



# Report from the event supported by RadioNet

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**TITLE** *MEASURING STAR FORMATION IN THE RADIO, MILLIMETRE, AND SUBMILLIMETRE*

**DATE:** *24-26 JULY 2017*

**LOCATION:** *MANCHESTER, UNITED KINGDOM*

**MEETING WEBPAGE:** *<http://www.alma.ac.uk/index.php/meetings/uk-arc-node-meetings/106-measuring-star-formation-in-the-radio-millimetre-and-submillimetre>*

**HOST INSTITUTE:** *JODRELL BANK CENTRE FOR ASTROPHYSICS, THE UNIVERSITY OF MANCHESTER*

**RADIONET BENEFICIARY / NO:** *UMAN / 6*

# Report:

## 1. SCIENTIFIC SUMMARY

The primary goal of the meeting was to bring together researchers who are exploring ways to measure star formation in the radio, millimetre, and submillimetre bands. The webpage for the meeting is at <http://www.alma.ac.uk/index.php/meetings/uk-arc-node-meetings/106-measuring-star-formation-in-the-radio-millimetre-and-submillimetre>.

The conference schedule was divided into seven sessions with titles based on the key scientific subjects that were discussed at the meeting. Below, we present summaries of the talks presented in each session.

- **Measuring star formation in the nearby universe** – This session was devoted to presenting new and novel ways for measuring star formation in nearby galaxies. Miguel Perez-Torres started with a description of using e-MERLIN for long baseline radio imaging of nearby LIRGs to separate emission from individual star forming regions and AGN. This was followed by Kouichiro Nakanishi's presentation on using ALMA to measure millimetre recombination line emission from star forming regions within the starburst NGC 253 at  $\sim 1$  arcsec resolutions, which presented a much clearer picture of the structures and dynamics of these regions than previous observations. Loreto Barcos-Munoz finished the session with a presentation on how 33 GHz continuum emission could be used to study star formation in LIRGs and ULIRGs. Barcos-Munoz showed that the star formation rates (SFRs) from infrared and 33 GHz emission were correlated, but she also found some inconsistencies in the computed ratio of synchrotron to free-free emission as compared to the spectral slopes of the data.
- **Star formation surveys of the moderate-z and high-z universe** – This session highlighted the range of different surveys being performed on galaxies at these redshifts. Tom Muxlow began the session with a presentation on initial e-MERGE results that illustrated how the survey could not only detect high-redshift sources but could also resolve these sources, thus separating emission from AGN and extended star formation. Sarah Higdon showed how redshifted fine structure lines, such as [CII], [NII], and [OIII], could be observed using ground-based submillimetre telescopes to measure SFR and metallicity. Sarah Leslie and Eric Faustino Jimenez-Andrade both presented results from the JVLA-COSMOS survey at 3 GHz. Leslie's analysis found that the main sequence flattens at  $z < 1.5$ , while Jimenez-Andrade's analysis found that the spatial distribution of radio emission is more compact in starburst galaxies than in main sequence galaxies. Hannah Stacey and Steven Duivenvoorden presented Herschel-based deep field survey results as well as submillimetre follow-up observations in which the dust emission is used to derive SFRs.
- **Calibrating star formation tracers** – Fatemeh Tabatabaei, Luke Hindson, and Martin Hardcastle (substituting for Gulay Gurkan Uygun) showed a strong correlation between various star formation tracers (particularly infrared emission) and radio emission from frequencies ranging from 150 MHz to 33 GHz. These analyses not only demonstrated the reliability of radio continuum emission in these bands but also led to new or updated conversion factors for calculating SFRs from radio flux measurements. Meanwhile, Volker Ossenkopf-Okada and Zhi-Yu Zhang both presented results on spectral line emission. Ossenkopf-Okada's study of the [OI] and [CII] fine structure lines from galactic star forming regions indicated that the lines are self-absorbed; the [OI] line is mostly unreliable as a star formation metric, while more careful modelling of the gas around PDRs are needed to use [CII] as such a metric. Zhang demonstrated that multiple molecular lines could be used in a novel way to calculate IMFs for high-redshift galaxies.
- **Comparisons of star formation tracers** – As in the prior session, many of the talks in this session focused upon the infrared-radio correlation. Jacinta Delhaize and David Molnar both illustrated how this relation varies as a function of redshift (although this seemed to be contradicted by the results from Lennox Cowie), Molnar also discussed how the relation differs between disc and spheroidal galaxies, and Jacqueline Monkiewicz discussed how the relation is affected by metallicity. Related to this, Matthijs van der Wiel discussed using LOFAR to identify protostellar objects within the Milky Way Galaxy and using these data to calibrate infrared emission as a star formation tracer. The other talks in this session compared SFRs from radio, millimetre, and submillimetre bands to SFRs from a broader range of other bands. George Bendo compared SFRs from ALMA observations of free-free and

recombination line emission from starbursts to SFRs from other bands and found some discrepancies with SFRs from both lower-frequency radio and infrared data. Miguel Pereira Santaella compared SFRs from millimetre ALMA observations of dust to SFRs from near-infrared recombination line data in ULIRGs and found that most SFRs were consistent with each other but that one specific object, ESO320-G030, where the millimetre-based SFR was anomalously high. Dillon Dong showed that the SFR from 33 GHz emission from nearby spiral galaxies correlated well with the SFR from the composite  $H\alpha + 24 \mu\text{m}$  metric. Hugo Messias performed comparisons of multiple star formation tracers observed from the gravitational lens H1429-0028. Finally, Lennox Cowie showed not only a correlation between infrared and radio emission but also suggested that X-ray emission could be used as a star formation tracer.

- **Spectral energy distribution analyses** – The goals of the talks in this session were to understand the relative contributions of synchrotron, free-free, and dust emission in the spectral energy distributions (SEDs) of galactic and extragalactic star forming regions as well as other galaxies. A few of the talks in this session focused mainly on the spectral indices of radio emission. Jonathan Westcott used measurements of the spectral indices within subregions of the dwarf galaxy NGC 1569 to argue that the free-free emission is relatively strong relative to the synchrotron emission, while Sean Linden used the spectral indices of 1.4-33 GHz observations to show differences in the ratio of free-free to synchrotron emission between nuclear and extranuclear regions in spiral galaxies and LIRGs. Naím Ramírez-Olivencia discussed identifying the AGN, its outflow, and star forming regions within the ULIRG Arp 299 using spectral index measurements as well as long baseline radio observations. Alasdair Thomson described how the radio spectral slope of submillimetre galaxies is very steep, suggesting cosmic ray aging effects. A couple of the other talks focused more on modelling the dust emission. Ciro Pappalardo showed how to use radiative transfer models to describe the ultraviolet-to-submillimetre SED of galaxies in deep-field observations so as to connect the dust emission to star formation, and Theresa Falkendal used SED models to separate synchrotron and dust emission in high-redshift radio galaxies so as to use the dust emission to measure SFRs. In other SED analyses, Anna Kapinska discussed the shape of the low-frequency SED of Sculptor Group galaxies observed by LOFAR, and Frederick Poidevin showed how anomalous microwave emission could affect the SEDs of star forming regions.
- **Disentangling emission from AGN and star formation** – Although a few talks in the previous sections had already mentioned this topic, it was a major focus of all of the talks here. Allison Kirkpatrick had built up an SED library focused on separating emission from these two sources in the infrared and submillimetre bands. In radio bands, while Rubén Herrero-Illana and Antxon Alberdi Odriozola showed how long baseline radio observations could be used for separating the emission from AGN and star forming regions. At the end of the session, Sarah White showed how the radio quiet quasars lied off the infrared-radio relation and argued that the radio emission was dominated by AGN emission.
- **The relation of molecular gas to dust and star formation** – While most of the meeting focused on improving ways to measure star formation, the talks in this session focused more on the relation between SFR and molecular gas. Chelsea Sharon explored this relation in a  $z \sim 2$  gravitationally-lensed galaxy and showed that the Kennicutt-Schmidt relation for regions within this galaxy was affected by the CO line transition and star formation tracers that were used. Kevin Harrington used CO observations of multiple gravitational lenses to examine both the CO spectral line energy distributions and to measure star formation efficiencies. Finally, Basilio Solís-Castillo showed a strong relation between mid-infrared emission from polycyclic aromatic hydrocarbons and both far-infrared dust emission and CO emission in nearby spiral galaxies.

Overall, this meeting was an excellent opportunity for researchers in the RadioNet community, particularly young researchers, to present their science results, to learn about results from other researchers, and to network with other people working on the radio, millimetre, and submillimetre astronomy.

## 2. AGENDA OF THE EVENT

See the Appendix 1. Daria Guidetti's and Lichen Liang's talks were cancelled; see below for details.



#### **4. RADIO NET FINANCIAL CONTRIBUTION**

The RadioNet funding was used to support the travel of five students: Dillon Dong, Sarah Leslie, Sean Linden, David Molnar, and Basiolio Solis-Castillo. All five students gave talks during the meeting. Each student was awarded €200. Three of these students were from the European Union (Germany and UK), and the other two were from the United States. The division between genders was 4 male and 1 female.

Note that Daria Guidetti could not attend the meeting because of a personal scheduling conflict and that Lichen Liang could not attend because of problems with obtaining a visa. Martin Hardcastle substituted for Gulay Gurkan Uygun, who was unable to attend because she was in the process of applying for a visa for an unrelated trip.



## **APPENDIX 1 - Agenda**

## Monday, 24 July (morning)

Time	Session	Speaker	Title
09:30-09:50	Introduction	George Bendo Jodrell Bank Centre for Astrophysics United Kingdom	
09:50-10:10	Measuring star formation in the nearby universe	Miguel Perez-Torres IAA-CSIC Spain	Measuring the SFR in LIRGs via direct detection of SNe and SNRs
10:10-10:30		Kouichiro Nakanishi NAOJ Japan	Dense ionized gas embedded with infant massive stellar clusters in the NGC 253 nuclear starburst
10:30-11:00	Coffee		
11:00-11:20		Loreto Barcos-Munoz Joint ALMA Observatory / NRAO Chile	Using 33 GHz continuum emission to trace star formation in local U/LIRGs
11:20-11:40	Star formation surveys of the moderate-z and high-z universe	Tom Muxlow Jodrell Bank Centre for Astrophysics United Kingdom	Initial results from the e-MERGE Study of Galaxy Evolution in the microJansky Radio Source Population
11:40-12:00		Sarah Leslie Max Planck Institute for Astronomy Germany	The specific star formation rate of galaxies out to $z < 5$ with 3GHz continuum emission
12:00-12:20		Sarah Higdon Georgia Southern University USA	The Jansky Very Large Array Survey of the hi-z ZEUS INvestigated Galaxies Reference Sample (ZINGRS)

## Monday, 24 July (afternoon)

Time	Session	Speaker	Title
13:40-14:00	Star formation surveys of the moderate-z and high-z universe (continued)	Eric Faustino Jiminez-Andrade University of Bonn Germany	Radio continuum size evolution of star forming galaxies in the COSMOS field
14:00-14:20		Hannah Stacey ASTRON Netherlands	Gravitational lensing reveals extreme dust-obscured star formation in quasar host galaxies
14:20-14:40		Steven Duivenvoorden University of Sussex United Kingdom	Red, redder, reddest: SCUBA-2 imaging of colour-selected Herschel sources
14:40-15:00	Calibrating star formation tracers	Fatemeh Tabatabaei IAC Spain	Mid-radio star formation calibration in galaxies
15:00-15:30	Coffee		
15:30-15:50		Luke Hindson University of Hertfordshire United Kingdom	The resolved radio continuum vs. star formation rate in nearby dwarf galaxies
15:50-16:10		Martin Hardcastle University of Hertfordshire United Kingdom	LOFAR/H-ATLAS: The low-frequency radio luminosity - star-formation rate relation
16:10-16:30		Volker Ossenkopf-Okada Universitat zu Koln Germany	[CII] and [OI] as star-formation tracers?
16:30-17:30	Discussion: Future observatory capabilities and needs		



## Tuesday, 25 July (morning)

Time	Session	Speaker	Title
09:10-09:30	Calibrating star formation tracers (continued)	Zhi-Yu Zhang University of Edinburgh United Kingdom	ALMA as a sensitive IMF probe in galaxies: opening a new frontier
09:30-09:50	Comparisons of star formation tracers	Jacinta Delhaize University of Zagreb Croatia	The behaviour of the infrared-radio correlation over $0 < z < 6$ and its use as a star-formation rate calibrator
09:50-10:10		Daniel Molnar University of Sussex United Kingdom	The infrared-radio correlation of spheroid- and disk-dominated star-forming galaxies to $z \sim 1.5$ in the COSMOS field
10:10-10:30		Jacqueline Monkiewicz Arizona State University USA	JVLA continuum observations of the Sextans A dwarf and the low-luminosity end of the radio/far-IR relation
10:30-11:00	Coffee		
11:00-11:20		Matthijs van der Wiel ASTRON Netherlands	Resolved protostellar populations: far-infrared versus radio
11:20-11:40		George Bendo Jodrell Bank Centre for Astrophysics United Kingdom	ALMA observations of recombination Line and free-free emission from nearby starbursts
11:40-12:00		Miguel Pereira Santaella University of Oxford United Kingdom	Multi-wavelength star-formation tracers in dusty galaxies
12:00-12:20		Dillon Dong Caltech UJSA	A comparison of high frequency radio, H alpha and 24 micron emission from resolved star forming regions in SINGS galaxies

## Tuesday, 25 July (afternoon)

Time	Session	Speaker	Title
13:40-14:00	Comparisons of star formation tracers (continued)	Hugo Messias Joint ALMA Observatory Chile	Assessing the star formation activity in the lensed merging system H1429-0028
14:00-14:20		Lennox Cowie University of Hawaii USA	FIR, UV, radio and X-ray star-formation rates in the GOODS-fields
14:20-14:40	Spectral energy distribution analyses	Jonathan Westcott University of Hertfordshire United Kingdom	Non-thermal and thermal radio continuum as tracers for star formation in NGC 1569
14:40-15:00		Naim Ramirez-Olivencia IAA-CSIC Spain	Sub-arcsecond LOFAR imaging of the nearby LIRG Arp 299
15:00-15:30	Coffee		
15:30-15:50		Anna Kapinska The University of Western Australia Australia	Star formation and physical processes in Sculptor Group galaxies at MHz radio frequencies
15:50-16:10		Sean Linden University of Virginia USA	A multi-band VLA comparison of star formation in normal galaxies to Luminous Infrared Galaxies in the local universe
16:10-16:30		Alasdair Thomson Durham University United Kingdom	The complex multi-frequency radio properties of ALMA-identified $z>2$ starburst galaxies
16:30-17:30	Discussion: Next steps in observing and modelling		

## Wednesday, 26 July (morning)

Time	Session	Speaker	Title
09:10-09:30	Spectral energy distribution analyses (continued)	Frederick Poidevin IAC Spain	Anomalous microwave emission characterisation in the Taurus Molecular Cloud complex
09:30-09:50		Ciro Pappalardo Universidade de Lisboa Portugal	Scatter between dust emission and SFR in galaxies: clues from dust-stars interplay
09:50-10:10		Theresa Falkendal ESO Germany	Evidence for quenching in high redshift radio galaxies from multi-resolution radio-to-IR SED fitting
10:10-10:30	Disentangling emission from AGN and star formation	Allison Kirkpatrick Yale University USA	Accounting for AGN dust heating in IR based star formation rates
10:30-11:00	Coffee		
11:00-11:20		Ruben Herrero-Illana ESO-Chile Chile	Star formation and AGN activity in local LIRGs through multi-wavelength characterization
11:20-11:40		Antxon Alberdi Odriozola IAA-CSIC Spain	e-MERLIN imaging of LIRGI
11:40-12:00		Sarah White Curtin University Australia	Disentangling the radio emission from "radio-quiet" quasars
12:00-12:20		Daria Guidetti Istituto di Radioastronomia Italy	The faint radio source population in GOODS-N through eMERGE ultra-deep JVLA observations

## Wednesday, 26 July (afternoon)

Time	Session	Speaker	Title
13:40-14:00	The relation of molecular gas to dust and star formation	Chelsea Sharon McMaster University Canada	The effects of star formation and gas tracers on the spatially resolved Schmidt-Kennicutt relation in a lensed $z \sim 2$ disk galaxy
14:00-14:20		Kevin Harrington University of Bonn Germany	Using CO as a physical probe of the SF supply in the extremely IR-luminous Planck-LMT identified sources
14:20-14:40		Basilio Solis-Castillo University of Bonn Germany	Exploring the relations between dust and molecular gas in nearby galaxies
14:40-15:00		Lichen Liang University of Zurich Switzerland	The dust and far-infrared properties of the cosmic noon galaxies
15:00-15:30	Coffee		
15:30-16:30	Discussion and summary		