The Interstellar Medium in Three Dimensions with Gaia

11-14 July 2011, University of Leiden, Netherlands

Summary
This workshop brought together astronomers with a wide range of expertise: optical and near-infrared photometric surveys of stars; spectroscopic surveys of stars; radio-frequency surveys for pulsars and masers; observations of radio-frequency and infrared emission by gas and dust; stellar- and gas-dynamical modelling. The participants considered how these data can be combined with Gaia's astrometric data to determine the three-dimensional structure and dynamics of the Galaxy's interstellar medium.

Science and Discussion
The workshop started with overviews by Kalberla, Dame and Ferriere of recent advances in surveys of the ISM at radio frequencies. The classical 21-cm window is still getting clearer through advances in sensitivity and angular resolution. The main problem in this area is converting the datacube of temperature as a function of (l, b, v) into the corresponding density of neutral atoms $n(\mathbf{x})$. Kinematic distances are still the main tool, but inside the solar neighbourhood they suffer from the classical near/far ambiguity as well as the non-circularity of the flow caused by the bar and spiral structure, and outside the solar circle the rotation curve remains very uncertain for want of good distances. Notwithstanding these difficulties, progress is being made in deciphering the global structure of molecular gas, in part by exploiting absorption as well as emission.

The sub-mm satellites Planck and Herschel are opening a new era in which the cold ISM can be studied at high angular resolution through continuum emission by dust (Planck) and line radiation from molecules. Soon ALMA will replace Herschel as the main tool for studying molecules. The potential here is enormous. Very long baseline interferometry now makes it possible to determine parallaxes of Gaia-like quality to masers associated with star-forming regions that are several kpc from the Sun. The number of masers with parallaxes will grow rapidly now the VLA can detect the 6.7 GHz line of methanol masers. These trigonometric distances offer the prospect of putting kinematic distances on a firm footing.

Ferriere reminded the workshop that the distribution of gas within the bar presents two major puzzles: why the larger-scale distribution is tilted out of the Galactic plane by $\sim 20^\circ$, and why $\frac{3}{4}$ of the dense gas in the nuclear molecular ring is at positive longitudes.

Marshall described the global model of the cool ISM that is being derived from Planck data. The densest clods, which feature in absorption at 21 cm are seen in emission in the Planck data. Distances estimates show these dense clouds are strongly clustered. Herschel is gathering more data on them.

The workshop explored the scope for mapping the ISM through absorption of starlight. Both line and continuum absorption are possible. Line absorption has the great advantage of giving the velocity of the absorbing material, but it requires spectra with $R > 20\,000$. Lines of Na I and Ca I are well correlated with A_V while lines of Ca II are sensitive to the hotter, space-filling component of the ISM so are well correlated with distance. Some controversy surrounds the usefulness of diffuse interstellar bands (DIBs) as probes of the ISM. If interstellar lines can be successfully measured in the spectra of later-type stars rather than the traditionally used early-type stars, the impact of line absorption will soon increase greatly as a consequence of the hundreds of thousands of high-resolution spectra that will be taken in the Gaia-ESO survey and the Hermes survey.

Continuum absorption of starlight is already a powerful probe of the ISM: Drew reported that although it is difficult to measure the reddening to an individual star to better than 0.01 in $E(B-V)$, by averaging over many individual measurements the emission by dust and CO have been successfully predicted using models based on reddening. These successes are possible because the ratio of reddening and extinction seems universal at wavelengths longer than ~ 1 mm. Drew pointed out that $r - H\alpha$ is a valuable colour, while Lombardi showed that extinction measurements suffer from a number of biases, for which one needs to correct. Brown gave an update on the several schemes that are being developed to determine the extinctions to stars observed by Gaia.

Our ability to map the ISM through continuum absorption of starlight requires knowledge of the distances of the studied stars. Burnett & Sale pointed out that distance determination is in practice part of

the general problem of parameter estimation. Casagrande & Drew emphasised that the key is wide spectral coverage in the data, and a combination of broad-band and narrow-band photometry or broad-band photometry with spectroscopy. We will not have Gaia distances much before 2020. Burnett described the status of distances to stars in the RAVE survey, which are half giants and half dwarfs; distances to stars in the Sloan survey are less problematic because these stars are mostly dwarfs. Schönrich presented a powerful kinematic check on distances.

Actually it is not necessary to know the distances to individual stars: Magorrian & Robin showed that knowledge of the density profile of stars suffices. Several participants emphasised the value of forward modelling and Bayesian inference over classical inversion.

The ISM is a dynamical system that is s driven far from equilibrium by the bar, spiral structure, supernovae and cosmic infall. Robin reported a new model of the bar and the dusty gas within it, Gerhard reported on driving by the bar, Kawata described simulations of spiral structure and Fraternali presented a model of the interplay between supernovae and accretion of intergalactic gas. Antoja discussed the signatures of spiral structure in the velocity distributions at the Sun and nearby locations. These are all areas meriting further work. A major issue is that spiral structure is mostly transient, and the impact of supernovae is stochastic, so we need a *statistical* theory of the ISM. A prerequisite for such a theory is a formalism such as a Fourier expansion that divides the phenomena into the part that is causal (such as the amplitudes of the Fourier modes) and the part that is random (such as their phases).

The workshop highlighted the extent to which the ISM is studied from two contrasting perspectives. At radio and sub-mm frequencies the ISM is seen mostly in emission and mostly in lines. There are few beacons at known locations and the physics giving rise to the emission and that is consequently involved in the interpretation of the observations is of enormous complexity. Observations of stars reveal the ISM in absorption and most often in the continuum. Tens of millions of beacons are available and the physics involved in the interpretation of observations is relatively straightforward.

Impact and Future Directions

Most crucially the workshop established contact between radio astronomers working on the ISM, optical astronomers who are working on stars, and dynamicists and modellers. The members of each group learnt what insights into the structure of the ISM can be gained by using techniques from other areas, and it was widely appreciated that the key to decisive progress in the era of Gaia would be to fuse all these insights into dynamical models of the ISM whose predictions can be compared with the observational data. There were many lively discussions during breaks in the formal proceedings, and several collaborative projects are expected to emerge from these discussions. Plans were discussed for a follow-on meeting under the auspices of the GREAT working group on the ISM.

Programme

Monday 11 July

Session 1: The ISM seen in emission

9.00-10-30

- Peter Kalberla: The distribution of 21-cm emission
- Tom Dame: The distribution of molecular gas

11.00-12.30

- Katia Ferriere: Gas in the inner Galaxy
- Marijke Haverkorn: The Galactic B field and what it says about the ISM
- Douglas Marshall: Planck early results: dust properties in the Galactic fountain

Session 2: Stars

14.00-15.30

- Tomaz Zwitter: Overview
- Ben Burnett: Distances to RAVE stars

16.00-17.30

- Ralph Schönrich: A statistics method to assess distances
- Luca Casagrande: Determining effective temperatures and metallicities

Tuesday 12 July

Session 3: Measuring extinction

9.00-10.30

- Janet Drew: Measuring extinction from narrow-band Halpha and broadband surveys
- Jacek Krelowski: Homogeneity of the extinction law in the Galactic disc

11.00-12.30

- Karl Menten: Probing the diffuse ISM with submillimetre absorption spectroscopy
- Coryn Bailer-Jones/Anthony Brown: Measuring extinction with Gaia

Session 4: 3D mapping of the ISM with absorption

14.00-15.30

- Eddie Schlafly: reconstructing the 3D distribution of dust and stars with PanSTARRS PS1
- Stuart Sale: 3D extinction mapping using hierarchical Bayesian models

16.00-17.30

- Rosine Lallement: 3D maps of the ISM by inversion of absorption and extinction data
- Marco Lombardi: Distance and structure of dark molecular clouds with Gaia
- Carlos Roman: Extinction maps with SASIR

Wednesday 13 July

9.00-10.30

- John Magorrian: the disc's vertical structure
- Annie Robin: Interplay between stellar population and extinction modelling & the bulge region

Session 5: Dynamical models of the ISM

11.00-12.30

- Ortwin Gerhard: Gas flow as a diagnostic of the gravitational field
- Arnaud Siebert: Spiral structure and non-circular velocities of stars and gas

14.00-15.30

- Teresa Antoja: Spiral arm models and kinematic groups across the MW disc
- Christophe Pichon: Matching spiral noise in simulations to radio-frequency data

Thursday 14 July

9.00-10.30

- Filippo Fraternali: Impact of the Galactic fountain on the HI datacube
- Daisuke Kawata: Modelling the impact of spiral structure on the ISM

Session 6: Simultaneous modelling of the ISM and stars

11-12.30

- Sanjib Sharma: Models from Galaxia
- James Binney: Summary and outlook

Scientific Organising Committee

James Binney	U of Oxford
Anthony Brown	U of Leiden
Janet Drew	U of Hertfordshire
Peter Kalberla	U of Bonn
John Magorrian	U of Oxford

List of participants

Teresa Antoja	U of Groningen
James Binney	U of Oxford
Anthony Brown	U of Leiden
Ben Burnett	U of Oxford
Luca Casagrande	MPA Garching
Tom Dame	Harvard U
Janet Drew	U of Hertfordshire
Hywell Farnhill	U of Hertfordshire
Francesco Fermani	U of Oxford
Katia Ferriere	U of Toulouse
Filippo Fraternali	U of Bologna
Ortwin Gerhard	MPE Garching
Marijke Haverkorn	ASTRON Dwingeloo
Peter Kalberla	U of Bonn
Daisuke Kawata	MSSL UC London
Jacek Krelowski	U of Torun
Koen Kuijken	U of Leiden
Rosine Lallement	Observatoire de Paris
Marco Lombardi	ESO Garching
Jan Lub	U of Leiden
John Magorrian	U of Oxford
Douglas Marshall	IRAP U Paul Sabatier
Paul McMillan	U of Oxford
Karl Menten	MPG Bonn
Giacomo Monari	U of Groningen
Christophe Pichon	Inst Astrophysique, Paris
Annie Robin	U of Besançon
Carlos Roman	U Nacional Autonoma de Mexico
Stuart Sale	IC London
Eddie Schlafly	Harvard U
Arnaud Siebert	U of Strasbourg
Ralph Schoenrich	MPA Garching
Sanjib Sharma	Sydney U
Dan Stinebring	Oberline College
Tomaz Zwitter	Ljubljana U