JCMT in the new era

Star-formation studies continue at the James Clerk Maxwell Telescope under new management, as **Jennifer Hatchell** and **Derek Ward-Thompson** report from an RAS meeting in March.

In February 2015, the James Clerk Maxwell Telescope (at Mauna Kea Observatory in Hawaii, figure 1) changed ownership after almost 30 years of continuous operation. The JCMT is now run by the East Asian Observatory, although the UK still has a stake in operations. Furthermore, the first generation of JCMT Legacy Surveys were completed in January 2015. Three of the six surveys involved studies of star formation and the interstellar medium. The change of ownership also marked the start of a new generation of Large Programs and follow-up observations to the Legacy Surveys, so it is an appropriate time to take stock. What has been learned from the Legacy Surveys? And what is planned for the Large Programs?

The Large Programs (2016–2018) are new, multi-hundred-hour, submillimetre astronomy campaigns; they are joint projects with East Asian astronomers, reflecting the new era of JCMT operations after transfer from the STFC. Like the Legacy Surveys before them (2012–2015), they make good use of the current suite of mapping instruments on JCMT, namely the SCUBA-2 submillimetre continuum camera (with an 8′ field of view), its associated polarimeter POL-2, and the HARP/ACSIS molecular line multi-beam receiver (2′ FOV). The JCMT Legacy Surveys mapped significant fractions of the galactic plane, nearby star-forming regions, debris discs and nearby galaxies. The Large Programs extend that work and take it in new directions, mapping submillimetre dust polarization, searching for variability in protostars, and exploring the Kennicutt–Schmidt relation in nearby galaxies. The commissioning of ALMA also brings in a new era for submillimetre astronomy, where single-dish telescopes provide the context – total fluxes and finding charts – for details to be revealed by high-resolution interferometry.

1 The JCMT, situated at an altitude of 4092 m in Hawaii, has been operating since 1987. (W Montgomerie)

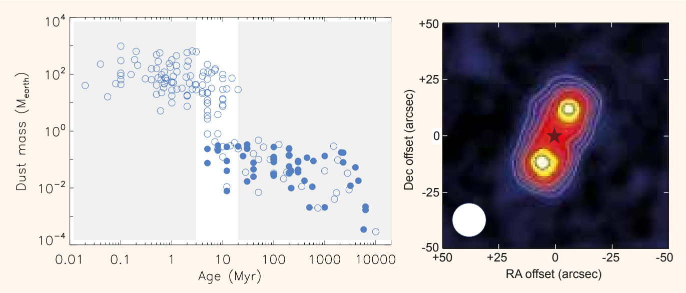
On Friday 11 March 2016, 40 star-formation researchers from both the galactic and nearby galaxies communities met at the RAS to discuss the results coming out of the Legacy Surveys and the prospects for the Large Programs.

JCMT Legacy Surveys

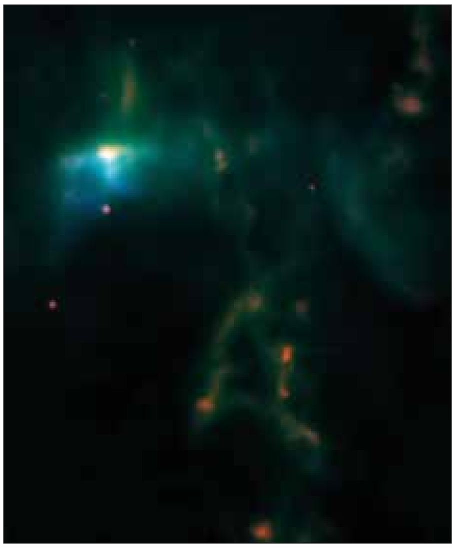
The JCMT Legacy Surveys began in preparation for the commissioning of SCUBA-2 and were the first multi-hundred-hour programmes on JCMT (apart from the UK-led cosmology survey SHADES). With SCUBA-2 and HARP molecular-line observations complete, data reduction and analysis for these surveys is now mature. The meeting was timely in bringing together the results from the UK community, focusing on three surveys: the debris disc survey (SONS); the Gould Belt Survey (GBS); and the JCMT Galactic Plane Survey (JPS).

Starting closest to home at the meeting "Star formation studies with the JCMT in the new era", **Mark Wyatt** (University of Cambridge) presented SONS data. This survey targets the submillimetre emission from millimetre-sized dust in debris discs surrounding nearby main-sequence stars, some of which also host planets. Having observed 100 stars with a roughly 50% detection rate, SONS has provided the first submillimetre data for many discs (Panic *et al.* 2013, Holland *et al.* in prep.), as well as detailed maps of the distribution of the debris for those near enough to be resolved, including the well-known examples Epsilon Eridani and Fomalhaut (figure 2 right). Combined with the shorter-wavelength fluxes, submillimetre fluxes from SCUBA-2 are vital to set constraints on the mass and composition of material in the disc (Churcher *et al.* 2011, Duchene *et al.* 2014, Lawler *et al.* 2014, Kennedy *et al.* 2015, Matthews *et al.* 2015). Debris discs, the main sequence counterparts to the protoplanetary discs found around younger stars, contain the raw materials for the formation of planetary systems. Coupling the results from SONS with JCMT work on younger systems shows that the transition at 10 Myr from protoplanetary disc to debris disc coincides with a drop in dust mass by a factor of roughly 100 (Panic *et al.* 2013) followed by a slow decline in dust mass (Matthews & Kavelaars 2016; figure 2 left).

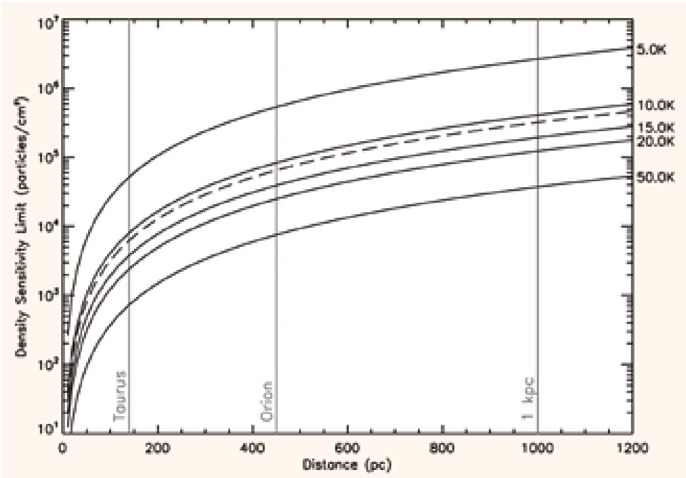
While the large angular scales of the faint debris discs studied by SONS present a challenge, several have now been followed up interferometrically with SMA and ALMA (see below), revealing the disc



2 Overview of SONS results. (Left): Sub-mm derived dust mass versus age showing both protoplanetary discs and debris discs, with masses derived from SONS detections shown by filled circles; note the sharp drop in dust mass following dispersal of the protoplanetary disc, followed by a slow decline with age. (Adapted from Paníc *et al.* 2013, including new data from Matthews & Kavelaars 2016). (Right): 850 μm SCUBA-2 image of one of the SONS detections, the 130 au radius Kuiper belt of the star Fomalhaut (Holland *et al.* in prep). (Courtesy of O Paníc and SONS Survey team)



3 Herschel and SCUBA-2 three-colour image of the L1495 region of Taurus. Note how SCUBA-2 (red channel) picks out the dense prestellar cores in the filaments (Ward-Thompson *et al.* 2016).



4 Sensitivity of the SCUBA-2 Gould Belt Survey as a function of density with distance at different temperatures (Ward-Thompson *et al.* 2016).

structure at high resolution for the first time. As well as evidence for clearing of the inner disc, many of the resulting images also show interesting structure and asymmetries that may represent the dynamical signature of as yet undetected planets (e.g. Ricci *et al.* 2015). An unexpected result from ALMA is the detection of CO at very low gas-to-dust levels in young (ages between 20 and 100 Myr) debris discs (Dent *et al.* 2014, Marino *et al.* 2016, Greaves *et al.* 2016). While CO in some of these discs may represent a long-lived remnant of the protoplanetary phase, in others the extremely low, optically thin levels indicate a second-generation scenario, in which molecules are quickly destroyed and hence must be continuously produced through the destruction of exocomets. This opens the exciting possibility of measuring the volatile composition of exocometary bodies during the final throes of planet formation (e.g. Matrà *et al.* 2015, Marino *et al.* 2016).

The Gould Belt

Many of the nearby newly forming stars are covered by the JCMT Gould Belt Survey (GBS), which targets molecular clouds in the closest 10% of our galaxy, including well-known regions such as Ophiuchus, Taurus and Orion. The RAS meeting was organized by the UK coordinators of the GBS, Derek Ward-Thompson and Jenny Hatchell.

Much of the survey work so far has focused on individual regions as their data became available. **Derek Ward-Thompson** (University of Central Lancashire) highlighted a comparison study between SCUBA-2 and Herschel to discover which property of a molecular cloud core is most detectable by SCUBA-2. Figure 3 shows a three-colour Herschel/SCUBA-2 image of the Taurus L1495 region. The filamentary structure of the region shows up clearly at Herschel wavelengths (green and blue channels), while the cores show up most clearly in the SCUBA-2 data (red channel). It transpires that core density is the most important parameter for detectability by SCUBA-2. Figure 4 shows the sensitivity of the SCUBA-2 Gould Belt Survey to core density as a function of distance at different temperatures. SCUBA-2's ability to trace the densest prestellar cores means that it is most sensitive to those cores that are most likely to go on to form stars, rather than their less dense starless counterparts (Ward-Thompson *et al.* 2016).

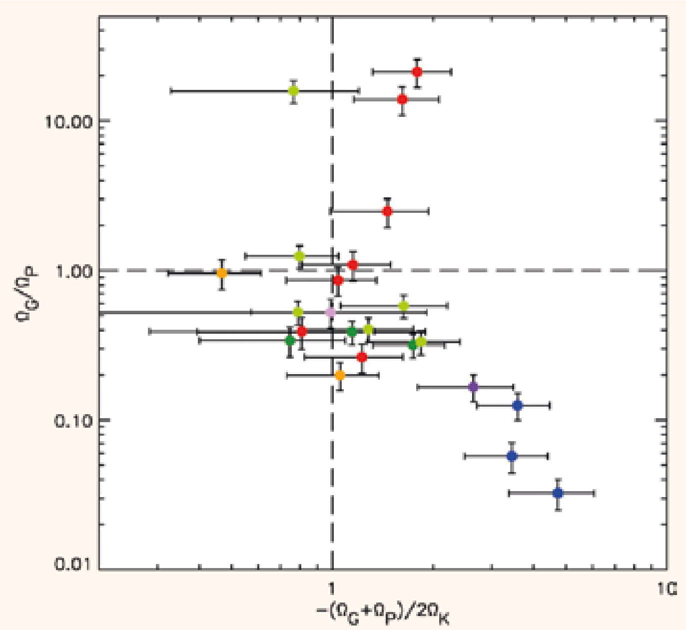
"SCUBA-2 observations are complementary to the Herschel observations"

Prestellar and protostellar cores

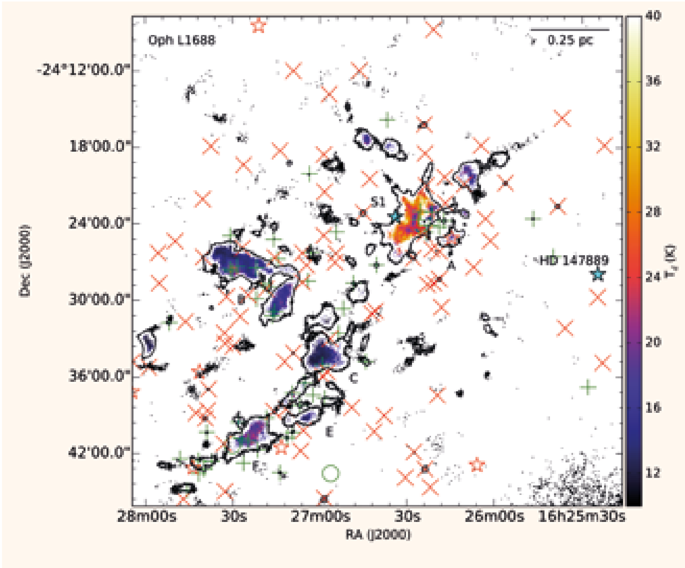
PhD students **David Bresnahan** (UCLAN) and **Chris Mowat** (Exeter) showed results of two of the lesser-known regions, Corona Australis and Lupus I. Corona Australis is a quiescent star-forming region not located exactly within the Gould Belt, but below the galactic plane (Neuhäuser & Forbrich 2008). The well-studied Coronet region (Taylor & Storey 1984) contains newly formed low- to intermediate-mass stars (Wilking *et al.* 1985, Nutter *et al.* 2005) that could be contributing to the future evolution of starless and prestellar cores within the region (Bresnahan *et al.* in prep). SCUBA-2 observations are complementary to the Herschel observations and present the opportunity to further constrain the properties of prestellar cores found in both JCMT and Herschel observations. A number of sources, including prestellar cores, appear as compact but slightly extended sources within the SCUBA-2 data.

Lupus I contains several Class II/III discs. Estimates of disc masses based on JCMT data suggest that only one of these, HT Lupi, reaches the "minimum mass solar nebula" of 0.013 solar masses, a result that is consistent with findings in other Gould Belt regions (Dodds *et al.* 2015, Buckle *et al.* 2015). There is one Class 0 protostar in Lupus I, with an envelope mass of around 1 solar mass, as well as a small number of Class I sources that still have residual envelopes (Mowat *et al.* 2016 in prep.)

Orion A is a well-studied region yet there are still insights to be gained. Herschel has highlighted the importance of filaments in star formation, so PhD student **Carl Salji** (Cambridge) has measured their profile at JCMT resolution, finding a fit with a Plummer-like profile with $p = 2.2$ density dependence (Salji *et al.* 2015).

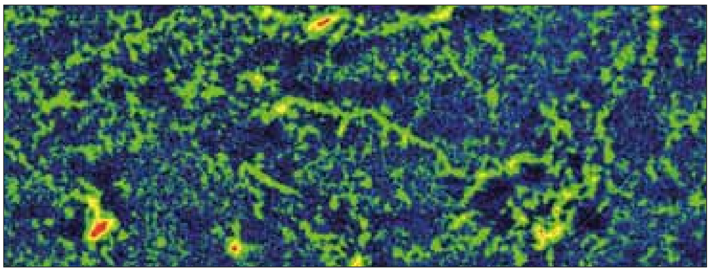


5 The virial plane (Pattle *et al.* 2015). The ratio of gravitational potential energy to external pressure energy is plotted as a function of the virial parameter. Cores to the right of the vertical dashed line are virially bound, those above the horizontal dashed line are gravitationally dominated. The data points each represent a different core in Ophiuchus. Colour coding refers to the different parts of Ophiuchus. Note the starless core desert in the top left (Pattle 2016).



6 Dust temperatures in Ophiuchus derived from SCUBA-2 450/850 μm ratios from the JCMT Gould Belt Survey. The B stars S1 and HD147889 dominating the heating are marked as cyan stars and known young stellar objects are marked as crosses. (Courtesy of D Rumble and JCMT Gould Belt Survey team)

7 A small region of the 850 μm JPS survey at galactic longitudes near 29°, showing a network of filamentary structures (green, yellow and red). The image width is around 1° in angular size.



Stability

Now that most of the SCUBA-2 observations of individual regions have been published, the GBS team has begun to turn its attention to further questions that can be addressed with the combined dataset. Studies of the stability of prestellar cores, starting with the Ophiuchus region, are yielding interesting results. By comparing gravitational potential energy with turbulent and surface pressure terms, **Kate Pattle** (UCLAN) has found that many Ophiuchus cores are bounded by surface pressure rather than gravitation.

In figure 5, showing the virial plane (Pattle *et al.* 2015), the ratio of gravitational potential energy to external pressure energy is plotted as a function of the virial parameter. Cores to the right of the vertical dashed line are virially bound, those above the horizontal dashed line gravitationally dominated. This result could imply that, just because a core is virially bound, it does not necessarily go on to form a protostar (Pattle *et al.* 2015). For a core to be considered definitively prestellar, it must be gravitationally bound, rather than simply pressure-confined, because some starless cores in the latter category may simply evolve to virial equilibrium (Pattle 2016).

The molecular-line data collected by the GBS with HARP are being used to address a longstanding question about star-forming clouds: do molecular outflows contribute significantly to driving turbulence? **Emily Drabek** (Imperial College) studied outflows in Ophiuchus, Serpens and Perseus. While outflows can inject kinetic energy fast enough to match turbulent dissipation rates, there is no correlation between levels of turbulence and current outflow activity in these regions. She concluded that coupling between outflows and the dense gas is not efficient enough for outflows to be the main driver of turbulence.

PhD student **Damian Rumble** (Exeter) has been investigating dust heating in the Gould Belt (Hatchell *et al.* 2013, Rumble *et al.* 2015, 2016). The dust temperature can be estimated using ratios of 450 and 850 μm fluxes. Comparing clump temperatures in different regions, for example in Ophiuchus (figure 6), he finds that the dominant source of heating across the Gould Belt is OB stars rather than embedded protostars.

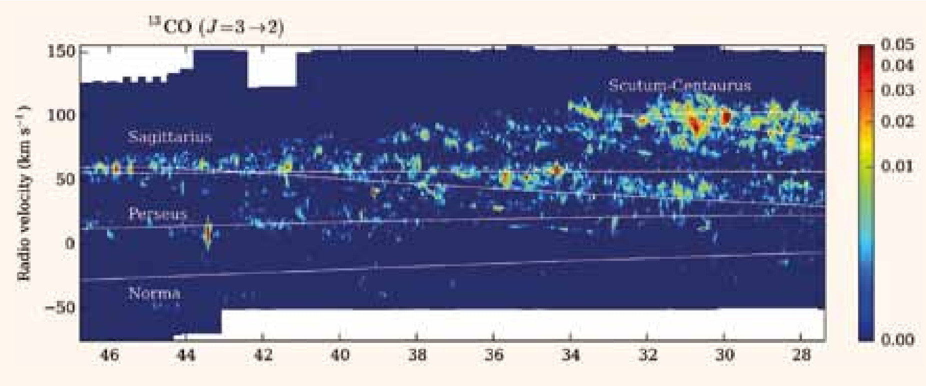
The galactic plane

Toby Moore (Liverpool John Moores University) explained that, further out in the Milky Way, the JPS (Moore *et al.* 2015) used SCUBA-2 to map significant fractions of the inner galactic plane at 850 μm, including star-forming complexes such as W43, W51 and G29.96. JCMT maps at 850 μm have higher resolution than Herschel at 500 μm and trace the high-column-density, star-forming filaments well (figure 7).

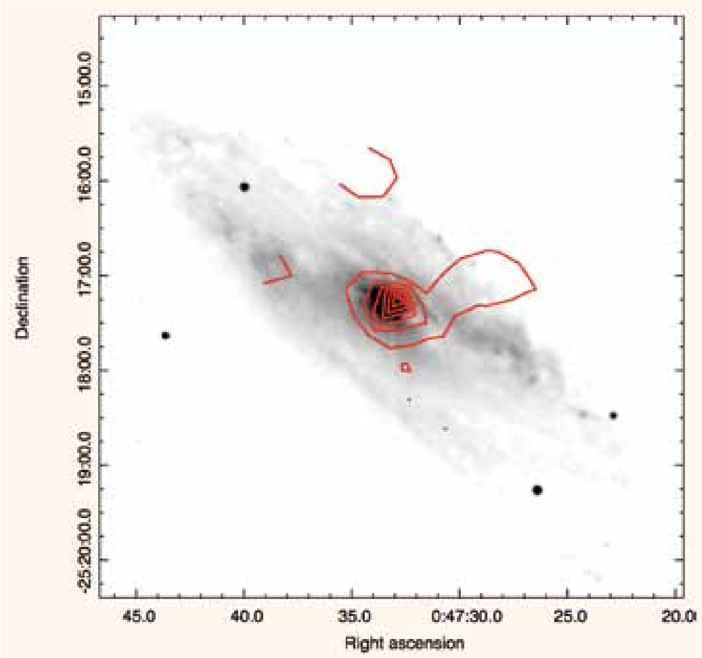
Alongside the continuum mapping, HARP was used in principal investigator time to survey the molecular gas in the same area in $^{12}CO/^{13}CO/C^{18}O$ $J=3–2$. In addition to allowing kinematic distance estimates by associating velocities with the continuum features and analysis of the connection between molecular-cloud gas physics and star formation, the molecular-line data can be used to reveal galactic structure. An intriguing result is that the spiral arms between galactic longitudes $l=30$ and $l=38$ and velocities around 75 km s^{-1} relative to the Sun do not fit the four-arm spiral model of Taylor & Cordes (1993), but show significant emission from inter-arm regions suggesting significant high-column-density spurs or additional arm features (figure 8; Rigby *et al.* 2016).

New JCMT Large Programs

The second part of the meeting focused on the JCMT Large Programs that began observing in January 2016 (a full list is available on the JCMT website, http://www.eaobservatory.org/jcmt). These programs extend the earlier set of surveys



8 (Above): Position–velocity map of ^{13}CO J=3–2 emission from the CHIMPS survey (Rigby *et al.* 2016). The white curves show the positions of the galactic spiral arms in the Taylor and Cordes (1983) model.



9 (Right): HCN(4–3) emission (red contours) tracing dense gas in the central region of NGC 253 as part of the MALATANG survey. The greyscale is the 2MASS J near-infrared image.

in different directions, introducing new samples and new observing techniques. Most have strong UK involvement.

Two Large Programs target the nearby star-forming regions already observed for the GBS using different observing techniques. The polarimetry survey BISTRO (B-fields In STar forming RegiOns), discussed by Kate Pattle, is taking advantage of the new SCUBA-2 polarimeter to map submillimetre polarization vectors and hence the direction of the magnetic fields. These magnetic fields may control the flow of mass onto filaments and so to protostars. Results so far are promising.

The program A Transient Search for Variable Protostars, presented by UK coordinator **Jenny Hatchell** (University of Exeter), uses repeat observations of GBS fields with SCUBA-2 to look for submillimetre variability in embedded protostars. Accretion variability is a promising solution for the long-standing "luminosity problem": Class 0/I protostars appear less luminous than predicted on the basis of a constant accretion rate. Increased luminosity heats the protostellar envelope, raising the submillimetre flux. Observing every month, and comparing with archival GBS data from 2012 onwards, the survey aims to detect any submillimetre variability above 3%.

Star formation is also being studied further out in the galaxy. SCOPE (SCUBA-2 Continuum Observations of Pre-protostellar Evolution), presented by **Mark Thompson** (Hertfordshire), targets Planck cold cores with SCUBA-2, using the SASSy strategy of mapping in poor weather (for Mauna Kea) in order to cover a large target list. While Planck provides a sample of cold, dense star-forming clouds, SCUBA-2 gives the resolution to study their structure and protostellar contents in detail.

Nearby galaxies

Star formation is not confined to our galaxy, and two further Large Programs target gas and dust in nearby galaxies. The MALATANG survey (MApping the dense moLecular gAs in the sTrongest stAr-formiNg Galaxies), presented by **Thomas Greve** (University College London), is using HARP to map the HCN and HCO^+ J=4–3 transitions in 23 of the nearest and IR-brightest galaxies beyond the Local Group (e.g. NGC 253, figure 9). The aim is to characterize the relationship between the dense gas phase and the star-formation properties on scales down to ~1 kpc in these 23 galaxies. The goal is to probe both low-surface-density regions found in the discs as well as in the nuclear regions where surface densities are high. MALATANG will bridge the gap, in terms of physical scale and luminosity, between extragalactic (i.e. galaxy-integrated) and galactic (i.e. single molecular clouds) observations. **Amelie Saintonge** (UCL) discussed JINGLE, the Legacy Survey that aims to bridge the gap between galactic star-formation surveys and the two deep high-redshift extragalactic surveys. Specific science goals include establishing scaling relations between gas, dust, star formation and a full range of integrated galaxy properties (masses, morphologies, metallicities etc), and linking the global gas contents of galaxies to the small-scale physics of star formation through a collaboration with the MaNGA optical IFU survey. JINGLE will shed light on the mechanisms that drive star formation across the galaxy population in the universe today, as well as providing benchmark relations that will be important to high-redshift studies. ●

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MORE INFORMATION

More information on the new Large Programs, including complete lists of coordinators, is available from http://www.eaobservatory.org/jcmt/science/large-programs.

The presenters at the meeting were Toby Moore (LJM), Mark Wyatt & Luca Matra (Cambridge), Derek Ward-Thompson (UCLAN), John Richer (Cambridge), Emily Drabek-Maunder (Imperial College, London), David Bresnahan (UCLAN), Chris Mowat & Damian Rumble (Exeter), Mark Thompson (UH), Kate Pattle (UCLAN), Jenny Hatchell (Exeter), Thomas Greve and Amelie Saintonge (University College, London).

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