHANGS MUSE surveys sample the full time sequence of the star formation process at resolutions matched to individual clouds across a representative sample of local galaxies. By combining resolution and physical detail using a survey type approach, these programmes aim to link the detailed physics of star formation to our understanding of galaxy evolution.

A representative sample of local star-forming galaxies

Detailed studies of clouds, HII regions, and cloud evolution have so far

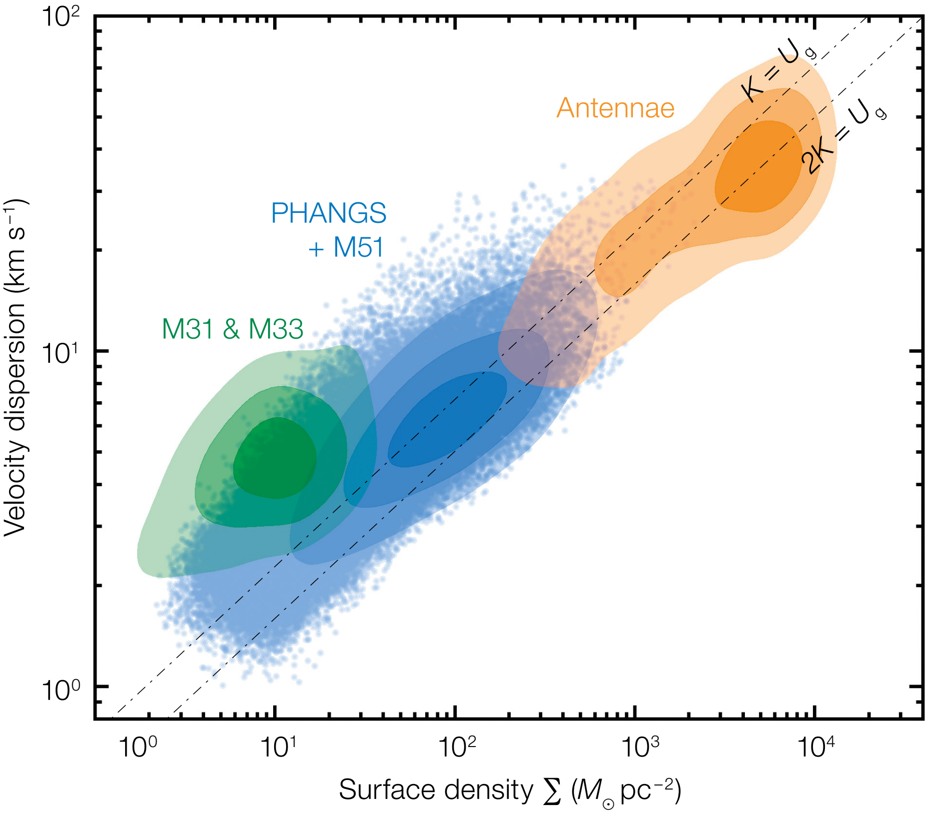

Figure 2. Molecular clouds in PHANGS ALMA. Line width at a fixed size scale (120 pc) as a function of gas surface density for the first ~ 10 PHANGS ALMA targets (blue) and several literature targets including the Antennae galaxies (NGC 4038/39). The figure, adapted from Sun et al. (2018), shows the properties of ~ 30 000 individual cloud-scale measurements (i.e., the equivalent of ~ 30 000 GMCs). The clouds span a wide range of surface density, line width, and internal (turbulent) pressure, but a relatively modest range of dynamical state (ratio of kinetic (K) to potential (U) energy). The visible variations in cloud properties can be mapped back to the locations of clouds inside the galaxy and the properties of the host galaxy.

been mostly restricted to individual case studies. Gas content, galaxy growth, and star formation are now understood to vary in important ways as a function of stellar mass (M_*) and specific star formation rate (sSFR). A key goal of PHANGS is to link the detailed physics of star formation to our understanding of galaxy evolution. To achieve this, both surveys aim to sample the so-called main sequence of star-forming galaxies, i.e., the M_*–SFR correlation that persists across redshift. To this end, PHANGS targets all massive ($9.5 < \log(M_*/M_\odot) < 11.0$), actively star-forming ($\log(\mathrm{sSFR/yr^{-1}}) > -11$) galaxies within D ~ 17 Mpc that are not too edge-on ($I < 75$ degrees) and which are easily observable with ALMA and MUSE (–75 < declination < 20 degrees). These criteria yield ~ 80 galaxies (see Figure 1) that sample the local M_*–SFR relation very well.

Cloud-scale surveys

The key physics described above plays out at the cloud scale, which is 50–150 pc. This is about the scale height of the cold gas disc, about the scale at which supernovae are expected to stir turbulence, and about the radius of a massive GMC. Current models of star formation and feedback predict a deep link between GMC properties, star formation, and feedback, setting the conditions for star formation to occur, its efficiency and duration. Violent cycling between stages of the star formation process also becomes visible at roughly this resolution.

ALMA and MUSE are efficient survey instruments thanks to their ~ one arcsecond resolution. We designed the sample to be close enough that this resolution corresponds to this key cloud scale. At this resolution, both instruments can still cover an area that includes most of the massive star formation in each target. Reaching these GMC scales in nearby galaxies allows us to connect detailed Galactic studies of Milky Way clouds to global galaxy properties, to make measurements that test theories and numerical prescriptions for star formation and feedback, and to resolve the time evolution of the ISM.

Resolving the star-forming units in nearby galaxies

Molecular clouds across galaxy discs with PHANGS ALMA

PHANGS ALMA resolves the molecular gas reservoir into individual GMCs across the full disc in ~ 80 targets. The survey focuses on mapping CO(2–1) line emission, which arises from the cold, molecular gas that forms stars. When complete, PHANGS ALMA will characterise more than 100 000 massive GMCs, roughly 100 times the number of clouds known in the Milky Way. Key science goals of PHANGS ALMA include:

A. *Uncover the dependence of molecular cloud populations on host galaxy and local galactic environment.*
Case studies of cloud properties in individual galaxies have already indicated that the distribution of cloud mass and the corresponding gravitational state are changing as a function of environment. The statistics provided by PHANGS ALMA will not only allow for a systematic assessment of these changes, but also identify the parameters that set or control the structure of the cold ISM. Figure 3 shows results from a pilot study using our first ~ 10 targets (Sun et al., 2018). These already reveal strong, systematic variations in the physical state of molecular gas across the galaxy population.

B. *Measure the efficiency of star formation by comparing the rate at which molecular gas forms stars to the gravitational freefall time.*
This efficiency per freefall time is a central parameter in many star formation theories. It captures the degree

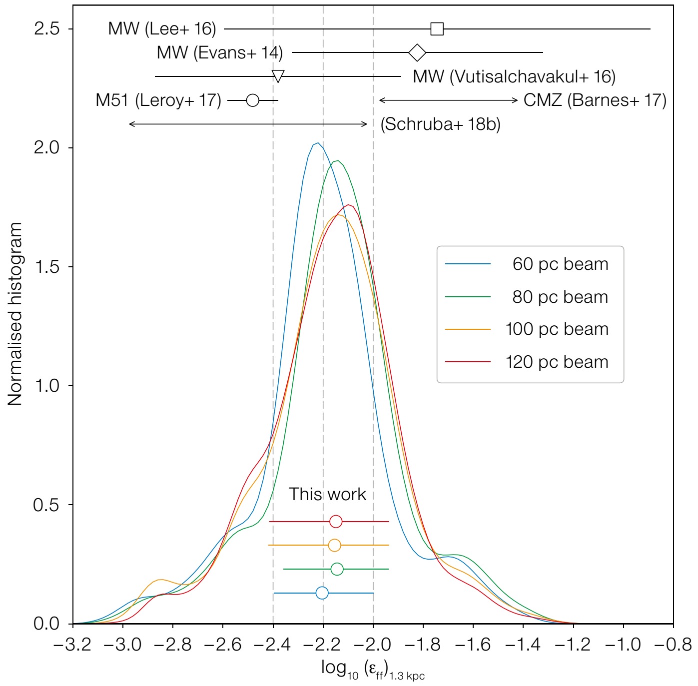

Figure 3. The distribution of star formation efficiency per freefall time ϵ_{ff}. The fraction of gas mass converted to stars per gravitational freefall time in the first ~ 10 PHANGS ALMA targets (from Utomo et al., 2018). This efficiency per freefall time ϵ_{ff} is a key benchmark for theory, capturing the inefficiency of star formation relative to gravitational collapse. It is uniquely accessible to PHANGS ALMA because the high-resolution ALMA imaging allows us to estimate the mean density of the molecular gas.

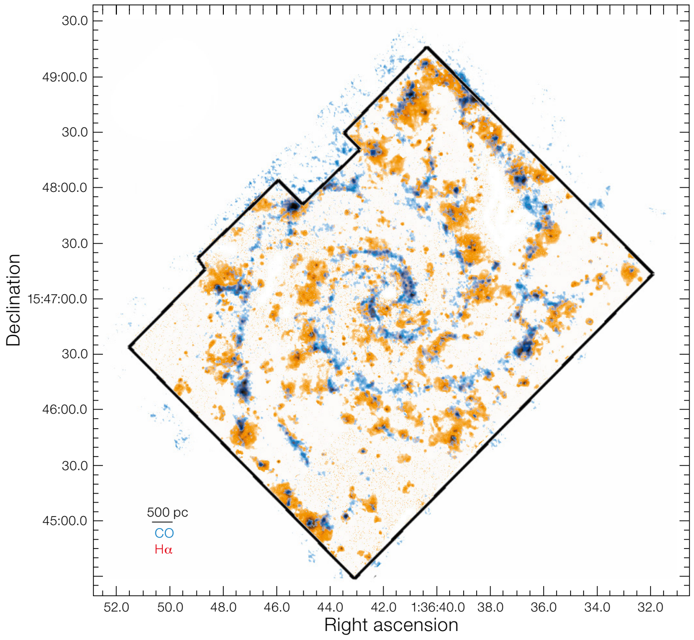

Figure 4. PHANGS ALMA and MUSE observations show the evolution of star-forming regions. ALMA observations of the cold gas reservoir (blue; CO [2–1]) overlaid with the PHANGS MUSE view of ongoing star formation activity (orange; Hα) in the the nearby spiral galaxy NGC628 (Kreckel et al., 2018). The molecular clouds seen in blue often appear visibly offset from the HII regions created by massive young stars. As gas flows through the spiral arms, cold, dense clouds visibly evolve into young star-forming regions. A key goal of PHANGS is to use statistical and dynamical modeling of these data to constrain the life cycle of molecular clouds.

to which star formation is slowed or curtailed by feedback, turbulence, and other means and represents a specific prediction of many models. Because this measurement requires knowing the gas density, it also requires high-resolution imaging. Already, using our first ~ 10 galaxies, PHANGS ALMA has provided the most definitive measurement of this quantity to date in normal local disc galaxies (Utomo et al., 2018).

C. *Quantify the life-cycle of molecular clouds.*
At high resolution, star-forming regions appear in discrete evolutionary states using ALMA and MUSE – that is as clouds, HII regions, and young star clusters (beautifully demonstrated in Figure 4, adapted from Kreckel et al., 2018). Via statistical and dynamical modelling, such observations constrain the evolution from diffuse gas to dense clouds to HII regions to clusters.

> The dominant feedback mechanism and timescale for cloud dispersal in different environments are still unknown and will be constrained via modelling.

At the time of writing, the observations for the Large Programme that forms the core of PHANGS ALMA are almost complete. All calibrated data products, cloud catalogues, and a host of other high-level data products are expected to be released to the community in 2020. Science papers addressing our key goals have already begun to appear.

Star-forming regions and stellar structures with PHANGS MUSE

Star formation and feedback are violent, rapid processes, with key roles played by ionising radiation, radiation pressure, stellar winds, and supernovae — all phenomena traced through the ionised gas phase. These sources of feedback impact, destroy, and reshape the cold gas that will form the next generation of stars. Meanwhile, the young stars deposit new metals into the ISM, while new material for future star formation must flow in through the galaxy disc. Star formation itself may be shaped by the underlying stellar potential, with important roles played by spirals, bars, and central stellar structures revealed by their stellar population distributions and kinematics. Resolving star-forming regions and stellar discs with PHANGS MUSE (which started as a Large Programme in ESO Period 100) will provide us with a dynamic view of star formation, stellar feedback and chemical enrichment of disc galaxies, allowing us to address the following:

A. *Estimate the timescales of the star formation process.* This is closely related to modelling the life cycle of molecular clouds. MUSE and ALMA working together (illustrated in Figure 4, adapted from Kreckel et al., 2018) offer the chance to address open questions: How long does star formation take to set in once a molecular cloud has formed? How long does stellar feedback take to disperse

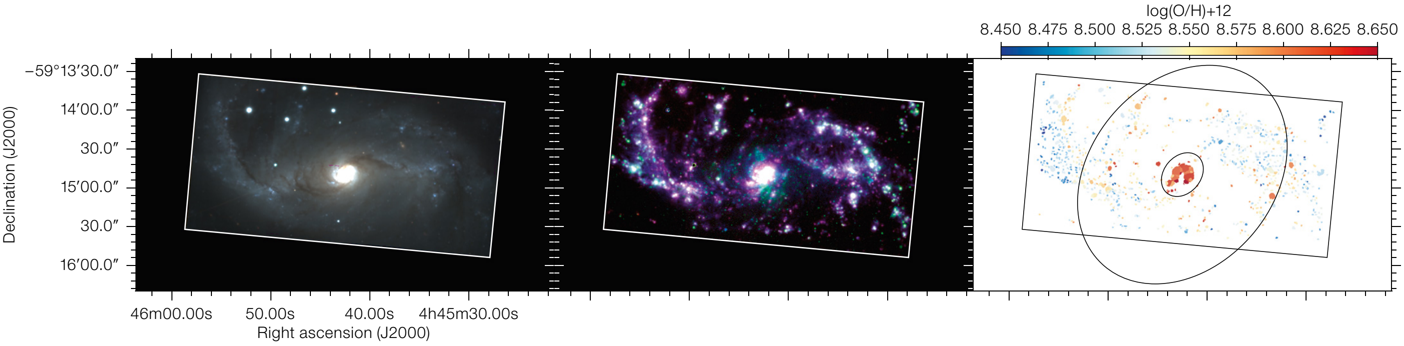

Figure 5. The PHANGS MUSE view of starlight, ionised gas and metals. PHANGS MUSE observations of NGC1672. Left: Simulated *gri* three-colour image derived from MUSE, showing starlight and prominent dust lanes. Middle: Emission line maps (red: Hα, green: [OIII], blue: [SII]) revealing active star formation and diverse physical conditions. Right: For each HII region in the galaxy, we use the MUSE spectra to estimate the metallicity. Even before removing the radial gradient, spatial correlations in metallicity, including azimuthal variations, are apparent. These trace the diffusion of metals and the flows of enriched and pristine gas across the galaxy.

a cloud? Is star formation triggered within a galactic disc (i.e., in spiral arms) or is it a stochastic process?

B. *Quantify the strength of stellar feedback across environment and scale.* Stellar feedback comes in many forms, including ionising radiation, radiation pressure, stellar winds, and supernova explosions. The high physical resolution and wide wavelength coverage provided by MUSE allow us to separate and characterise HII regions, SNe remnants and PNe (for example, Kreckel et al., 2017, apply this method to our pilot data). Together with the ALMA data, the MUSE cubes can directly assess the interactions between the warm gas (10 000 K), the cold gas (< 100 K), and the young stellar population.

C. *Measure the diffusion of metals and chemical enrichment.* The details of metal production and diffusion remain major open questions in the chemical evolution of galaxies. With metallicity estimates for ~ 15 000 HII regions across 19 galaxies, PHANGS MUSE gives us a powerful handle on how metals are built and distributed. Patterns in the small-scale distribution of metals (see Figure 5) constrain the flows of pristine and enriched gas in and out of galaxies, and the redistribution of metals from their birth sites to the surrounding medium.

PHANGS MUSE targets 19 nearby star-forming galaxies that are also targets of PHANGS ALMA. We expect to identify and characterise ~ 15 000 resolved star-forming regions, measuring metallicity and other physical diagnostics for each. MUSE also captures a host of PNe and SNe remnants (for example, Kreckel et al., 2017) and yields exquisite stellar and gas kinematics, offering signatures of stellar feedback and (with ALMA) the relative motion of different phases of the ISM. Full spectral fitting of the MUSE datacubes will produce “movies” of stellar mass in several bins of ages and metallicities. The survey is currently approximately three-quarters done, with a full release of major data products expected by 2021.

PHANGS beyond ALMA and MUSE

Young stars and stellar clusters with PHANGS HST

Direct observations of young stellar clusters offer a powerful complement to the observations of clouds by ALMA and those of HII regions and integrated starlight by MUSE. These clusters have typical sizes of a few parsecs, and so observing them requires the resolving power of the Hubble Space Telescope (HST). As of 2019, PHANGS HST (Principal Investigator: Janice Lee, Infrared Processing and Analysis Center [IPAC] at Caltech, USA), has been observing an overlapping sample with the goal of connecting young star clusters to the cold and warm gas traced by ALMA and MUSE.

The PHANGS HST Large Programme builds on the successful Legacy ExtraGalactic Ultraviolet Survey (LEGUS) Treasury programme, using a similar five-filter observing strategy with the Wide Field Camera 3 (WFC3) camera. PHANGS HST expands from LEGUS towards more massive (more Milky Way-like) galaxies and focuses on regions covered by ALMA and MUSE (see Figure 6). When completed, it will cover 38 disc galaxies. We expect the high-resolution ultraviolet and optical imaging from PHANGS HST to yield catalogues of 100 000 star clusters and associations.

Combining HST with ALMA and MUSE will dramatically improve our answers to the questions listed above (for example, from much improved knowledge of the young stellar population) and also constrain: (a) the timescale for the removal of gas from young stellar clusters (YSC); (b) the relation between the YSC and GMC mass functions; (c) the link between cloud properties and the fraction of stars formed in clusters; and (d) the connection between the multi-scale structure visible in young starlight and cold gas structure. The release of joint HST-ALMA data products revealing the detailed properties of stellar clusters and gas clouds will be a key part of the PHANGS legacy and will help lay the scientific groundwork for future facilities like the James Webb Space Telescope (JWST).

Other major efforts

Building around the core ALMA, MUSE, and HST samples, the PHANGS team is committed to building a complete characterisation of the stellar, gas, and kinematic structure of our sample. Key efforts include: (1) making high quality maps of

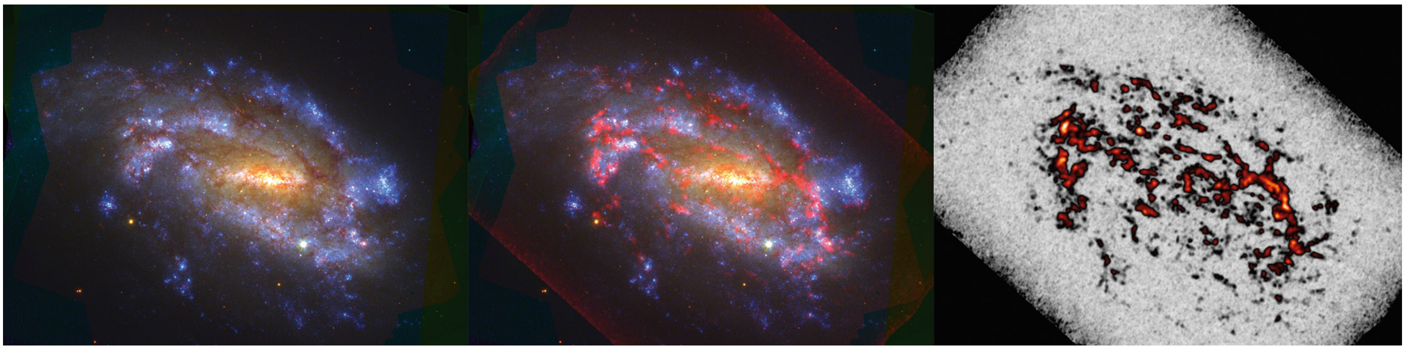

Figure 6. HST and ALMA probing the life-cycle of star formation regions. PHANGS HST and PHANGS ALMA observations of the nearby spiral galaxy NGC1559. The high angular resolution afforded by HST allows for the identification of individual young star clusters that have just emerged from their birth cloud as seen by ALMA. Optical light (HST red: white light, green: *H*-band, blue: near ultraviolet; left), with the molecular gas distribution added in red (middle). The distribution of molecular gas (ALMA; right) is remarkably similar to that of the dust lanes seen in optical light.

the stellar mass distribution for each target using Spitzer and Wide-field Infrared Survey Explorer (WISE data); (2) assembling new and archival narrow-band imaging of the Hα emission line for the whole PHANGS ALMA sample; (3) using the Indian Space Research Organization (ISRO) AstroSat satellite to obtain high-angular-resolution imaging of far-ultraviolet emission for a subset of targets; (4) new and archival Very Large Array observations of the 21-cm line to trace the atomic gas reservoir; (5) construction of detailed environmental masks; (6) reprocessing, fitting, and analysis of archival infrared (Spitzer, Herschel, WISE) and ultraviolet (Galaxy Evolution Explorer, GALEX) observations; and (7) observations of high critical density tracers of "dense gas" using ALMA, the Institut de radioastronomie millimétrique (IRAM) facilities, and the Green Bank Telescope. These efforts leverage a diverse, distributed team and promise to pair the unprecedented ALMA and MUSE data with the most complete view of stellar and gas structure for any sample to date.

Synergy of observations and theory

The combination of ALMA, MUSE, HST and the deep supporting observations represents a complex, high-dimensional data set. The full exploitation of such a unique resource requires a close synergy between careful observational analysis, modelling and statistical analysis techniques, numerical simulations, and analytic theory. With this in mind, PHANGS has pursued development of new tools and close comparison with numerical modelling and theory as a core activity. The development of new statistical tools focuses on robust statistical characterisation of the full multi-dimensional, multi-scale data set, with a focus on moving resolved studies of nearby galaxies into the "big data" regime. The team is also running dedicated state-of-the-art simulations. Our observations capture the underlying physical processes filtered through a complex combination of projection, chemistry, and radiative transfer. Implementing a realistic forward modelling perspective into the PHANGS theoretical efforts is therefore key to both uncovering the underlying physics that drives star formation and constructing new innovative tracers.

A modern scientific collaboration

The PHANGS collaboration brings together experts on ISM physics, dynamics, stellar populations, and galaxy evolution. It includes expertise distributed across different wavelengths and combines both observational and theoretical points of view. PHANGS started in 2015 with a small group of enthusiasts dedicated to seizing the opportunities described above. Today, PHANGS is a medium-sized collaboration distributed around the globe (with substantial representation in Australia, Europe, Chile, and North America).

The team is committed to diversity. We aim to fill scientific leadership roles with a mixture of junior and senior scientists and to enhance the visibility of female scientists. Currently about half of all leadership positions are occupied by female scientists. Following good practice of other large collaborations, "builder status" has been granted to junior scientists who have spent significant time generating data products for use by the astronomical community. Junior scientists have also taken on high profile roles such as leading follow-up proposals and planning the next generation of PHANGS projects.

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Links

[1] PHANGS survey webpage: http://www.phangs.org/