Central Lancashire Online Knowledge (CLoK)

Title	Star Formation in the Milky Way and Beyond in the Era of JWST and ALMA
Type	Article
URL	https://clok.uclan.ac.uk/id/eprint/51647/
DOI	https://doi.org/10.1093/astrogeo/atae027
Date	2024
Citation	Pattle, Kate and Ward-Thompson, Derek (2024) Star Formation in the Milky Way and Beyond in the Era of JWST and ALMA. Astronomy & Geophysics, 65 (3). 3.30-3.35. ISSN 1366-8781
Creators	Pattle, Kate and Ward-Thompson, Derek

It is advisable to refer to the publisher's version if you intend to cite from the work. https://doi.org/10.1093/astrogeo/atae027

For information about Research at UCLan please go to http://www.uclan.ac.uk/research/

All outputs in CLoK are protected by Intellectual Property Rights law, including Copyright law. Copyright, IPR and Moral Rights for the works on this site are retained by the individual authors and/or other copyright owners. Terms and conditions for use of this material are defined in the http://clok.uclan.ac.uk/policies/

New Eyes on the Cold Universe
Kate Pattle and Derek Ward-Thompson

On 2023 November 10 a Specialist Discussion Meeting took place on the subject of 'Star Formation in the Milky Way and Beyond in the Era of JWST and ALMA' at which a number of exciting results were unveiled and discussed.

Introduction

The process of star formation has been studied for many decades and significant progress has been made. However, many important aspects of the astrophysics involved remain unclear. The last decade has provided a wealth of information on the dynamics, kinematics and magnetic fields of molecular gas and dust on all size scales, from the detailed physics of individual star-forming cores (e.g. Pineda at al. 2023, Pattle et al. 2023) to resolved observations of molecular cloud complexes in nearby galaxies (e.g. Saintonge & Catinella 2022).

Many of these advances have been driven by observations made with far-infrared and submillimetre instrumentation, particularly interferometric arrays such as the Atacama Large Millimeter/submillimeter (mm/submm) Array (ALMA) and the NOrthern Extended Millimetre Array (NOEMA), and large mm/submm single-dish telescopes such as the James Clerk Maxwell Telescope (JCMT) and the International Radio Astronomie Millimetrique (IRAM) 30-m telescope. Remarkably, data archives from telescopes that have ceased operations, or are winding down, are still yielding new results. These include the Hubble, Herschel and Spitzer Space Telescopes, the Infrared Space Observatory (ISO), the Planck Observatory and the Stratospheric Observatory for Far Infrared Astronomy (SOFIA).

Now, the James Webb Space Telescope's (JWST) exquisite near- and mid-infrared spectroscopy and photometry are poised to revolutionise our understanding of young protostars, their environments, and the effects of their feedback on molecular clouds. Simultaneously, significant advances in simulations, including the development of zoom-in simulations and the integration of realistic astrochemical networks, have allowed star formation to be modelled from galactic scales (~10-100kpc) down to core and circumstellar disc scales (~10-100AU). In this meeting we heard about some of the latest advances from these telescopes and simulations.

JWST – more than just a pretty picture

The invited guest speaker was **Klaus Pontoppidan** (NASA Jet Propulsion Laboratory), who explained that his research project had begun as an outreach programme with JWST, by having the telescope make eye-catching images of some star-forming regions, eventually concentrating on the core of Ophiuchus. It had subsequently evolved into a research project when it was realised how much science could be gleaned from the images.

He began by showing Mid-Infrared Imager (MIRI) pictures of galaxies at z=0.5 to 1.5, where the detected mid-IR images are actually rest-frame emission from Polycyclic Aromatic Hydrocarbons (PAHs), large interstellar molecules (Pontoppidan et al. 2022; Langeroodi & Hjorth 2023). The first 'local' star-forming region that the JWST imaged (with the Near Infrared camera, NIRcam) was the so-called 'Cosmic Cliffs' of Carina, closely followed by the

'Pillars of Creation' (of course). Then the JWST first anniversary image was of the core of the Ophiuchus molecular cloud. The amazing data of this region show absolutely unprecedented detail. He discussed each aspect of this latter image in turn.
The brightest object in the image is the B-star simply labelled as S1 that was so named because it was the brightest source to be discovered in the first near-infrared survey of the region (Grasdalen et al. 1973). It can be seen clearly in the JWST image, and is surrounded by a photon-dominated region (PDR). This has previously been detected by many studies, most recently in polarised far-IR emission by the High Altitude Wide-field Camera plus polarimeter (HAWC+) on SOFIA (Lee et al. 2021). However, none have seen it in the detail of the JWST image. Structure on the edges in particular is incredibly detailed. Future studies of these features will undoubtedly yield new insight into PDRs and how they form and grow.
Also visible in the JWST image is the location of the radio source VLA1623, which was the first ever recognised 'Class 0' protostar (André et al. 1993), and which drives powerful jets and outflows. The jet details visible in the JWST data shed fascinating light on the driving mechanism of the jet, as well as the interaction between the jet and the surrounding medium. The multiplicity of VLA1623 is also apparent in JWST data, as well as in ALMA data. There appears to be a close binary star in the centre, one component of which is the origin of the outflow. Then there is at least one other component in a wider orbit. This is just one example of the advances that can be made in this field 'in the era of JWST and ALMA'.

Nearby Galaxies as seen by JWST and ALMA

Elizabeth Watkins (University of Manchester) introduced the concept of super-bubbles in nearby galaxies, using the Physics at High Angular resolution in Nearby GalaxieS (PHANGS) project on the ALMA telescope (Leroy et al. 2021). This gives resolution at 100-pc scales in 90 nearby galaxies. The first PHANGS-JWST observations of nearby galaxies unveiled a rich population of bubbles. She found that the super-bubbles are consistent with Supernova Remnants (SNRs). As the bubbles expand, they sweep up the local Interstellar Medium (ISM) (Barnes et al. 2023).

Then she moved on to the large scale and the JWST image of NGC628 at high resolution (12pc), which appeared to have bubbles everywhere. She counted ~1700 bubbles in this one galaxy alone, with radii between 6 and 550pc (Watkins et al. 2023). Of these, 31% contain at least one smaller bubble at their edge, indicating that previous generations of star formation have a local impact on where new stars form.

To quantify the feedback energetics on the star-forming gas, she presented the largest molecular super-bubble catalogue found to date within nearby galaxies using ^{12}CO (J=2-1) observations. Using 18 PHANGS-ALMA galaxies at resolutions of ~50-100pc, a catalogue was produced of 325 super-bubbles with radii between 30 and 330pc and expansion velocities of ~10km/s. By focusing on a subset of these that have clear super-bubble signatures (unbroken shells, etc.), the kinematic information available with ^{12}CO helps to constrain the feedback processes. Most are found to be supernova-driven, and rather than dispersing, molecular clouds are swept-up into a shell that grows over time. Therefore, these super-bubbles can potentially form stars in their shells, matching what is observed in the higher-resolution JWST bubble catalogue.

Helena Faustino Vieira (Cardiff University) used dust extinction to trace the star-forming gas in M51 with a view to understanding the initial conditions of star formation and dependencies on local environment within galaxies (Faustino Vieira et al. 2024). For this, it is vital to study the cold molecular phase of the interstellar medium, traced by the cold dust, at the small scales of molecular clouds. She presented an innovative dust extinction technique for obtaining high-resolution (sub-arcsecond or parsec-scale) maps of the ISM of nearby disc galaxies, using archival Hubble data in the optical (Faustino Vieira et al. 2023).

This technique does not compute the extinction of individual stars, but instead measures the attenuation caused by dust against a modelled, smoothly varying stellar distribution, along each individual line-of-sight. Her estimates of dust mass were calibrated using lower-resolution dust emission observations from the Herschel Space Telescope.

She specifically used the results of the application of the extinction technique to M51, which correlated well with previous independent dust and CO studies of the galaxy at lower resolution. The physical resolution achieved (5 parsec) is roughly a factor of 8 higher than the resolution achieved by the current best-resolved CO survey of M51, the Plateau de Bure Interferometer Arcsecond Whirlpool Survey (PAWS; Schinnerer et al. 2013).

She investigated the impact of large-scale environment and dynamics by analysing the distribution and properties of molecular clouds across the galaxy, which were extracted from the extinction-derived map of M51. She found that large-scale dynamical features (i.e., bar and spiral arms) have a strong influence on the organisation of gas across M51. In regions less affected by strong shearing motions, molecular clouds are allowed to grow and develop into higher masses.

Additionally, there is a clear difference in average cloud surface densities within spiral arms in the inner galaxy versus the outer galaxy, a behaviour that is not present in the inter-arm regions. She hypothesised that this behaviour is caused by the tidal interaction between M51 and its companion. This study highlights the power of larger number statistics on resolved cloud populations (as a result of wider galactic disc coverage) in unravelling the potential effects of environment on molecular clouds, and consequently star formation.

Andrew Blain (University of Leicester) introduced the interactions between Gamma-Ray Bursters (GRBs) and the ISM in galaxies. He mentioned that graduate student **Miti Patel** (University of Leicester) had first brought his attention to this topic. The recent possible (or at least plausible) detection of ultra-high energy photons from GRBs offers the prospect to read out the conditions in the circumstellar environment from arrival time measurements, and to understand features of the astrophysics of acceleration. Even with ALMA and JWST, the time domain offers finer effective resolution, and potential access to first light on giant molecular cloud scales.

The timescales on which GRBs vary are of order hours, corresponding to light travel times of less than 100pc. Furthermore, the energies involved generate peta-electron-volt (PeV) photons! This can destroy the ISM along a very long but very narrow track. It is then interesting to see how a track such as this might interact with a SNR.

Chemistry of Galactic and Extra-Galactic Star-forming Regions

Janet Bowey (Cardiff University) discussed carbonates (chalk dust) and ices in stellar nurseries within the Milky Way and beyond. She introduced a pair of bands at 6.0 (H_2O-ice) and 6.9 µm taken with the spectrometers on ISO and Spitzer. These are observed in Milky Way molecular clouds and YSOs and in the z = 0.886 rest-frame of a molecule-rich spiral galaxy obscuring blazar PKS 1830–211. The 6.9-µm band carrier(s) are uncertain, but CH_3OH (methanol) ice is thought to contribute. Previous observers ruled out carbonates, even though carbonates produce the band in meteoritic samples.

Bowey (2023) fits ISO and Spitzer observations with new carbonate spectra (Bowey & Hofmeister 2022) and CH_3OH ice. 4 of the 5 observations require a carbonate component. CH_3OH abundances relative to H_2O are 10 times higher in the galaxy-absorber (~40%) than in 3 of the 4 Milky Way sources (< 7%, outlier 35%), but the carbonate (-CO_3) abundance is ~33% of the Milky Way abundances. Carbonates match the Jones & Ysard (2019) abundance model in which solids with a C:O ratio of 1:3 explain the disappearance of atomic oxygen at the diffuse-medium-to-molecular-cloud interface. All of this is consistent with high rates of massive star formation, again illustrating why we need to better understand this process.

Observations of the dynamics and kinematics of Galactic Star-forming Regions

We heard about recent observations of Galactic star-forming regions on a wide variety of size scales. **Andrew Rigby** (University of Leeds) gave a description of infrared dark clouds (IRDCs) studied with NOEMA and the New IRAM Kinetic inductance detector Array-2 (NIKA2) camera on the IRAM 30-m Telescope. He was a part of the Galactic ASTronomy On NIKA2 (GASTON) survey (Rigby et al. 2021) that found numerous candidate IRDCs that he has followed up with NOEMA. IRDCs are where high-mass stars form, and high-mass stars (greater than 8 solar masses) have a disproportionate effect on the ISM and on the evolution of galaxies. Hence a deep understanding of the formation and evolution of such stars is crucial to an understanding of the evolution of galaxies. Within this context, he showed images of the central parsec of a sample of seven IRDCs with a range of masses and morphologies. Using high-resolution combined observations from NOEMA and the IRAM 30-m Telescope, he examined the links between the core populations identified at 2.8mm, the kinematics of the dense gas within which they are embedded, and the properties of the clump-scale environment (Rigby et al. 2024).

N_2H^+ spectra of the sample of IRDCs appeared to show multiple velocity components. Distributions of N_2H^+ (J=1-0) linewidths – tracing dense gas – within the most massive IRDCs are similar to the ambient clump gas, suggesting that they are not dynamically decoupled from the wider clump environment, but are similarly chaotic. These results support a picture of clump evolution in which globally collapsing clumps become more like hub-filament systems over time as gravity draws in nearby filamentary structures, driving an increasing accretion rate onto a central region of collapse, where the core population grows within a highly dynamic environment. This hub-filament collapse mechanism could be the primary route by which high-mass stars form.

Zacariyya Khan (University College London) also stressed the importance of high-mass stars on the ISM, and specifically presented a study of magnetic fields in the hub-filament system G34.26+0.15, which falls under the influence of HII region feedback. He pointed out that hub-filament systems are molecular clouds that play host to massive star-formation, often containing multiple high-mass stars within their central hubs. However, the physics of the fragmentation and collapse of hub-filament systems is poorly understood at present, especially the role played by magnetic fields.

G34.26+0.15 is a molecular cloud at a distance of 3.3kpc and is part of the W48 complex. It is clearly composed of the characteristic long filaments extending out from a dense central hub. This hub contains multiple ultra-compact HII regions which have been extensively studied, indicative of massive star formation. He presented an analysis of the magnetic field structure across the region, inferred from observations of polarized dust emission at 850µm, taken using the Submillimetre Common-User Bolometer Array-2 (SCUBA-2) and its polarimeter, POL-2, mounted on the JCMT. By considering the alignment of the magnetic field to the filaments of G34.26+0.15, he showed that, although some filaments appear to be undergoing gravitational in-fall towards the central hub as would be expected in a hub-filament system, a substantial portion of the cloud appears to have been altered by an expanding HII region. This intense form of feedback appears to have both reshaped the magnetic field in the cloud and affected the structure of the material surrounding the HII region, potentially even triggering further massive star formation.

David Eden (Armagh Observatory) has been using the Massive Active JCMT-Observed Regions of Star formation (MAJORS) survey. The MAJORS survey is observing over 100 of the highest-mass star-forming regions observable from the JCMT in the HCN and HCO+ (J=3-2) transitions. This survey is designed to determine the role that dense gas plays in star formation. He is attempting to test the various scaling relations.

The strongest correlation is found between the column density of the dense gas and the near-infrared luminosity, which is believed to be the best tracer of star formation. This holds over many orders of magnitude. He used the W49 complex as an example of high-mass star formation. He referred to it as a 'star-burst' star-forming region, as it is arguably the most active region of star formation in the Milky Way. He presented the first-look observations and analysis from this region and gave a demonstration of the science that can be done on individual regions within the MAJORS survey.

Janik Karoly (University of Central Lancashire) presented some preliminary results from the B-fields In STar-forming Region Observations 3 (BISTRO-3) survey using SCUBA-2/POL-2 on the JCMT. This third round of observations of the BISTRO surveys is nearing completion and he shared some of the preliminary results. The third round of observations has focused on two extremes in star formation: cold and dense nearby isolated cores, and massive distant star forming regions such as the Central Molecular Zone (CMZ) in the Galactic Centre. These observations fill out the three parameter axes of star formation that BISTRO set out to investigate, namely the age, distance and mass axes.

A large mosaic of the CMZ traced the magnetic field in most of the Galactic Centre clouds, including Sgr A, B2 and C, as well as the so-called 'Brick' and the 30 km/s clouds. A great wealth of detailed structure was observed that astronomers are still trying to disentangle.

At the other end of the mass axis lie the Lynds dark clouds. BISTRO-3 has targeted a number of these**,** especially those that have not formed protostars yet (the starless cores with no embedded near-infrared sources), and Janik described what has been learnt about a few of them:

L43 (Karoly et al. 2023): this core is brighter than the others because it lies adjacent to the protostar RNO91, which is driving an outflow, although L43 itself does not contain a protostar. The edge of the outflow lies along the edge of the L43 core, and BISTRO-3 shows that the magnetic field also lies along the edge of the outflow cavity. This also explains an earlier BISTRO result that magnetic fields generally lie at ~30^{o} to the outflow axis (in projection) in protostars (Yen et al. 2021). The fields tend to lie along outflow cavity walls, and the cavity opening angles are typically ~30^{o}.

L1498: this object is the faintest of the BISTRO-3 sample of cores. and high levels of polarisation have yet to be detected from it, although not all the data have been taken yet. However, the polarisation that has been detected indicates a magnetic field lying perpendicular to the long axis of the core, as predicted by many models.

L1495 (Ward-Thompson et al. 2023): this region is part of a filamentary complex that contains a number of cores. It is hypothesised to be in a state whereby the early magnetic field-dominated phase gives way to the matter-dominated phase of evolution of dense cores.

He is continuing to study a larger sample of these cores, to produce an overall picture of what factors affect their evolution, and in what way. By the time the BISTRO-3 survey is complete, this should be the largest sample of such cores, whose magnetic fields have been observed at this high a resolution and sensitivity.

Simulating Star Formation in the Era of JWST and ALMA

To determine how global galactic processes might regulate how molecular clouds are formed, shaped, and ultimately able to form stars, it is essential that we understand the evolution of the gas as it travels through a galaxy, experiencing a wide range of conditions, densities and processes, at different scales. With this in mind, **Ana Duarte-Cabral** (Cardiff University) introduced the FFOGG project (Following the Flow Of Gas in Galaxies), using the AREPO (Weinberger et al. 2020) moving mesh model code (named after the enigmatic word AREPO in the Latin palindromic sentence *sator arepo tenet opera rotas*, the 'Sator Square') to study star formation in nearby galaxies, and in particular to understand the evolution of the gas as it travels through a galaxy in order to determine how global galactic processes might regulate how molecular clouds are formed, shaped, and ultimately able to form stars. She takes a sample of face-on galaxies so as to unambiguously separate material from the spiral arms and inter-arm material. She focusses particularly on the work on the numerical modelling of the evolution of the ISM and star formation in specific nearby spiral galaxies using tailored AREPO simulations with live stellar potentials and sophisticated ISM physics. Ultimately, the FFOGG project aims at determining whether star formation self-regulates, or whether it might be influenced or controlled by the global dynamics of the spiral/bar structures of spiral galaxies.

Models such as these will be essential to understand the complex data being generated by the latest telescopes.

Eva Duran Camacho (Cardiff University) talked about self-consistent modelling of the Milky Way using live potentials. She is aiming to investigate the role of the large-scale dynamics of the Galaxy on star formation, using the hydrodynamical AREPO moving-mesh code to perform numerical simulations of Milky Way-type galaxies using a live dark matter halo, stellar disc, and stellar bulge. She has generated a set of 15 isothermal models whose parameters have been observationally constrained, to investigate the structure and dynamics created by the stellar potential and followed by the gaseous disc. She finds that the overall galactic structures are very sensitive to the initial stellar distribution, with some models developing long bars whilst others create none. She ultimately finds the best fit of the Milky Way by comparing the models to observations via longitude-velocity plots of the projected gas surface densities, from which she extracts the skeletons of the main features (arms, etc.), as well as the contours defining the terminal velocities of the gas. Combining all these results, she selects an overall best fit which serves as the Milky Way template.

She then presented details of distinctive features, such as the spiral pattern, the 3-kpc expanding arm and the CMZ. The final model acts as the basis for inclusion of more physical processes, such as chemistry, feedback, magnetic fields, and increased resolution of individual regions. Those models can then be compared to observations using radiative transfer codes to mimic dust continuum and molecular line emission from the interstellar medium. These will be essential for testing the validity of the models and the physical processes behind the observables.

Understanding the role of magnetic fields in controlling the large-scale dynamics of the ISM has historically proven to be a difficult challenge. **Kamran Bogue** (University of Manchester) has carried out simulations that used the cutting edge high-resolution, three-dimensional AREPO code of an isolated galaxy. He ran near-identical simulations with only one difference – the addition of a magnetic field! This was to investigate how a dynamo-generated field can shape the alignment of dense structures in the ISM and their subsequent star formation.

Understanding the role of magnetic fields in controlling the large-scale dynamics of the ISM has historically proven to be a difficult challenge. By running models of both a hydrodynamic and magnetohydrodynamic case, he is able to specifically interrogate the impact of the field in star forming environments. He compared the global properties of isolated galaxy disc models, studying differences in morphology and vertical extent, dense gas fractions, and star formation rates.

One of the most interesting – and potentially controversial – results is that adding a magnetic field seems to lower the star-formation rate.

Conclusions

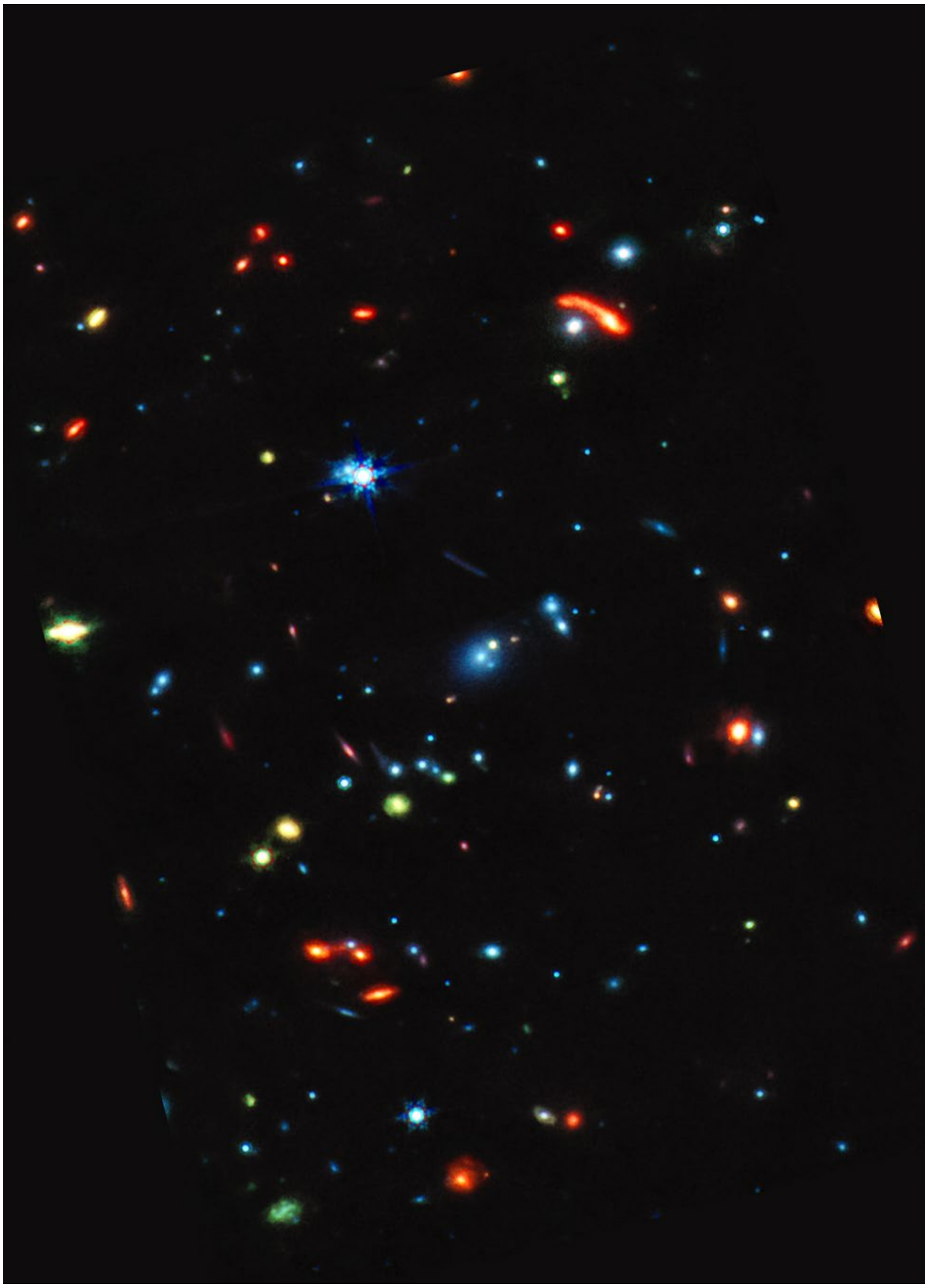
This meeting has shown us tantalising evidence of what JWST is already bringing to studies of star formation. It has also demonstrated the power of interferometers like ALMA, and the ongoing importance of large, ground-based single-dish telescopes like the JCMT. However, above all, it has shown us that to make progress in any field of astronomy in the modern era, it is necessary to put together the findings from many telescopes, both old and new, as well as state-of-the-art model simulations.

One other question captured the attention of a few in the meeting – why does Derek think that the JWST image of Ophiuchus looks like a monster fighting a jellyfish?

References

André, Ward-Thompson & Barsony 1993, ApJ 406 122
Barnes et al. 2023, ApJ 944 22
Bowey 2023, MNRAS 524 2446
Bowey & Hofmeister 2022, MNRAS 513 177
Faustino Vieira et al. 2023, MNRAS 524 161
Faustino Vieira et al. 2024, MNRAS 527 3639
Grasdalen, Strom & Strom 1973, ApJ 184 L53
Jones & Ysard 2019, A&A 627 A38
Karoly et al. 2023, ApJ 952 29
Langeroodi & Hjorth 2023, ApJL 946 L40
Lee et al. 2021, ApJ 918 39
Leroy et al. 2021, ApJS 257 43
Pattle et al. 2023, ASPC 534 193
Peretto et al. 2013, A&A 555 A112
Pineda et al. 2023, ASPC 534 233
Pontoppidan et al. 2022, ApJ 936 L14
Rigby et al. 2021, MNRAS 502 4576
Rigby et al. 2024, MNRAS in press, arXiv:2401.04238
Saintonge & Catinella 2022, ARA&A 60 319
Schinnerer et al. 2013, ApJ 779 42
Ward-Thompson et al. 2023, ApJ 946 62
Watkins et al. 2023, ApJL 944 L24
Yen et al. 2021, ApJ 907 33

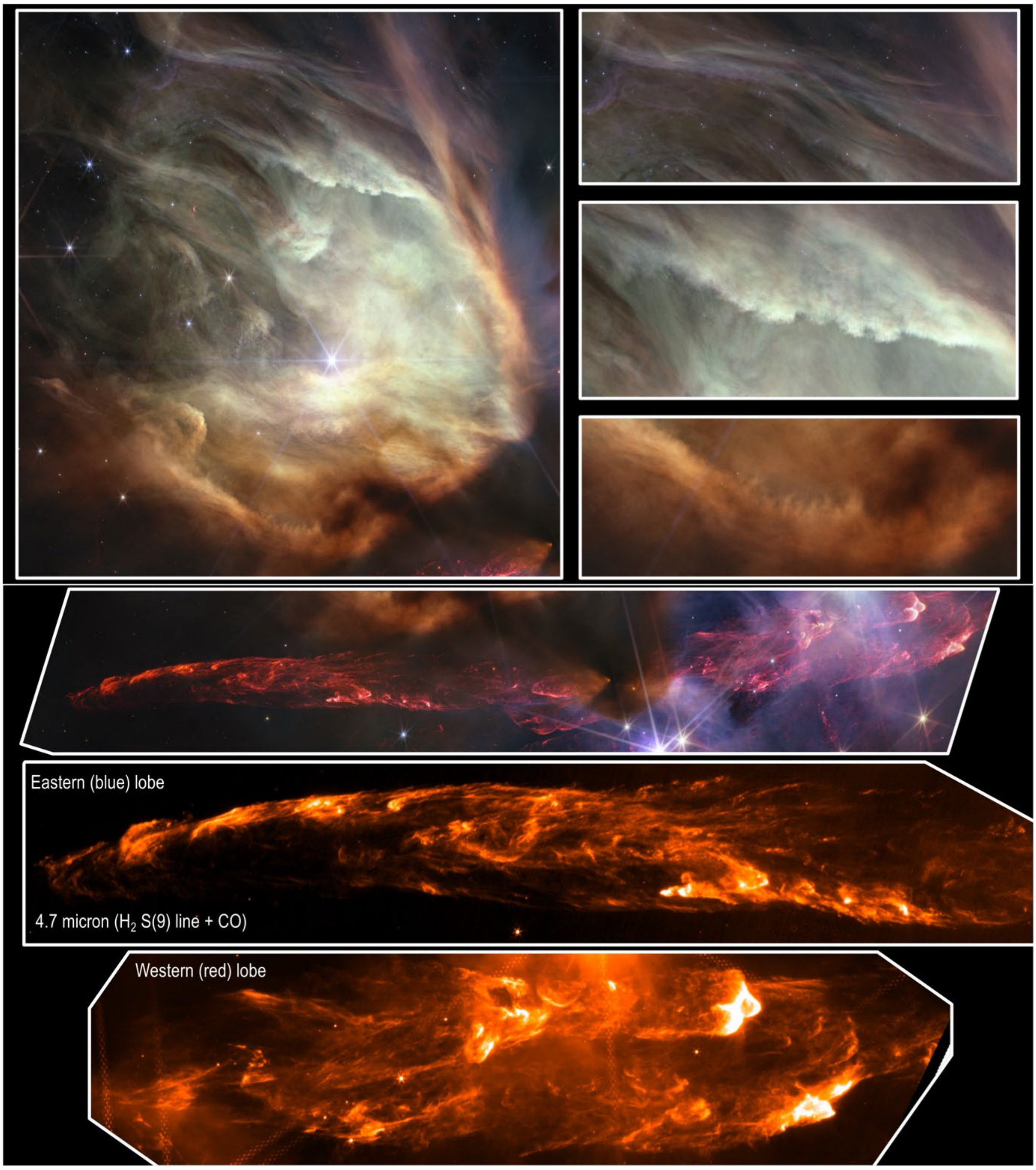
Figures



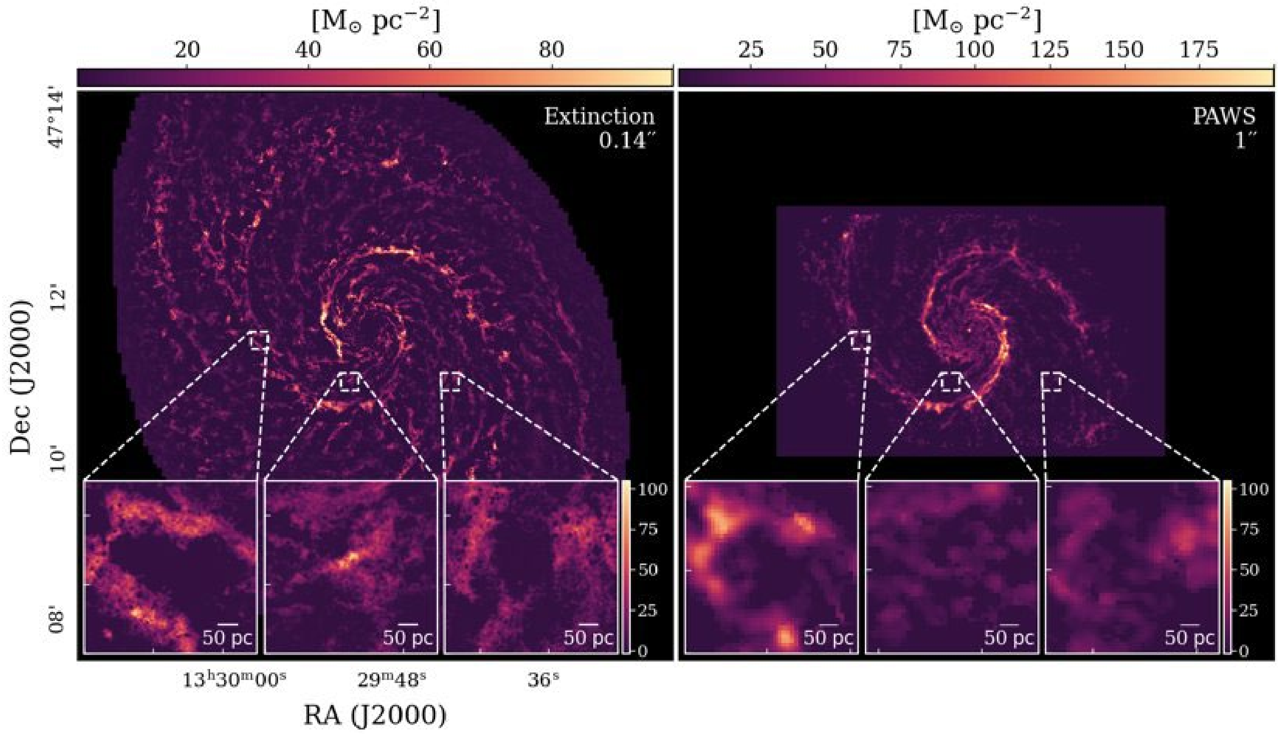
“Skittles” – galaxies dominated by PAH emission at z=0.5-1.5 – observed with MIRI at 7.7-18 µm (Pontoppidan et al. 2022).

The ‘Cliffs of Carina’ are actually the edges of a nearby, young, star-forming region in the Carina Nebula. Captured in infrared light by NASA’s new James Webb Space Telescope, this image reveals for the first time previously invisible areas of star birth.

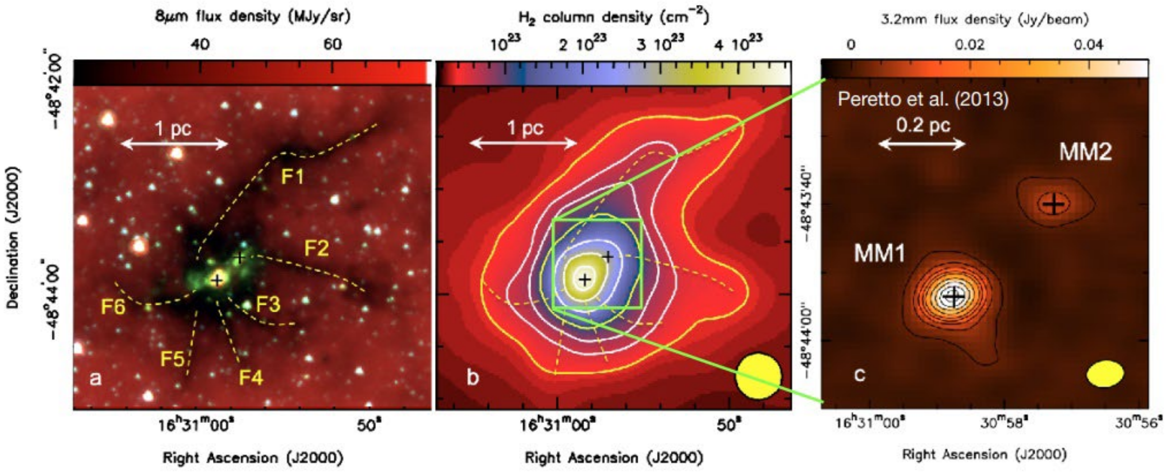
The JWST view of the brightest part of the Ophiuchus star-forming region, known as Oph A. (First-anniversary JWST image.)



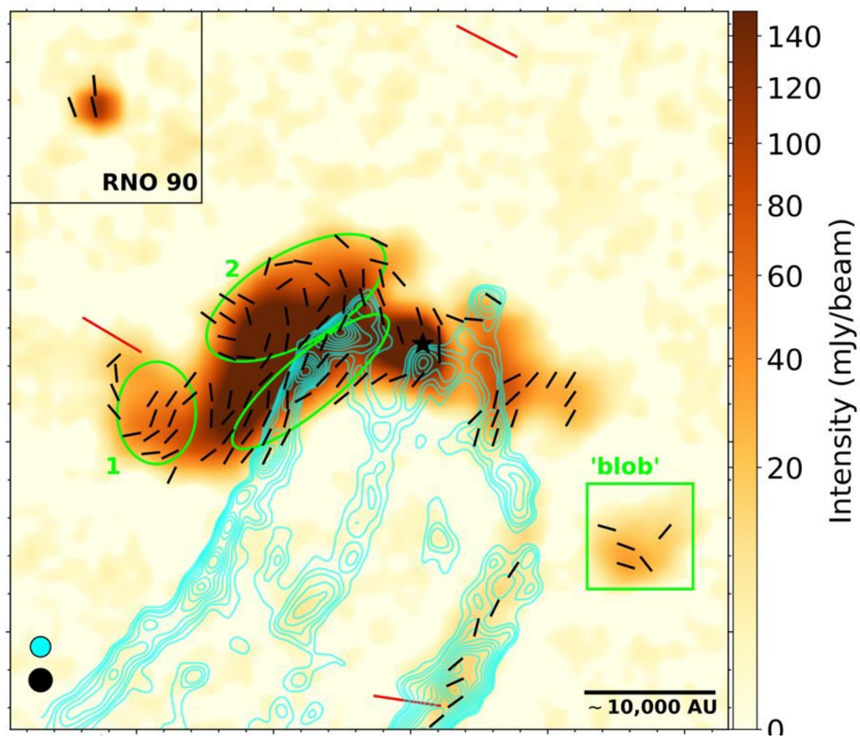
JWST views of the reflection nebula around S1 (the bright star at the centre of the top left image), some incredibly fine detail of the PDR (top right column), and the structure of the VLA 1623 outflow (lower three panels).



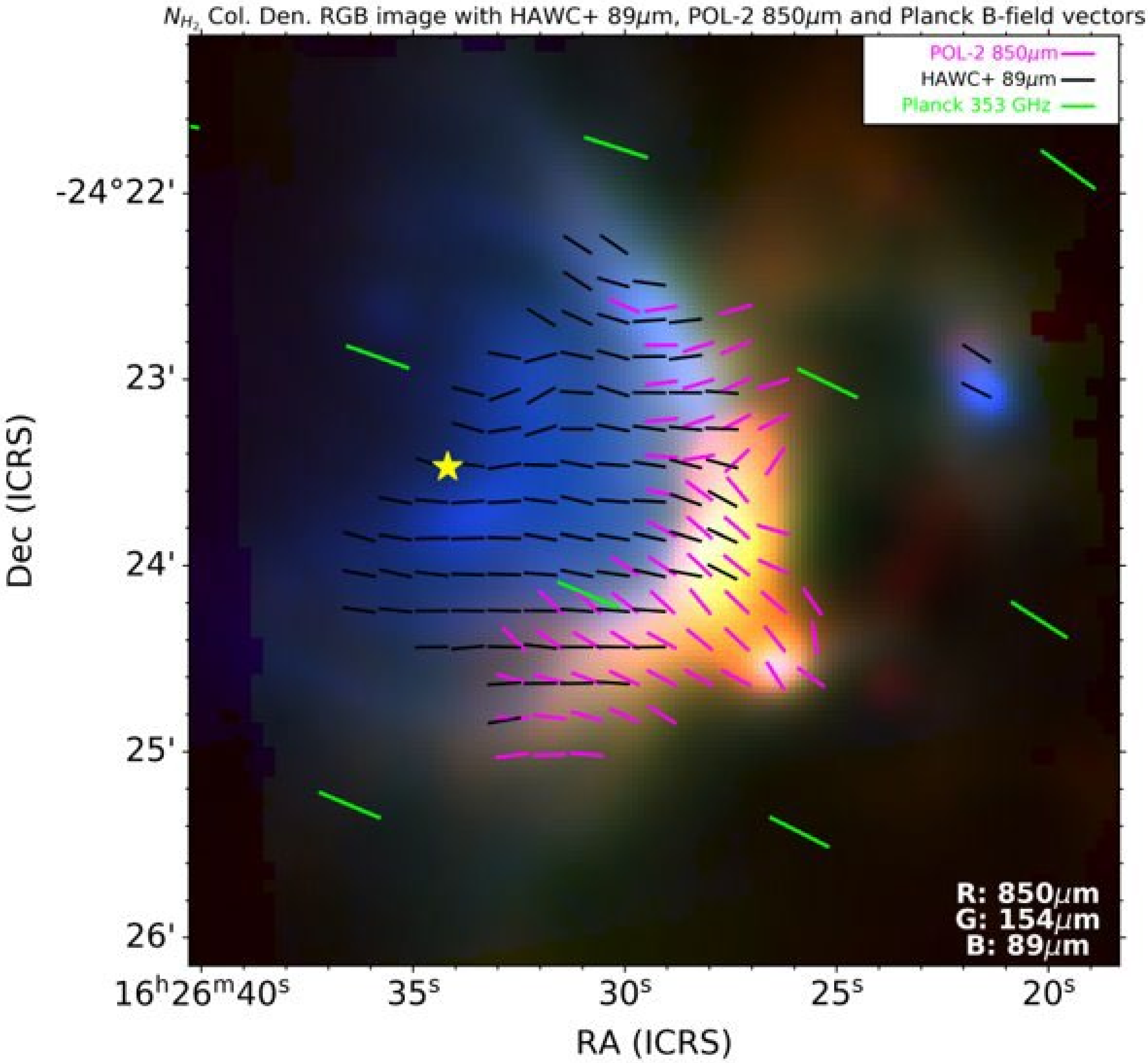
Helena Faustino Vieira showed two methods of extracting molecular clouds from M51. Images from Faustino Vieira et al. (2023) and Schinnerer et al. (2013).



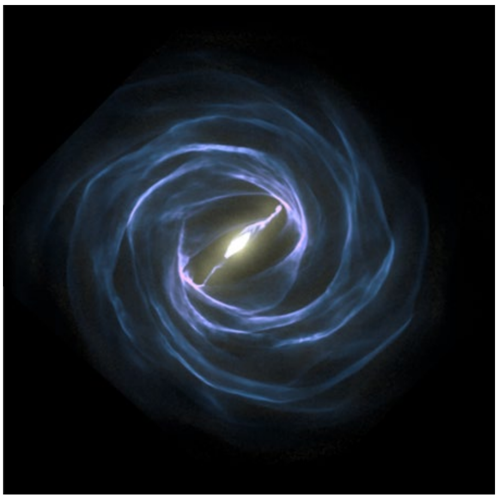
Andrew Rigby discussed the earliest stages of massive star formation and showed a variety of data of the infrared dark cloud SDC335, which has a mass of 5500 solar masses. Images from Peretto et al. (2013), using Spitzer, Herschel and ALMA respectively.



Janik Karoly discussed magnetic fields in low-mass dark cores. In this case we see the magnetic field following the outflow cavity in L43, as observed by JCMT SCUBA-2/POL-2.



Janik Karoly showed the same region in Ophiuchus as the JWST image above, but now with the magnetic field superposed, as measured by SOFIA HAWC+, JCMT SCUBA-2/POL-2, and the Planck Observatory.



Eva Duran Camacho showed a simulation of the Milky Way Galaxy.