Astronomy in Focus, Volume 1
XXIXth IAU General Assembly, August 2015
Piero Benvenuti, ed.

DOI: 00.0000/X000000000000000X

IAU Division H: Interstellar Matter and Local Universe

Ewine F. van Dishoeck (president)[1,2], Joss Bland-Hawthorn (vice-president)[3], Bruce G. Elmegreen (secretary)[4], H. Baumgardt[5], G. Carraro[6], E. Friel[7], S. Kwok[8], D. Mardones[9], M. Meyer[10], T.J. Millar[11], B. Nordström[12,13], and A. Robin[14]

[1]Leiden Observatory, Leiden University, the Netherlands
email: `ewine@strw.leidenuniv.nl`
[2]Max Planck Institute for Extraterrestrial Physics, Garching, Germany
[3]School of Physics, University of Sydney, NSW 2006, Australia
[4]IBM T.J. Watson Research Center, Yorktown Heights, NY 10598, USA
[5]School of Physics, University of Queensland, St. Lucia, QLD 4072, Australia
[6] European Southern Observatory, Santiago, Chile
[7] Astronomy Department, Indiana University, Bloomington, IN 47405, USA
[8] Department of Physics, The University of Hong Kong, Pokfulam, Hong Kong, China
[9] Departamento de Astronomía, Universidad de Chile, Santiago, Chile
[10] Institute for Astronomy, ETH Zurich, CH-8093 Zurich, Switzerland
[11] School of Mathematics and Physics, Queen's University Belfast, Belfast, BT7 1NN, UK
[12] Niels Bohr Institute, Copenhagen University, Copenhagen, Denmark
[13] Dept. of Physics and Astronomy, Aarhus University, Aarhus, Denmark
[14] Observatoire de Besançon, Besançon, France

Abstract. The nature and future prospects of the research carried out in IAU Division H on *Interstellar Matter and the Local Universe* is briefly reviewed, based on the presentations at the Division H meeting at the IAU General Assembly 2015 in Honolulu, with a focus on recent results and future prospects.

Keywords. ISM: general; ISM: jets and outflows; stars: formation; planetary systems: protoplanetary disks; Galaxy: structure; galaxies: star clusters; galaxies: abundances; galaxies: kinematics and dynamics; Local Group

1. Introduction

The research covered by Division H centres around the study of the interstellar medium (ISM) and the stars in our Milky Way and in nearby galaxies (out to ∼15 Mpc). The ISM and stars, the two major visible components of a galaxy, are coupled to each other through star formation, stellar feedback and their gravitational potential. Topics range from detailed studies of the physics and chemistry of different components of the ISM (ionized, neutral, molecular), both locally and on galaxy-wide scales, to measurements of resolved stellar populations and star clusters in the Local Universe and the dynamics of galaxies. The formation and evolution of atoms, molecules and dust during all phases of star formation and death are an integral part of ISM studies. On the smallest scales, the structure and composition of protoplanetary and debris disks around pre-main sequence stars set the scene for planet formation theories.

Division H was founded at the 2012 IAU General Assembly meeting in Beijing and is a merger of the old Division VI on 'Interstellar Matter' and Division VII on the 'Galactic System'. The extension to nearby galaxies stems from the increasing interest in studying the local universe (near field) as distinct from the high redshift universe (far field). Near-field cosmology is now a distinct topic from far-field cosmology, but what constitutes 'local' or 'nearby' means different things to different communities. For the purposes of Division H, the Local Volume is defined by the distance (∼10 Mpc) over which stellar populations in galaxies can be resolved by the Hubble Space Telescope. This definition is extended to include Virgo (∼15 Mpc) so as to cover the full range of galaxy environments, from voids to massive groups and clusters. In the era of ELTs, it will be possible to extend our definition of the Local Volume to even greater distances.

On the other hand, studies of the detailed physics and chemistry of the ISM and star- and cluster formation in Division H can extend well beyond this 15 Mpc Volume, complementing the galaxy-wide physics and structure formation topics in Division J. See §2.1 for further description.

The activities of the Division H Steering Committee (DSC) in the 2012–2015 period included making the transition from the old to the new Division; the overhaul of the Commissions; stimulating and evaluating proposals for IAU Symposia each year and Focus Meetings at the GA, as well as other non-IAU sponsored meetings in the field; organize the Division meeting at the GA with the aim to promote integration of the different communities; other IAU business such as commenting on draft resolutions and organizing elections.

Up to the GA 2015, Division H had three Commissions: C33 'Structure and Dynamics of the Galactic System'; C34 'Interstellar Matter' and C37 'Star Clusters and Associations'. It also had three Working Groups: 'Astrochemistry'; 'Planetary Nebulae' and 'Galactic Centre'. In the new structure, there are three Commissions directly under Division H: H1 'The Local Universe', H2 'Astrochemistry'; and H3 'Planetary Nebulae'. There are also three inter-division Commissions involving Division H: H4 'Stellar clusters through cosmic space and time'; J1 'Galaxy spectral energy distributions', and J2 'Intergalactic medium'. Note that Commissions do not span the full range of science within a Division: they mostly center around topics in which there is considerable international scientific activity and coordination.

This document summarizes the science presented at the Division H meeting at GA 2015, which consisted of seven subtopics. While incomplete due to space limitations and somewhat biased toward the speakers' choices of material, it provides a 'taste' of recent research in Division H and a forward look. Some topics were covered much more extensively in IAU Symposium 315 'From interstellar clouds to star-forming galaxies: universal processes'; IAUS 316 'Formation, evolution and survival of massive star clusters'; and IAUS 317 'The general assembly of galactic halos: structure, origin and evolution'; and several Focus Meetings, in particular FM4 'Planetary nebulae as probes of galactic structure and evolution'; FM15 'Search for 'Life's building blocks in the universe'; and FM 18 'Scale-free processes in the universe'.

PDF files of most presentations are posted at the Division H website at www.iau.org/IAU-H and www.strw.leidenuniv.nl/IAU-H.

2. Structure and dynamics of galactic systems in the Local Universe

2.1. *Local Universe description*

As described above, the Local Universe is taken to be a sphere of radius ∼15 Mpc centred at the Local Group. This sphere encloses all galaxies that have accurate distances determined from the tip of the red giant branch and surface brightness fluctuation methods. This sphere is also known as the Local Volume and includes the Local Void. Out to ∼15 Mpc, the 3D distribution of galaxies is well known, in particular through the Tully

Catalogue of Galaxies. Detailed 3D flow models for all galaxies have become possible for the first time. This volume falls within the scope of the Local Universe considered by N-body simulations.

The DSC considers the Local Universe to be a useful and physically motivated working definition. Over this volume, all galaxies can be considered to be at roughly the same cosmic epoch. The local density field varies by a factor of about 100. Thus, large-scale evolutionary effects are more likely to be due to the underlying density field (i.e. environment) than to any variation in epoch. All galaxies with masses equivalent to the SMC or larger can be imaged in most wavelength bands (e.g., X-rays, infrared, radio). The most detailed and complete observations of galaxies will always come from this volume and will therefore continue to dominate studies of physical processes of the ISM and stars in galaxies.

Note that this volume of $\sim$15 Mpc mostly excludes galaxies identified in all-sky galaxy redshift surveys (2MASS, 2dFGRS, SDSS, 6dFGS, GAMA).

2.2. *Local Universe galaxies*

At the IAU GA 2015, the basic structural properties of local galaxies were summarized by **Simon Driver**, based on the GAMA survey and decomposition of 200,000 galaxies into spheroidal and disk components. Galaxies with stellar masses above 10^{10} $M_\odot$ tend to be spheroid dominated, while galaxies with lower masses tend to be disk dominated. At larger than 10^8 $M_\odot$, the mass fraction of spheroid-dominated galaxies is 72%, while the spheroids themselves total 46% of the mass, with the rest in disks or disk-like pseudobulges. These nearly equal masses for the two components suggest there are two routes to structure formation.

The status of local dwarf galaxies was summarized by **Claude Carignan**. Lambda CDM models predict a much larger number of dark matter halos with extremely small masses than are actually observed in the form of dwarf galaxies, with the deficit equal to a factor of 10 or so at galaxy masses of around 10^7 $M_\odot$. Deep optical and HI surveys are adding more tiny dwarfs all the time, though, so it is not clear whether there is a fundamental discrepancy with the theory or whether the galaxy surface brightnesses are fainter than expected. Dwarf galaxies further than the virial radius from the Milky Way and M31 have large ratios of HI mass to V-band luminosity, while those inside the virial radii have much less gas. Still, all of the dwarfs with luminosities less than 10^7 $L_\odot$ have about the same total mass within their inner 300 parsecs, which is about 10^7 $M_\odot$. As the luminosity gets smaller below this limit, the dark matter fraction increases. Galaxies with luminosities less than 10^5 $L_\odot$ have dark matter fractions larger than 99% within this inner 300 pc. This means that galaxies drop off the baryonic Tully Fisher relation at rotation speeds less than about 15 km s^{-1}.

Juntai Shen reviewed the Milky Way structure in the context of local galaxies. The Bulge Radial Velocity Assay (BRAVA) survey of the galactic bulge at Cerro Tololo gives constraints on dynamical models. The Milky Way bulge/bar contains an X-shaped structure (peanut-shaped) and so does that of M31. An unanswered question is why M33 is unbarred. Gas features may be used to constrain the properties of the Milky Way bar and spiral patterns. Further progress will come from several upcoming large surveys (SDSS-APOGEE2, Gaia).

2.3. *Milky Way Galaxy*

Amina Helmi discussed galactic dynamics in the era of GAIA, the satellite launched in 2013 that will measure stellar positions and motions for 10^9 stars. She noted that the whole sky has already been observed in one pass and that the first data release will be mid-2016. Among the many science goals for GAIA, the determination of dark halo properties was highlighted in her talk. GAIA will discover and measure sub-structure in the outer halo of the Milky Way, observing the kinematics and positions of halo stars to distinguish possibly hundreds of stellar streams. The stream shapes and velocities will help determine the shape of the dark matter halo. The granularity of the halo will also be evident in the structure of the streams, telling us something about missing satellites.

Cristina Chiappini reviewed developments in ongoing large observational programs and in modeling to understand the formation and evolution of the Galaxy. Galactic archaeology strives to reconstruct the past history of the Milky Way from the present day kinematics and chemical information and has become an important tool to study mechanisms of formation and evolution of the Milky Way, but it has turned out to be more difficult than first thought. The formation processes are encoded in the location, kinematics and chemistry of its stars but the available data has up to now been too sparse. For example, stars move away from their birth places (i.e., migrate radially), but stellar chemical composition is largely preserved during migration. It is then necessary to combine kinematics, chemistry and ages to understand how the Milky Way was formed. Accurate ages can break degeneracies in the models but are often not available. The need for accurate ages and chemical yields for large samples of stars is paramount. Important ongoing surveys include: SDSS-APOGEE, RAVE, HERMES, and the GAIA-ESO survey. Future major developments are expected from GAIA (distances and orbits); near-infrared spectroscopy of the inner disk/bulge with telescopes such as APOGEE-South; accurate photometry with the K2 mission (mass and radius of distant giant stars, and thus distances and ages); and multi-object optical spectrometers such as 4MOST and WEAVE (chemical abundances).

Gamma-ray observations of the center of the Milky Way reveal a bipolar emission region extending above and below the galactic plane for about 60^o and on either side of the center along the plane by about 20^o, the so-called Fermi-bubble. This emission was only observed after tedious subtraction of foreground emission that is known to correlate with the total gas column density and the radio emission. In a talk prepared by **Joss Bland-Hawthorn** (and delivered by Bruce Elmegreen), the evidence for this emission arising from an AGN-like outburst from the black hole in Sgr A^* was summarized. There is an X-ray bipolar structure closer to the plane and with the same width as the gamma ray lobes, presumably indicative of hot gas flowing along the walls of the cavity. Smaller but analogous infrared structures are seen close to the plane presumably from weak, more recent outbursts. There are highly excited and fast-moving absorption lines in background quasar spectra, suggesting an upward flow speed along the walls of some 900 km s^{-1}. And there is highly excited and decaying ionization in the part of the Magellanic Stream that passes directly overhead of Sgr A^* (as viewed from the southern sky). Evidence for a thousand-fold variability in SgrA^* comes from yearly variations in fluorescent Fe K-alpha lines that backscatter off the surfaces of galactic center molecular clouds. The outburst needed for the Fermi bubble and the Magellanic Stream amount to an energy input between 10^{55} to 10^{57} erg. This energy can be explained by an increase in the black hole accretion disk luminosity by a factor of 10^7 occurring several million years ago.

Andrea Ghez reviewed the present knowledge on the Galactic Center black hole. Adaptive Optics has transformed our understanding of the center of our Galaxy. The star S2 offers the strongest case for the existence of a black hole from its orbit. Accurate orbits also provide an opportunity to test General Relativity in an unexplored regime. Individual stellar orbits give direct evidence for a single, nearly edge-on stellar disk with a 20% young star population. The data also help to understand the evolution of galactic nuclei in general (e.g., black hole merger rates in other galaxies).

3. Star clusters and associations in the local universe

Douglas Geisler reviewed observational results of globular clusters in local group galaxies. Star clusters were thought to be simple stellar populations: their stars should have the same age, initial chemical composition and distance. Observations tell us that it is no longer true. The discovery of multiple stellar populations has revolutionized the study of globular clusters and their formation theories.

Diverse elemental abundances, especially an anticorrelation between the Na/Fe and O/Fe ratios, suggest an unusual mode of star formation in globular clusters, possibly extending for hundreds of millions of years or consisting of several generations combined with long-term gas infall. This complexity contrasts with the more uniform stellar populations in open clusters, which tend to be lower mass. In the future, there will be more cluster detections in extended galactic outskirts. Also, there will be increasingly spectroscopic characterization with ground-based 8–10 m telescopes which will provide cluster ages, metallicities, kinematics, masses, and lifetimes. The census and characterization of young clusters in star-forming galaxies will be improved via HST surveys and ground-based follow-up.

In a talk prepared by **Eva Grebel** and delivered by Denija Crnojević, globular star clusters as tracers of the evolution of Local Group galaxies were discussed. M31 has the richest system in the Local Group with about 700 globular clusters as compared to about 160 in the Milky Way. The clusters in M31 are on average more metal rich. In M33 there is an age-metallicity relation but no radial age gradient in the inner 6 kpc. Star clusters younger than 4 Gyr rotate with the disk, but with increasing age, their rotation speed decreases and their velocity dispersion increases, as in the Milky Way.

All massive dwarf galaxies contain globular clusters, and many of the metal-poor Galactic halo clusters could have come from dispersed dwarfs. This follows partly from the low metallicities at a given age, which may reflect the metallicities of their low mass hosts at the time of their formation, from their structural parameters, and from the association of some halo clusters around M31 with long tidal tails. The Sgr dwarf galaxy, for example, is contributing 8 ± 2 clusters to the Milky Way halo as it tidally disrupts. Globular cluster dissolution in the Milky Way halo is observed in the form of leading and trailing tails. A consideration of light element abundance anomalies in halo stars suggests that about 17% of the halo field stars were originally in globular clusters.

The star formation history in the LMC and SMC can be traced by the ages and positions of their clusters. Using ages of approximately 1200 populous LMC clusters and more than 300 populous SMC clusters, similar peaks in the age distribution were found, suggesting triggered cluster formation during past encounters. The SMC is the only Local Group dwarf galaxy that formed surviving massive star clusters throughout its lifetime. Intriguingly, these clusters show a broad range of metallicities at any given age.

Giovanni Carraro discussed open star clusters as tracers of the structure and evolution of the Milky Way. Open clusters are small, gravitationally bound groupings of stars that co-move through the galaxy and share the same age and chemical composition. They differ from globular clusters, which are more massive, symmetric, and contain evidence for multiple stellar populations. The vast majority of open clusters are younger than 300 Myr because of internal dissolution and interaction with the Milky Way. Distributions of clusters trace the chemical evolution and assembly of the Milky Way thin disk. Cluster metallicities are derived from high-resolution spectroscopy of resolved stars, while cluster distances and ages are derived from color-magnitude isochrone fitting. There is a clear variation in the metallicities of clusters with galactocentric radius, from a value of $[\mathrm{Fe/H}] \sim 0.3$ at 3 kpc to $[\mathrm{Fe/H}] \sim -0.3$ at 13 kpc and beyond. There is also a slight variation in metallicity with age at a given galactocentric radius, from ~ -0.3 at 10 kpc radius for 4 to 11 Gyr old clusters, to ~ -0.1 at the same radius for < 0.8 Gyr clusters.

Open clusters in the outer Milky Way suggest a maximum distance along any given line of sight, but this could be the effect of the warp in the outer disk, with clusters continuing further along the warp. The radial distribution of stellar density in the Milky Way looks like a two-component exponential, with the outer part shallower than the inner part. This is similar to a Type III exponential disk seen in a surface brightness profile. The cluster population also shows a flare in the outer disk.

4. Star formation: theory and observations

Star formation research in Division H was summarized in talks covering molecular clouds in the Milky Way and nearby galaxies, high mass star formation close to the Sun, links between observations of local clouds and numerical simulations, and water emission in protostellar outflows. More details on these and many other aspects of star formation are provided in the proceedings of IAU Symposium 315.

According to **Jin Koda**, the Milky Way has a modest molecular fraction in the inner disk region, reaching a value close to 50%, while the brighter galaxy M51 has a much higher fraction, close to 90%. These high values suggest that molecular clouds do not convert to atomic form after star formation, but stay mostly molecular. In this case the growth of new clouds can be viewed as one of reassembly or coagulation from the pieces of old clouds. In addition, a substantial fraction of gas near the solar neighborhood, perhaps 30%, is in a CO-dark form, which means in the form of molecular hydrogen or cold atomic hydrogen having little or no associated CO emission. A line of sight along the first quadrant that intersects both arm and interarm regions at different velocities shows the conversion of massive, clumpy spiral arm molecular clouds into smaller, less clumpy, and lower mass interarm molecular clouds. This observation reinforces the idea that spiral arms act as collection fronts for impinging interarm clouds and that star formation feedback inside the arms breaks these clouds apart again. These collection fronts would presumably be the physical realization of the dust lanes and interstellar shock fronts predicted 50 years ago for density wave flows. The processes that initiate star formation in these collection fronts are not observed directly yet but cloud-cloud collisions and turbulent compression are the usual suspects.

The formation of massive stars has been difficult to observe because they are rare and the nearest formation sites are far away. Following new surveys of massive star-forming regions within 3 kpc of the Sun, **Frederique Motte** showed that about half of the massive stars form in filamentary or ridge-like structures and half form in more spherical structures. The ridge-like structures could have formed by compression from nearby OB stars. The probability distribution functions for column density were measured for these dense and massive clouds. They typically show a power law behavior at high column density, and sometimes have a second power law at their highest densities. The first power law seems to reflect a self-gravitating component in the dense cloud, while the second could be from some slowing of a collapse or feedback compressions, leading to excessively high densities.

Star formation is believed to be the result of turbulent and other gas compressions in self-gravitating gas. The compression converts the gas to a cold and dense phase, and then gravity compresses it further, leading to contraction, fragmentation, and collapse to stars. **Jouni Kainulainen** reported observations of the distribution of gas densities and column densities in the local interstellar medium using wide field absorption surveys to background stars. The distributions illustrate the relative roles of turbulence and self-gravity. Self-gravity tends to give a more prominent component of dense gas than turbulence alone, and clouds with such prominent dense components tend to be those which form stars. Numerical simulations first predicted this effect and there is a growing consistency between these simulations and the observations.

An important component of star-forming regions are the winds and jets from young stars, which can stir the surrounding gas and clear it away. **Lars Kristensen** reported *Herschel* observations of water molecules in regions of star formation, using them as tracers of hot gas. Water can be formed by cold and hot processes, and it can also form as ice on grain surfaces. The hot process means that water is a good tracer of shocks: nearly all of the shocked oxygen that is not in CO will end up in water, which can then reach an abundance relative to hydrogen of around 10^{-4}, although often a lower value is seen due to enhanced UV radiation. The observations show no spatial overlap between water and low-lying rotational transitions of CO, but good correspondence with the high$-J$ CO emission. Evidently the water and highly excited CO are both tracing jet-outflow interaction regions. The density in these regions necessary to collisionally excite water is very high, on the order of 10^7 cm^{-3}.

5. Circumstellar disks around young stars

This session consisted of talks covering the earliest phases of gas-rich disk formation to the later stages of disk dispersal and gas-poor debris disks. Exciting new results on the link between protoplanetary disks and the young planets embedded in them were presented. This field is developing rapidly thanks to ALMA becoming fully operational and the next generation of high contrast optical and near-IR imagers coming on line.

Michiel Hogerheijde summarized the pre- and post-ALMA view of the structure, composition and evolution of disks. It is well established that most young stars have disks with a mass that is typically 1% of that of the star and which last on average several Myr. Even in the nearest star-forming regions, they are only a few arcsec across, so ALMA is needed to spatially resolve the structure of disks. Recent highlights include ubiquitous cases of disks that are generally much smaller in mm-sized dust than in gas due to radial drift, a phenomenon predicted decades ago; the imaging of dust gaps in disks, even in the embedded phase of star formation; the routine detection of CO and its minor isotopologs leading to improved estimates of disk gas masses, disk structure (e.g., flaring angle), and outer disk radii and revealing slow disk winds. Disks have huge radial and vertical temperature gradients leading to chemical differentation throughout the disk, including freeze-out in the coldest parts and photodissociation in the warm surface layers. ALMA has imaged the CO snowline in several disks, important for planet formation; and it has detected the first complex molecule in a disk, CH_3CN. The next years will see a move toward population studies for large samples of disks (of order 100), combined with detailed studies of the full physics and chemistry of individual objects.

Shu-ichiro Inutsuka discussed simulations of the formation and early evolution of protoplanetary disks. Ideal MHD simulations without magnetic braking had difficulties forming disks, even though they have been observed in the deeply embedded phases. Recent advances in modeling with resistive magneto-hydrodynamical codes has enabled improved understanding of the formation of protostars with outflows/jets and disks in a self-consistent manner from molecular cloud cores. Magnetic de-coupling enables massive disks to form and these disks are subject to gravitational instability. The frequent formation of planetary mass objects in those disks suggests the possibility of constructing a hybrid scenario of planet formation, i.e., giant planets form first and the rocky planets form later under the influence of giant planets. Another important aspect is the possibility of secular gravitational instability where a dynamically stable disk can create a multiple ring-like structure such as seen in HL Tau by ALMA over a timescale many orders-of-magnitude longer than the rotation period, without the need for a planet.

Lucas Cieza summarized the recent observations of transitional disks, i.e., disks with a dust depleted inner cavity as identified through a dip in their mid-IR SED. Recent ALMA observations have shown astonishing, sometimes highly asymmetric, dust structures in these disks, which together with data on CO and its isotopologues, provide insight into their origin (e.g., close binaries, photoevaporation, giant planet formation). Using *Spitzer* and *Herschel*, the demographics of transition disks in nearby star-forming regions can be studied, when combined with complementary data on accretion rates from optical spectroscopy, binary information from high contrast imaging, and disk mass from mm continuum data. The transitional disks are clearly a heterogeneous sample, with all clearing mechanisms playing a role.

Paola Pinilla reviewed models of grain growth and dust trapping, which can explain many aspects of the ALMA dust observations in normal and transitional disks. Planet formation starts with the coagulation of micron-sized particles to larger dust aggregates. This process, which covers more than forty orders of magnitude in mass, has different physical challenges. One of the oldest mysteries is how planetesimals are formed, in spite of fragmentation collisions and rapid inward drift. Radial drift theory predicts that millimetre grains rapidly move inward in the cold disk regions. This old paradigm can be solved by the presence of long-lived pressure bumps. Indeed, disk models that include dust coagulation, fragmentation, and the presence of such pressure bumps leads to good agreement with observations. Millimetre observations of transition disks reveal crescent- and ring-shaped emissions that lend credence to the notion that planetesimals may form in localised hotspots or pressure traps, giving major support for models of particle trapping induced by embedded planets.

Sascha Quanz presented the latest high-contrast and high-spatial resolution near-infrared images which reveal a few objects that are best explained with young planets that are still embedded in the circumstellar disks of their host stars. For the first time, these objects may allow us to derive empirical constraints on the immediate formation process of gas giant planets.

Meredith Hughes reviewed the tenuous, dusty debris disks around main-sequence stars which hold clues to the evolution and architecture of planetary systems. The dust in these disks is thought to be produced by collisions of planetesimals rather than directly inherited from the collapsing cloud. With the unprecedented sensitivity of ALMA it is now possible to study the spatial distribution of large dust grains in debris disks at a high level of precision, as well as investigating the surprising presence of gas disks that persist well past the protoplanetary disk stage.

6. Astrochemistry

Astrochemistry is defined as the study of the formation, destruction and excitation of molecules in astronomical environments and their influence on the structure, dynamics and evolution of astronomical objects. Astrochemical studies range from molecules in the early universe and local galaxies to those in envelopes of evolved stars, solar system, and protoplanetary disks. This topic therefore cuts across all topics of Division H, as well as several other Divisions (e.g., F and J).

Jill Rathborne highlighted recent large-scale surveys of dense gas in the Galactic plane which enable one to probe star formation in the Milky Way. The MALT90 survey used the MOPRA telescope to study 16 molecular lines at 90 GHz across the inner

Galaxy. The general result is that dense gas forms clumps of at least a few hundred solar masses, most of which show infall, with different molecules probing different aspects of the clouds. These dense clumps are the basic units of star formation.

Jes Jørgensen presented the use of chemistry to probe material as it is transferred from these clumps to protoplanetary disks to stars. Important questions here include how disks form, what is the chemical composition of material entering the disk and what is the effect of episodic accretion on the chemistry. He showed that there is a fruitful interaction between theoretical MHD modeling of low mass star formation and ALMA observations.

Ted Bergin discussed the distribution of both solid and gas-phase water in molecular clouds and disks. Observations and models suggest that the gaseous water abundance is low, and the ice abundance is high, in the protostellar stage. Thus, most water is likely delivered to disks unaltered since its formation in pre-stellar cores. Further clues come from deuterated water observations. The young disk is the least understood stage in this process. The weak emission of gaseous water from disks indicates that water is sequestered early into large bodies (pebbles, planetesimals) near the disk midplane.

Tony Remijan discussed the use of ALMA to determine the detection, spatial distribution and formation routes of complex organic molecules. These molecules often show differential distributions on small scales and can be used to probe, in particular, the gas-ice chemistry. Further laboratory spectroscopy is essential to identify the many U-lines observed in, for example, Orion.

7. Diffuse interstellar medium

Bruce Draine reviewed the status of dust models. The *Spitzer*, *Herschel*, and *Planck* missions have provided observational data that inform and challenge existing models for interstellar dust. For dust in the general diffuse medium, these three missions have provided: 5-20 μm PAH emission spectra for a range of regions; determinations of the 10 and 18 μm silicate profiles; new determinations of the wavelength-dependent extinction in the mid-IR; spectral energy distributions out to 160 μm (with *Spitzer*), to 500 μm with *Herschel*, and out to 3mm with *Planck*; observations of 'anomalous microwave emission' from dust near 1 cm; and polarization of the dust emission from 4 mm to 850 μm. Models are also constrained by many other observational data, including scattering, extinction and polarization of starlight at optical wavelengths, scattering and extinction of X-rays by dust, and elemental abundance studies. A major mystery is that $\sim$25% of the oxygen and 80% of the iron is unaccounted for with standard silicate dust material. Some of this 'missing' O and Fe may be in iron oxides, but this still leaves about 20% of the oxygen in some unknown form. Fits to the all-sky dust emission from *Planck* demonstrate that existing models can reproduce many features but that the far-infrared opacities need to be increased by a factor of two, mitigating also the too low polarized intensity in the models. Varying amounts of ferromagnetic inclusions may explain the apparent drop in polarization with decreasing frequency. So far, the anomalous microwave emission does not appear to be correlated with the fraction of PAHs in galaxy-wide maps; perhaps spinning non-PAH (silicate?) nanoparticles dominate this phenomenon.

David Neufeld demonstrated that observations with *Herschel* have greatly enhanced our understanding of neutral diffuse material in the interstellar medium. In particular, high-resolution absorption line spectroscopy at THz frequencies has led to the discovery of several new interstellar molecules - including SH^+, OH^+, H_2O^+, H_2Cl^+, HCl^+, and ArH^+ (the first known astrophysical molecule containing a noble gas atom). This has enabled astrochemical studies in which the abundances of multiple species are measured and modeled. Because of the different chemical pathways responsible for their formation and destruction, different molecules probe specific aspects of the interstellar environment. Carefully interpreted, they provide unique information about the cosmic ray density, the ultraviolet radiation field, and the dissipation of energy within the turbulent ISM, and they point to the existence of a new ISM phase with a low molecular fraction. Future ALMA and SOFIA observations promise to extend our understanding of fundamental physical and chemical processes in the neutral diffuse ISM, also in other galaxies.

Marijke Haverkorn discussed the warm ionized interstellar gas that is not in HII regions but is ubiquitously present in a broad layer around the Galactic plane. Since this gas is ionized, it is mostly frozen into the Galactic magnetic field, implying a complex interaction with feedback from both components. One of the most important ways to study this magnetized gas is through radio polarimetry, which allows decomposition of Rotation Measures into various (Faraday depth) components along every sightline. This yields information on the magnetic field structure, showing highly structured polarized synchrotron emission in all fields surveyed to date. Information about the scale height of the diffuse ionized gas, its filling factor and turbulence can be derived.

8. Envelopes of evolved stars and dust production

Evolved low-and intermediate mass stars expel their material in the form of a stellar wind. These winds create huge dusty envelopes which are cool, with temperatures around 20–1000 K. **Leen Decin** reviewed recent observations of these envelopes in the infrared and sub-millimeter domain. Thanks to the imaging and spectroscopic capabilities of *Herschel* and ALMA, astronomers now have a unique possibility to study these stellar winds, including the dust formation zone. Different chemical formation routes dominate at different distances from the star and there is a relation between chemistry and dynamical processes. The overall morphology of the winds is roughly spherical during the asymptotic giant branch (AGB) phase, but changes dramatically during the post-AGB and planetary nebula phase, where bipolar and multi-polar structures are commonly observed. High resolution ALMA observations reveal the presence of spiral structures indicative of close binary companions.

Mikako Matsuura highlighted the major changes in our understanding of the role of supernovae in dust prodction; it has been long proposed that supernovae are dust destroyers, but now recent observations show that core-collapse supernovae can become major dust factories, producing 0.1-1 $M_\odot$ of dust. *Herschel* and ALMA detected unambiguously 0.5 $M_\odot$ of dust in the ejecta of Supernova 1987A. *Herschel* also found nearly 0.1 $M_\odot$ of dust in the historical supernovae remnants Cassiopeia A and the Crab Nebula. If dust grains can survive future interaction with the supernova winds and ambient interstellar medium, core-collapse supernovae can be an important source of dust in the interstellar media of galaxies. The total dust mass injected by AGB stars and SNe into the interstellar medium of the Magellanic Clouds were also discussed.