

Astro2020 Science White Paper

The Cycling of Matter from the Interstellar Medium to Stars and back

- 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

Principal Author:

Name: Robert Simon
Institution: Universität zu Köln
Email: simonr@ph1.uni-koeln.de
Phone: +49-221-470 8353

Co-authors: (names and institutions)

Nicola Schneider, Universität zu Köln (UzK); Frank Bigiel, Universität Bonn; Volker Ossenkopf-Okada, UzK; Yoko Okada, UzK; Doug Johnstone, National Research Council Canada; Peter Schilke, UzK; Gordon Stacey, Cornell University; Markus Röllig, UzK; Álvaro Sánchez-Monge, UzK; Daniel Seifried, UzK; Jürgen Stutzki, UzK; Frank Bertoldi, Universität Bonn; Christof Buchbender, UzK; Michel Fich, University of Waterloo; Terry Herter, Cornell University; Ronan Higgins, UzK; Thomas Nikola, Cornell University

Abstract:

Understanding the matter cycle in the interstellar medium of galaxies from the assembly of clouds to star formation and stellar feedback remains an important and exciting field in contemporary astrophysics. Many open questions regarding cloud and structure formation, the role of turbulence, and the relative importance of the various feedback processes can only be addressed with observations of spectrally resolved lines. We here stress the importance of two specific sets of lines: the finestructure lines of atomic carbon as a tracer of the dark molecular gas and mid-J CO lines as tracers of the warm, active molecular gas in regions of turbulence dissipation and feedback. The observations must cover a wide range of environments (i.e., physical conditions), which will be achieved by large scale surveys of Galactic molecular clouds, the Galactic Center, the Magellanic clouds, and nearby galaxies. To date, such surveys are completely missing and thus constitute an important science opportunity for the next decade and beyond. For the successful interpretation of the observations, it will be essential to combine them with results from (chemical) modelling and simulations of the interstellar medium.

1. Scientific context

The science case outlined in this white paper is built around the question: *How do the processes involved in star formation and stellar feedback shape the interstellar medium in galaxies?*

1.1 The cycle of matter

The cycling of matter in the interstellar medium (ISM) begins with the accretion of gas onto galactic disks and cooling to form a neutral phase. It progresses with the formation of molecular clouds out of the diffuse, atomic gas and the formation of denser sub-structures such as filaments and cores which ultimately form stars and clusters. These stars in turn interact with the ambient ISM via feedback (radiation, mechanical, supernovae), shaping the ISM properties and chemically enriching galaxies over cosmic time.

1.2 Molecular cloud and star formation

How in detail molecular clouds, dense structures within them, and stars are forming remains disputed and is a highly active field in observational and theoretical astrophysics. We promote here a scenario supported by numerical simulations (e.g., Vázquez-Semadeni et al. 2006, Heitsch & Hartmann 2008) in which molecular clouds assemble fast from converging H I flows in the warm neutral medium. Turbulence plays a key role because it supports clouds at large scales but also creates a highly inhomogeneous molecular cloud structure that is characterized by large density contrasts (Mac Low & Klessen 2004). Most of these density fluctuations are transient, but where turbulent energy is dissipated and shocks are present (Neufeld & Dalgarno 1989, Godard et al. 2019), dense structures in the form of filaments can emerge. Fragmentation on small scales then leads to the formation of individual stars and star clusters. The observed broad molecular lines (Goldsmith et al. 2008) and the complex structures seen in the dust continuum support the omnipresence of supersonic turbulence in whole molecular clouds and even larger scales.

1.3 Injection of turbulence into the ISM

Turbulence in molecular clouds must be constantly replenished or it would decay on time scales of the order of the crossing time. In spite of the ubiquity of interstellar turbulence, the main driving mechanisms are still poorly understood. The observed network of filaments can be qualitatively explained by numerical simulations of magneto-hydrodynamic turbulence (e.g., Padoan & Nordlund 2011, Federrath & Klessen 2013) in gravitationally infalling gas. Supersonic turbulence has been attributed to a number of factors, including magnetic fields, protostellar outflows, H II regions, supernovae, and on-going mass accretion. Observational tests have shown that the first four mechanisms are relatively inefficient. In their theoretical study of the evolution of molecular clouds, Goldbaum et al. (2011) proposed that the accretion of new material from the surrounding environment can drive the observed turbulent motions, but this has not been thoroughly investigated observationally yet. This study is also consistent with observations that suggest the global filamentary structure of molecular clouds is created by large scale colliding flows of atomic material at earlier times (Walch et al. 2015, Seifried et al. 2017).

1.4 Heating and cooling in the ISM

The thermodynamics of the gas depends on the balance between heating and cooling processes, probably moderated by magnetic fields, on large and small scales. The most important processes are provided by stellar feedback (radiation, wind), low- and high-velocity shocks, and cosmic-rays/X-rays. Cooling happens predominantly via dust and line emission at (sub)mm, far-,

and mid-infrared (IR) wavelengths so that studying this wavelength range is the key to understand the relevant processes related to Galactic and extragalactic cloud and star formation.

Understanding the matter cycle in the interstellar medium of galaxies from the assembly of clouds to star formation and stellar feedback remains an important and exciting field in contemporary astrophysics. To achieve significant progress is truly a multi-scale and multi-physics problem that needs to be addressed in the coming decade from the observational and theoretical side.

2. State of the art

To study the cloud and star forming ISM in the Milky Way and external galaxies over large spatial scales and different environmental conditions requires sensitive, high spatial resolution observations in dedicated tracers. The past decades have seen important advancements in multi-wavelength observations of the ISM driven by the access to better (higher) sites (including air- and space-borne observatories) and improvements in technology (higher sensitivity, multiplexing). The routine operation of the Atacama Large Millimeter Array (ALMA) is clearly a highlight in high-angular resolution submm astronomy. ALMA covers a broad science case, cooling lines in high-redshifted galaxies. ALMA, however, can not efficiently survey large (many square degree) regions of the sky.

Dust continuum surveys of large parts of the Milky Way, ranging from the infrared to the submm, have become available thanks to satellite missions such as Spitzer or Herschel (see Fig. 1) and ground-based telescopes (e.g., IRAM 30 m, JCMT, CSO, APEX). These data sets are invaluable to determine the dust temperature and column density structure of the ISM. However, they do not provide information on the dynamical state of the gas, the chemical state of the gas, or even the phase of the gas. To obtain this, we need spectroscopic measurements of a suite of molecules, atoms, and ions.

Wide field spectral line mapping in the Milky Way is so far limited to atomic hydrogen (e.g., VLA and ATCA) and low energetic CO lines (starting with the pioneering Columbia survey (Dame et al. 2001) and taken to higher angular resolution with, e.g., FCRAO, Mopra, JCMT, Nobeyama, APEX). They trace the diffuse, neutral atomic and the cold and moderately dense molecular gas, respectively.

The past 2 decades have also seen enormous progress in high-resolution, cloud-scale (~ 100 pc and below) dust continuum and CO line observations of external galaxies (e.g., IRAM 30 m/HERACLES (Leroy et al. 2009), ALMA/PHANGS (Sun et al. 2018)), including the Magellanic Clouds. These studies allowed to assess the importance of environmental factors such as metallicity for star formation.

For a deeper understanding of the processes forming molecular clouds and stars, and how this links to galaxy evolution, it is essential to **combine observations with modelling and simulations**. Over the last 30 years, the main focus was on modelling Photon Dominated Regions (PDRs). Starting with plane-parallel geometries (Hollenbach & Tielens 1997, Sternberg & Dalgarno 1989), PDR models now incorporate more complex geometries (Röllig et al. 2006, Andree-Labsch et al. 2017) and turbulence (Wolfire et al. 2010, Bialy et al. 2017). In parallel, considerable progress was made in galaxy-wide modelling (Dobbs et al. 2008, Inoue & Inutsuka 2012, Smith et al. 2014). However, only coupling the chemistry with (magneto)-hydrodynamics, including self-gravity, variations in metallicity, UV radiation and cosmic-rays has the potential for

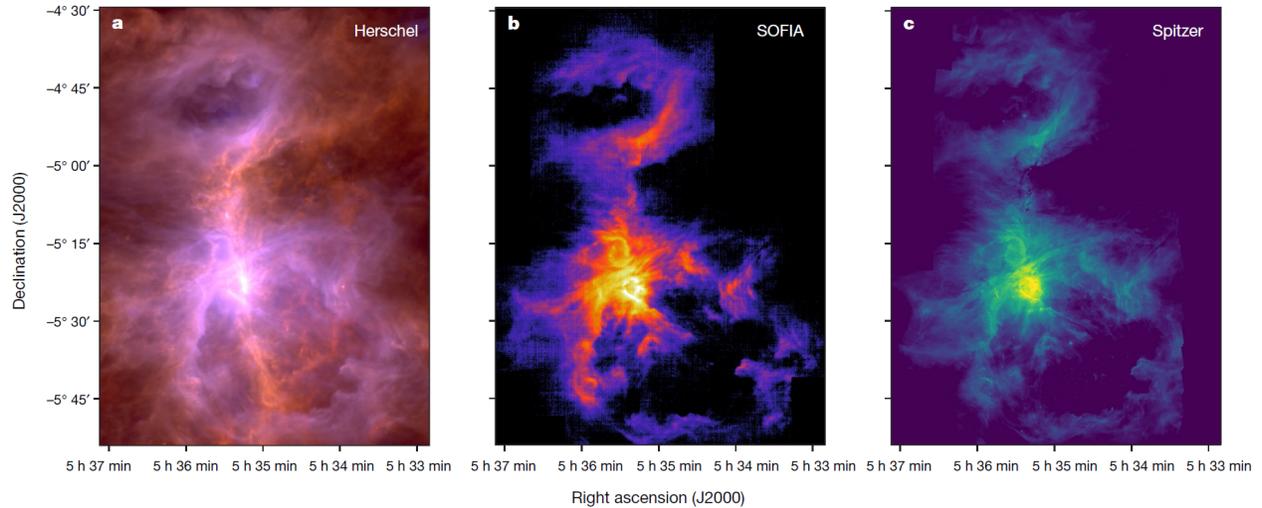


Figure 1: The Orion A molecular cloud in the dust continuum (left: FIR/submm, right: mid-IR and [C II] spectral line emission (middle). From Pabst et al. 2019.

realistic modeling of the ISM on a large scale. Because of increased computing power and laboratory work in molecular chemistry, these models have become available (Walch et al. 2015, Kim & Ostriker 2017). With the inclusion of radiative transfer, synthetic spectral line maps (Seifried et al. 2017, Franeck et al. 2018, Clark et al. 2018) of the most important cooling lines of [C II], [C I], and CO now can directly be compared to observations. To overcome the still existing discrepancies between observations and predictions from simulations requires an intense synergy between modellers and observers.

3. Future opportunities

The assembly of mass to form clouds, dense structures, and stars, and the impact of stellar feedback are highly dynamic processes that require spectrally resolved observations of atomic and molecular lines. Wide-field spectral line surveys, however, are still hampered by either low angular resolution, limited sky coverage or sensitivity, and, as we will specifically argue below, lack of important atomic and molecular tracers.

Novel surveys employing large format (several 100 pixels), high sensitivity heterodyne arrays open completely new opportunities: **large scale, unbiased surveys** covering hundreds of square degrees, possibly even the whole Galactic Plane and nearby galaxies. Such observations will allow unique studies not possible in the past (e.g., of arm versus interarm gas, the effects of varying cosmic ray fluxes, etc.) and a wide range of physical conditions (e.g., density, temperature, pressure, radiation field, cosmic rays, metallicity, star formation activity/rate). And they will allow to explore the unexpected.

In this context, **molecular clouds of the Milky Way** provide the opportunity to study cloud assembly and the highest possible spatial resolution to trace the details of structure formation, turbulence dissipation, the formation of stars out of the densest gas, and the feedback of stars into the ISM. The **Galactic Center and its Central Molecular Zone (CMZ)** serves as template for other galactic nuclei. The overall conditions (temperature, density, pressure, radiation field) in the

CMZ are quite similar to other galactic nuclei, although the star formation rate in the CMZ at the moment is rather low. Observations of **nearby galaxies** provide important context to Milky Way studies as they expand the range of astrophysical environments (e.g., star formation activity, metallicity, dynamics) and provide insight into the role of host galaxy properties related to molecular cloud and star formation. High angular and spectral resolution is important to resolve processes in the Milky Way and nearby galaxies spatially and dynamically to understand global properties of distant galaxies which we will not be able to resolve even with the best instruments.

3.1 The formation of molecular clouds

It is uncertain how molecular clouds gain their mass as the relative role of the inflow of material from high Galactic latitudes onto the gravitational potential of the disk and compression of gas in spiral density waves or expanding shells of atomic hydrogen produced by supernovae is unknown.

Low energy CO surveys reveal the distribution of the cold, moderately dense H_2 gas, but chemical models predict that the formation of CO lags behind that of H_2 and consequently, a different tracer is required to account for this CO-dark H_2 gas. Simulations (Clark et al. 2018) show that this gas emits in the fine structure lines of atomic and ionized carbon [C I] and [C II]. While [C II] is emitted from all phases of the interstellar medium, [C I] is specific to the CO-dark molecular gas as it traces only the outer layers or early stages of molecular clouds. Franck et al. (2018) showed that [C II] is mainly emitted from the atomic, not the CO-dark molecular gas. Only when combining CO observations with those of [C I] as a tracer of the dark gas, we obtain a full picture of the molecular material, in particular including the cloud mass accretion via low density H_2 .

Compared to the 21 cm line of atomic hydrogen, those lines have the advantage that they are narrow enough to resolve individual gas streams separated in velocity space. In contrast to H I, [C I] shows much less line of sight confusion. To measure the kinetic energy injected into the turbulent eddies through accretion, a velocity resolution better than 1 km s^{-1} is required. Due to the random nature of turbulence, a conclusive comparison between models and observations is only possible with a statistically significant sample of large-scale observations, ideally of the full Galactic Plane in [C I] and CO lines.

To date, spectrally resolved [C I] and mid-J CO surveys of large areas of the Galactic Plane and external galaxies are completely missing!

Such surveys and dedicated smaller mapping projects, possibly at even higher observing frequency, will become possible within a few years with the CCAT-prime observatory (Stacey et al. 2018) and are planned for later ground based observatories (ATLAST at higher angular resolution) and space missions (e.g., OST). CCAT-prime is a 6 m aperture, very high surface accuracy, very large field of view (2 degrees in diameter at 809 GHz) telescope at the superb (5600 m elevation overlooking the ALMA plateau) Cerro Chajnantor site. CCAT-prime, together with a large format heterodyne receiver such as CHAI (Stacey et al. 2018) can successfully complete the science described here at better than $30''$ angular resolution in the next decade.

3.2 Star formation and feedback

While active star forming regions predominantly cool via the far- to mid-IR dust continuum, line cooling is dominated by the fine structure lines of [C II] and [O I] at 158 and $63 \mu\text{m}$. These two lines can only be observed from air- or space-borne platforms and the Stratospheric Observatory for Far-Infrared Astronomy (SOFIA) is currently the only available facility. Large scale

observations in the [C II] line are becoming available for whole molecular clouds and even galaxies (Pabst et al. 2019 for the Orion A cloud (Fig. 1) and Pineda et al. 2018 for M51).

A significant fraction of the cooling is nevertheless in mid- to high-J CO lines, some of which are accessible from the ground. Observations of [C II], [C I] and mid-J CO lines thus have the power to discriminate quiescent (typically seen in low-J CO and [C I] lines) from active gas in stellar feedback regions, which enables the detailed study of PDRs, shocks (to be complemented by [O I] observations), outflows (in particular pc scale outflows that interact mostly with the neutral atomic and ionized medium), collapse, and signatures of low-velocity shocks due to turbulence dissipation, the “smoking gun” for the formation of dense structures.

In addition, sampling the Spectral Line Energy Distribution (SLED) towards higher J-lines (i.e., higher energies) is important to get an accurate handle on excitation and cloud masses. Similarly, it is important to also observe the higher energetic [C I] (2-1) line in order to unambiguously determine the total amount of carbon. Both provide valuable input for chemical models of molecular clouds and PDRs, which are indispensable for the interpretation of the observations.

3.3 The galactic context

The diverse population of nearby galaxies (Milky Way analogues, massive disk galaxies, low-metallicity dwarfs, interacting systems) extend significantly the phase space of conditions found in the ISM of the Milky Way.

Key sub-mm science cases for extragalactic observations in the future include resolved, full-disk, kpc-scale observations of [C I] and mid-J CO lines of a diverse sample of nearby galaxies. Observations covering the low-J CO lines are available for many such targets (e.g., from the IRAM 30 m, JCMT, ALMA, SMA), as are ancillary multi-wavelength data (e.g., dust and star formation rate tracers) and increasingly also wide-area [C II] mapping (e.g., from Herschel KINGFISH, Smith et al. 2017, or SOFIA, Pineda et al. 2018, Bigiel et al. in prep.). [C I] observations are rare in nearby galaxies; a comprehensive [C I] survey in combination with existing CO and [C II] data thus yields a complete carbon census resolved across galaxy disks and will provide the most accurate calibration of these extragalactic molecular gas tracers to date. This is of particular importance in light of [C I] being routinely detected at high redshift (e.g., Weiß et al. 2005, Popping et al. 2017). [C I] has furthermore been proposed as an effective dense gas tracer (and a viable alternative to popular, extragalactic high critical-density lines like HCN or HCO⁺, e.g., Papadopoulos & Geach 2012).

Other important applications are the role of [C I] as an optically thin molecular gas tracer (e.g., Papadopoulos & Greve 2004), in particular in environments where CO fails as an effective H₂ tracer, e.g. at low metallicity. As the relative emissivities of [C I], [C II] and CO in molecular clouds changes with metallicity, wide area [C I] surveys of the LMC and SMC will provide a first systematic study of this ratio at low metallicity.

These science cases are also immediately related to observations at high redshift, where both [C I] and mid-J CO lines are routinely observed due to them being shifted into favorable bands with sub(mm) interferometers like ALMA or NOEMA. A careful calibration in diverse environments in the local universe is thus the key link between detailed, sub-cloud scale work in the Milky Way and distant galaxies.

References

- Andree-Labsch, S., Ossenkopf-Okada, V., & Röllig, M. 2017, *A&A*, 598, A2
- Bialy, S., Burkhart, B., & Sternberg, A. 2017, *ApJ*, 843, 92
- Clark, P. C., Glover, S. C. O., Ragan, S. E., & Duarte-Cabral, A. 2018, arXiv:1809.00489
- Dame, T. M., Hartmann, D., & Thaddeus, P. 2001, *ApJ*, 547, 792
- Dobbs, C. L., Glover, S. C. O., Clark, P. C., & Klessen, R. S. 2008, *MNRAS*, 389, 1097
- Federrath, C., & Klessen, R. S. 2013, *ApJ*, 763, 51
- Franeck, A., Walch, S., Seifried, D., et al. 2018, *MNRAS*, 481, 4277
- Godard, B., Pineau des Forêts, G., Lesaffre, P., et al. 2019, *A&A*, 622, A100
- Goldbaum, N. J., Krumholz, M. R., Matzner, C. D., & McKee, C. F. 2011, *ApJ*, 738, 101
- Goldsmith, P. F., Heyer, M., Narayanan, G., et al. 2008, *ApJ*, 680, 428
- Heitsch, F., & Hartmann, L. 2008, *ApJ*, 689, 290
- Hollenbach, D. J., & Tielens, A. G. G. M. 1997, *ARAA*, 35, 179
- Inoue, T., & Inutsuka, S.-i. 2012, *ApJ*, 759, 35
- Kennicutt, R. C., Calzetti, D., Aniano, G., et al. 2011, *PASP*, 123, 1347
- Kim, C.-G., & Ostriker, E. C. 2017, *ApJ*, 846, 133
- Leroy, A. K., Walter, F., Bigiel, F., et al. 2009, *AJ*, 137, 4670
- Mac Low, M.-M., & Klessen, R. S. 2004, *Reviews of Modern Physics*, 76, 125
- Neufeld, D. A., & Dalgarno, A. 1989, *ApJ*, 344, 251
- Pabst, C., Higgins, R., Goicoechea, J. R., et al. 2019, *Nature*, 565, 618
- Padoan, P., & Nordlund, Å. 2011, *ApJ*, 730, 40
- Papadopoulos, P. P., & Geach, J. E. 2012, *ApJ*, 757, 157
- Papadopoulos, P. P., & Greve, T. R. 2004, *ApJL*, 615, L29
- Pineda, J. L., Fischer, C., Kapala, M., et al. 2018, *ApJL*, 869, L30
- Popping, G., Decarli, R., Man, A. W. S., et al. 2017, *A&A*, 602, A11
- Röllig, M., Abel, N. P., Bell, T., et al. 2007, *A&A*, 467, 187
- Seifried, D., Walch, S., Girichidis, P., et al. 2017, *MNRAS*, 472, 4797
- Smith, R. J., Glover, S. C. O., & Klessen, R. S. 2014, *MNRAS*, 445, 2900
- Smith, J. D. T., Croxall, K., Draine, B., et al. 2017, *ApJ*, 834, 5
- Stacey, G. J., Aravena, M., Basu, K., et al. 2018, *Ground-based and Airborne Telescopes VII*, 10700, 107001M
- Sternberg, A., & Dalgarno, A. 1989, *ApJ*, 338, 197
- Sun, J., Leroy, A. K., Schruba, A., et al. 2018, *ApJ*, 860, 172
- Vázquez-Semadeni, E., Ryu, D., Passot, T., González, R. F., & Gazol, A. 2006, *ApJ*, 643, 245
- Walch, S., Girichidis, P., Naab, T., et al. 2015, *MNRAS*, 454, 238
- Weiß, A., Downes, D., Henkel, C., & Walter, F. 2005, *A&A*, 429, L25
- Wolfire, M. G., Hollenbach, D., & McKee, C. F. 2010, *ApJ*, 716, 1191