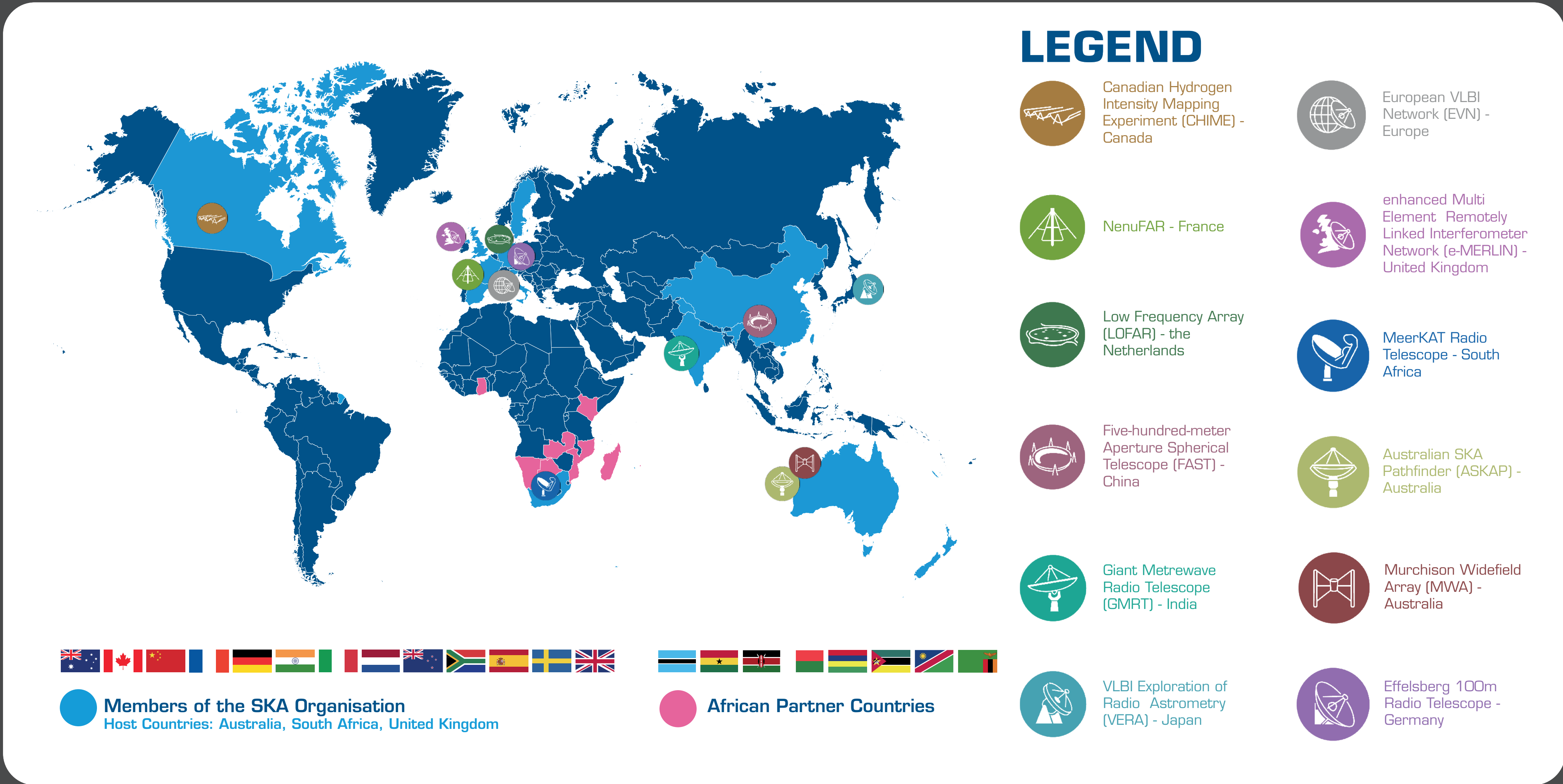
SKA
SQUARE KILOMETRE ARRAY

Calendar 2020

The Pathfinder View of the Sky



In the lead up to the SKA, many new groundbreaking radio astronomy facilities have sprung up around the world in the past 10 years. These facilities are part of a global effort to design and build ever-more sensitive instruments to detect some of the faintest signals in the universe and grow new scientific and technical communities while benefiting society through cutting-edge R&D.

These pathfinders are allowing astronomers to develop improved techniques and explore new phenomena like the elusive Fast Radio Bursts. They're also allowing engineers to develop new technical solutions like aperture arrays or Phased Array Feeds. In so doing, they are paving the way for the world's largest radio telescope, the SKA.

These facilities are now open to the community or going through commissioning, and already they are providing incredible insights into the radio sky. Insights that the SKA will be able to build on to transform our view of the universe.

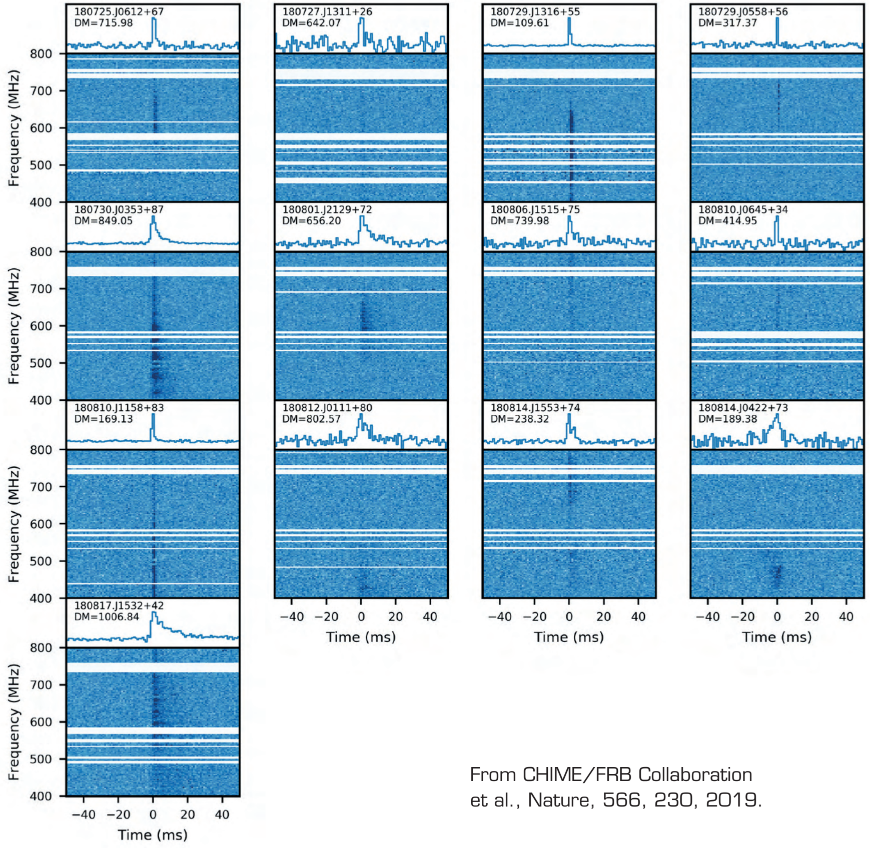
The 2020 SKA calendar, called The Pathfinder View of the Sky and featuring a small selection of the results already coming out of 12 of these telescopes, is our tribute to the pathfinder family as a whole, the people who have built them and the people who are using them. The knowledge and experience they've accumulated will guide us through construction and operation, and will be at the heart of a productive and groundbreaking use of the SKA telescopes in the years to come.

Canadian Hydrogen Intensity Mapping Experiment (CHIME)

The Canadian Hydrogen Intensity Mapping Experiment (CHIME) Fast Radio Burst Project (CHIME/FRB) uses the 80m x 100m CHIME radio telescope, located at the Dominion Radio Astrophysical Observatory in Penticton, British Columbia, Canada, to detect Fast Radio Bursts (FRBs) in real time. Fast Radio Bursts consist of millisecond bursts of radio waves coming from cosmological distances and arriving at Earth at least 1000 times per day across the full sky. Their origin is unknown.

CHIME is a powerful FRB detection machine thanks to its large > 200 sq. deg field of view, large collecting area, wide 400-800 MHz bandwidth, and a powerful FX-style correlator and FRB search engine. It began detecting Fast Radio Bursts in 2019, demonstrating the FRB phenomenon extends down to frequencies as low as 400 MHz. CHIME/FRB reported a second repeating FRB in early 2019, and by the summer had reported an additional 8 repeaters, thus identifying a new population of objects. This was followed by more such detections later in the year. These new repeaters provide opportunities for the worldwide community to commence follow-up observations in the hope of localising some of these sources interferometrically, and subsequently identifying host galaxies and determining redshifts. In 2020, the CHIME/FRB collaboration will be working toward characterising and making public the hundreds of FRBs they have detected, and, together with the astrophysical community, digesting what the data tells us about the origin of FRBs.

The image shows a selection of FRBs observed by CHIME. A key distinguishing factor is that for many of these FRBs the signal is strong at 400 MHz, the bottom of the telescope's frequency range, suggesting that SKA-Low, operating up to 350 MHz, will be a powerful FRB hunter too. Before CHIME all FRBs were found at much higher frequencies.



From CHIME/FRB Collaboration et al., Nature, 566, 230, 2019.

JANUARY

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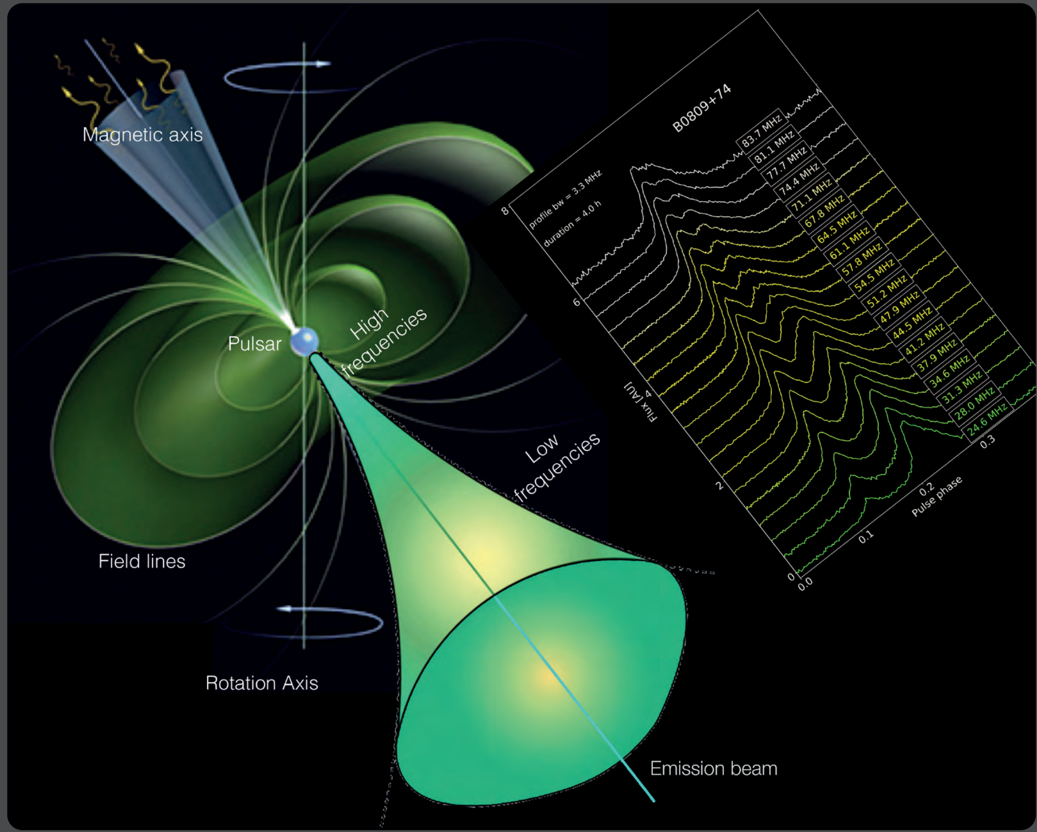
NenuFAR

NenuFAR (New Extension in Nançay Upgrading loFAR) is a SKA pathfinder developed and built in Nançay, France. It is a large antenna array (more than 1,200 presently) designed to observe the largely unexplored frequency window from 10 to 85 MHz with a high sensitivity all across the band. Its science programme started in July 2019.

One of NenuFAR's main scientific objectives is the study of pulsars - these are remnants of a star between 8 and 20 solar masses after the supernova at the end of its stellar evolution. Too light to become a black hole and too heavy to become a white dwarf, the residual object of the supernova is a pulsar. These typically weigh around 1.4 solar masses for between 25 and 30km of diameter (a density equivalent to putting Earth's entire human population inside a thimble).

Pulsars emit extremely regular pulses that can be detected from the ground as a radio beacon. The shape of the pulsation is a unique signature characterising the pulsar magnetosphere. Observing pulsars at low frequency allows us to explore a large fraction of this magnetosphere. The diagram on the right shows that the shape of the pulsation of pulsar B0809+74 varies throughout the frequency band. This extreme variation of the shape of the pulsation between the top and the bottom of the band makes it possible to better characterise the magnetosphere and the mechanisms related to the emission.

Doing so gives us a much clearer view of how pulsars work. NenuFAR's wide bandwidth allows us to study the geometry of the magnetosphere by establishing where emission is coming from at different heights above the neutron star surface. While pulsar rotations themselves are stable, we use the radio light as a means to measure their clock-like rotation. The emission itself can be erratic, and without a wide observing bandwidth our view of the connection between emission and rotation can be hazy and uncertain. Better understanding the magnetosphere therefore means we can more accurately measure these rotations, and use each spin of the star like the tick of a cosmic clock. NenuFAR is paving the way for SKA-Low, which should provide a complete census of pulsars in the Milky Way, and their emission behaviour across a wide observing band.



Pulsar artist impression. Credit: Mark A. Garlick (space-art.co.uk). B 0809+74 diagram. Credit: L. Bondonneau, 2019

FEBRUARY

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Low Frequency Array (LOFAR)

LOFAR's network of radio antennas spans seven countries across Europe, with its heart in the Netherlands. Operated by ASTRON, LOFAR is unique in its capabilities to map the sky in fine detail at metre wavelengths, and is considered to be the world's leading telescope of its type.

LOFAR is conducting a major sky survey at unprecedented sensitivity, involving more than 200 astronomers from 18 countries. The results of the survey's first phase made the news in 2019, revealing hundreds of thousands of previously undetected galaxies, shedding new light on many research areas including the physics of black holes and how clusters of galaxies evolve.

Image 1 & 2: LOFAR's observations have included the spiral galaxy M51 in the HETDEX region (image 1) and galaxy cluster Abell 1314 (image 2), located in Ursa Major at a distance of approximately 460 million light years from Earth. This image combines the radio emission detected by LOFAR (in red and pink) with the X-ray emission detected by the Chandra telescope (in grey) overlaid on an optical image.

Image 3: Among the many international researchers using LOFAR, an INAF team used the telescope to observe a radio ridge connecting two galaxy clusters in a filament of the cosmic web.

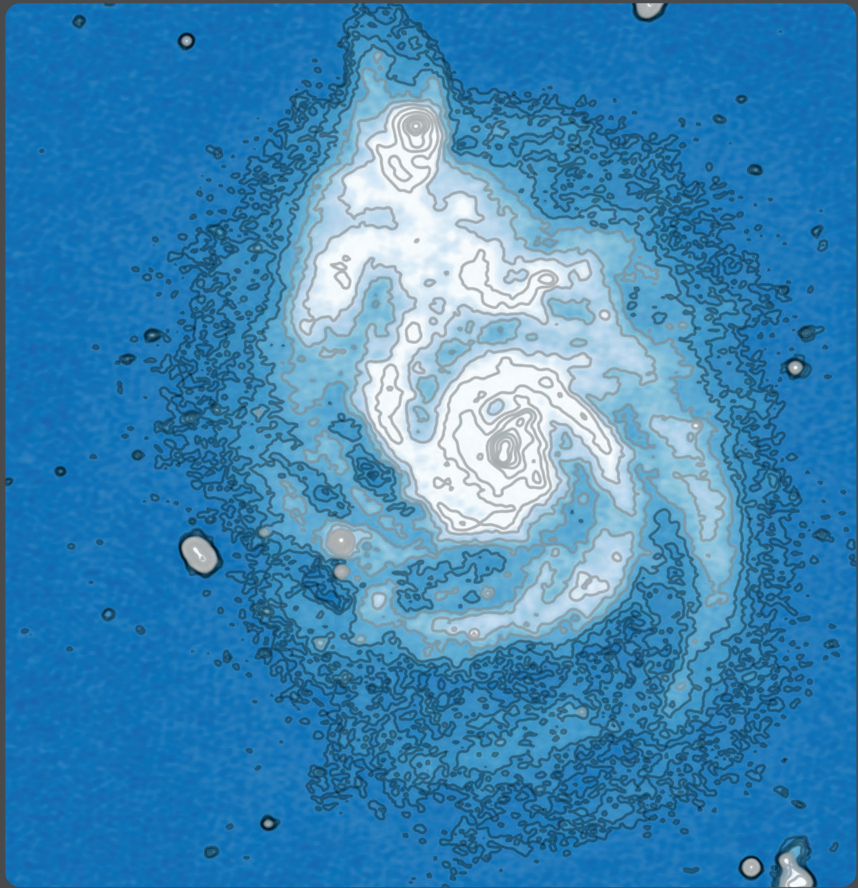

Image 1. M51 in the HETDEX region. Credit: Tim Shimwell and the LOFAR surveys team.

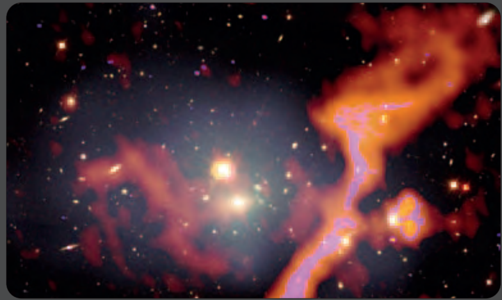

Image 2. Galaxy cluster Abell 1314, radio emission (LOFAR) in red and pink, X-ray emission (Chandra telescope) in gray, overlaid on an optical image. Credit: Amanda Wilber/LOFAR Surveys Team

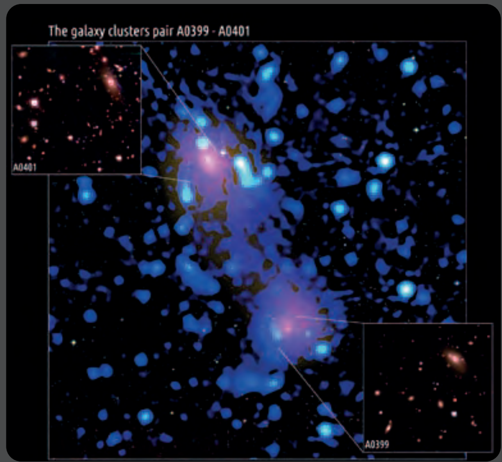

Image 3. Credit: F. Govoni et al. 2019, Science. Optical: DSS and PAN-STARRS1 (insets) – Red, X-rays: XMM-Newton – Yellow, y-parameter: PLANCK satellite – Blue, radio 140 MHz: LOFAR. Image credits: M.Murgia (INAF)

MARCH

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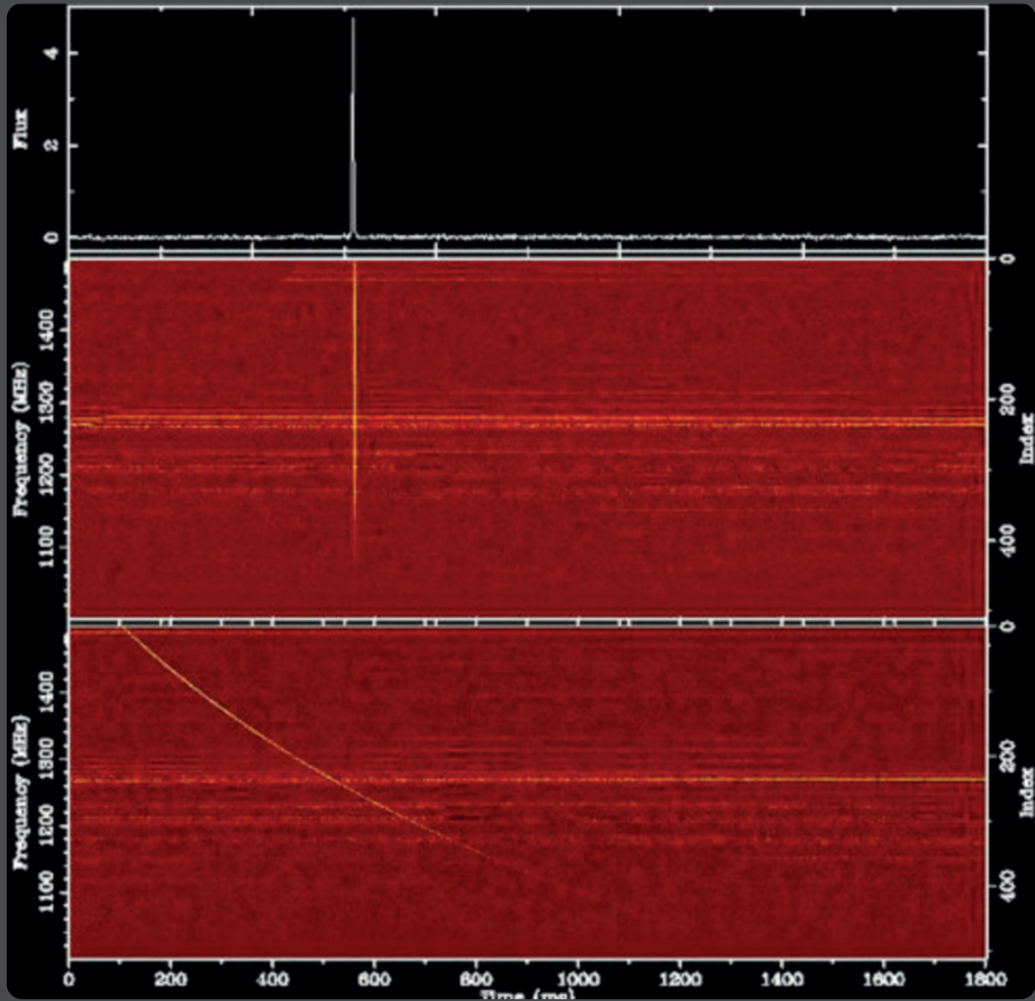
Five-hundred-meter Aperture Spherical Telescope (FAST)

The Five-hundred-meter Aperture Spherical radio Telescope (FAST), known as 'China Sky Eye', is the world's largest, most sensitive single-dish radio telescope, covering the frequency range 70 MHz to 3 GHz.

Construction started in 2011 and came to an end on 25th September 2016, with a successful first light. With commissioning complete, FAST is now ready for use by the astronomical community.

FAST's key science cases include: surveying of neutral hydrogen in the Universe; searching for pulsars; leading the VLBI network in low frequencies; detecting interstellar molecules; SETI (Search for Extra Terrestrial Intelligence).

Since the beginning of commissioning in 2017, FAST has conducted observations on early scientific objectives. The first scientific results were published in May 2019. To date, FAST has detected more than 150 high-quality pulsar candidates, over 100 confirmed. Some are among the weakest radio pulsars ever detected, fully demonstrating the high sensitivity of FAST. In August 2019, FAST detected repeating bursts of Fast Radio Burst (FRB) 121102 (image on the right), and has so far accumulated the largest number of pulses for this important source.



FAST FRB 121102. Credit: NAOC

APRIL

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Giant Metrewave Radio Telescope (GMRT)

The Giant Metrewave Radio Telescope is the largest steerable radio telescope array in the world at metre wavelengths, with its thirty 45m dishes spread over a 25 km baseline. Operated by NCRA-TIFR, it is a very versatile instrument for investigating a variety of radio astrophysical problems ranging from the nearby Solar System to the edge of the observable Universe. Astronomers from all over the world have used it to produce many exciting new results since its commissioning in 2002.

A major upgrade in 2018 saw a range of improvements, including near seamless frequency coverage from 50 to 1500 MHz, more sensitive receivers and 10 times larger instantaneous bandwidth (400 MHz). This upgrade will keep the observatory on the forefront at the international level for many more years to come.

The upgraded GMRT (uGMRT) has enabled a wave of exciting new science results, a sample of which are shown here.

Image 1 is from the exciting new field of magnetic stars; it shows the uGMRT detection of radio emission from such a star, inferred to be arising from Electron Cyclotron Maser mechanism, until recently regarded to be a rare phenomenon. Image 2 shows the uGMRT detection of a "dead radio galaxy", rejuvenated due to interactions in a large galaxy cluster (A4038). Image 3 shows the emission from distant radio galaxies, obtained by stacking signals from hundreds of galaxies, with the uGMRT. This work has led to the most distant detection of neutral hydrogen in the Universe.

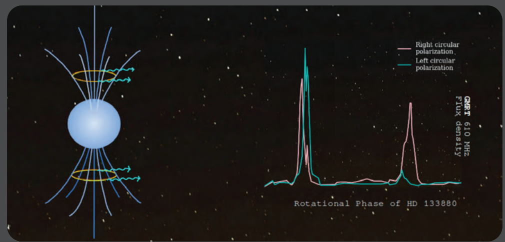

Image 1. Cartoon picture of magnetic star and detection of strong circularly polarised radio signals (right) Credit: B. Das, P. Chandra, G. Wade

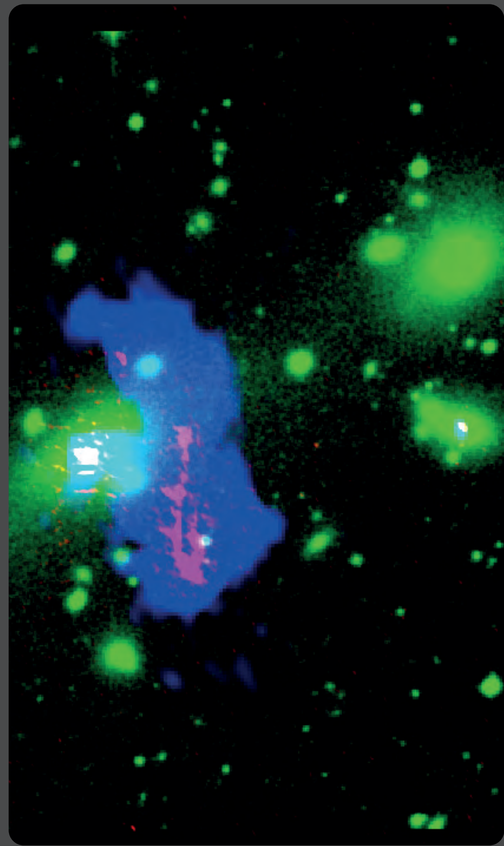

Image 2. Radio image (blue and purple) of radio relic in cluster Abell 4038, overlayed on an optical image (in green). Credit: R.Kale, V.Parekh, K.Dwarkanath

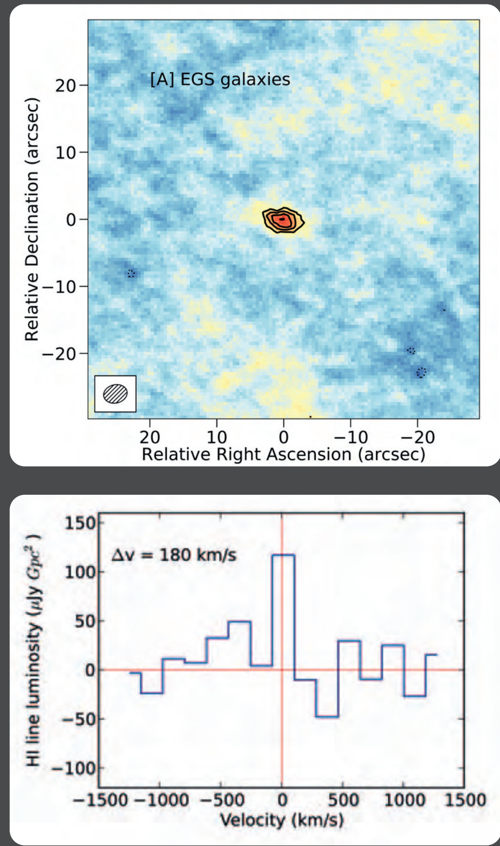

Image 3.The stacked radio continuum image (top) and the stacked spectrum (bottom) showing detection of H1 from galaxies at z ~0.34. Credit: A.Bera, N.Kanekar, J. Chengalur, J.Bagla

MAY

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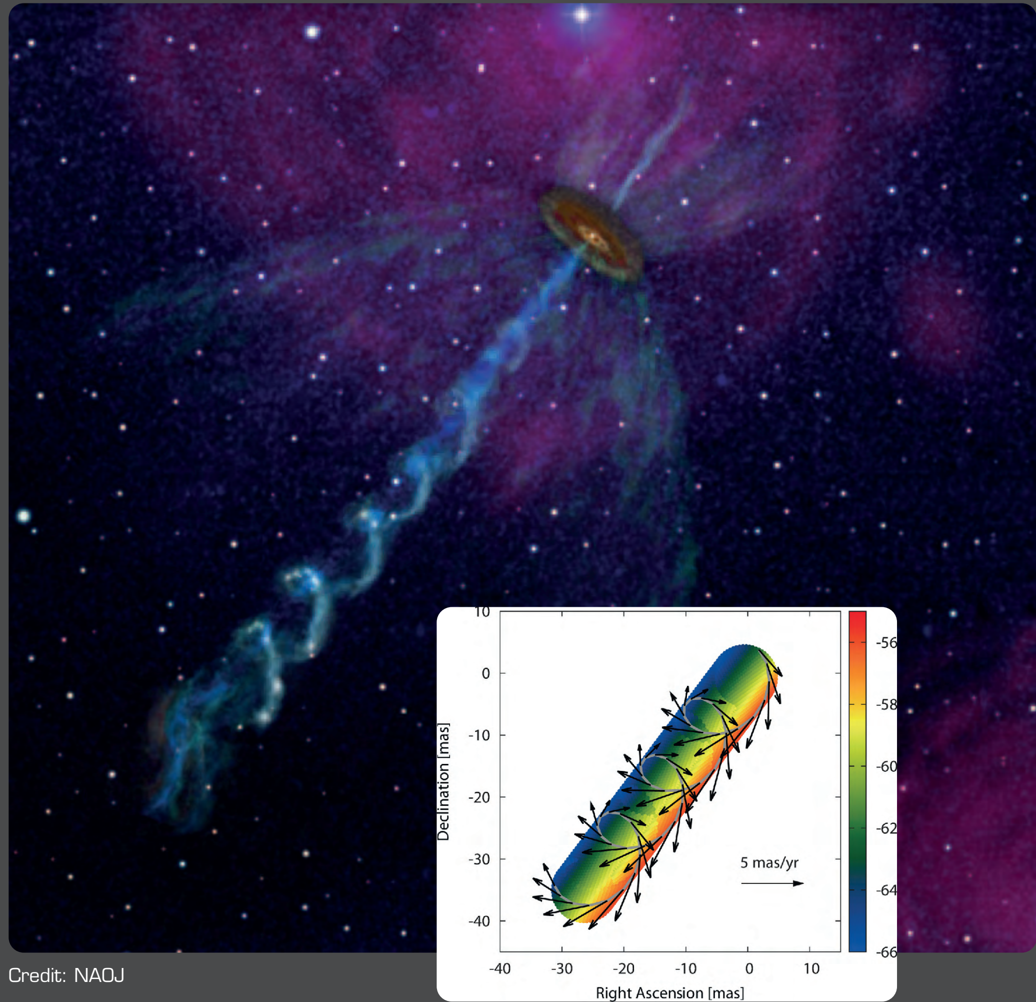
VLBI Exploration of Radio Astrometry (VERA)

The VLBI Exploration of Radio Astrometry (VERA) telescope comprises four 20m-diameter antennas spread across Japan. In operation since 2003, VERA uses Very Long Baseline Interferometry (VLBI) to explore the three-dimensional structure of the Milky Way.

Using VERA, astronomers observed an outflow of gas from a newborn star named S235AB, and found that radio spots show a helical motion. It's known as a "waterspout" because these radio spots are visible by the radio emission line of water molecules. The right image (artist impression) shows the position and motion of each spot, and the colour represents its radial velocity; redder spots are moving away, while bluer spots are coming towards us. The arrows attached to some spots show their motions on the sky. From these results astronomers understand these spots follow the single helical motion. This transports angular momentum away from the star.

Some stars, like the Mira variable stars, change in brightness. In 1912 an American astronomer, Henrietta Swan Leavitt, published her finding that some variable stars in the Small Magellanic Cloud show a relation between their brightness and variable period and their mean actual luminosity. Astronomers call it the "Period-Luminosity relation". It is a powerful tool both to estimate the distance to objects like galaxies and to understand more about variable stars themselves. But the relation for Mira variables in the Milky Way is not established. Using VERA, the distance to each variable can be measured based on its apparent motion on the sky and we can construct the Period-Luminosity relation for them. The current results show the Period-Luminosity relations for Mira variables in the Milky Way is consistent with that of other known types of variable stars in the Large Magellanic Cloud.



Credit: NAOJ

JUNE

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European VLBI Network (EVN)

The European VLBI Network (EVN) is an interferometric array of radio telescopes spread across Europe, and far beyond, that conducts unique, high resolution, radio astronomical observations of cosmic radio sources. It is the most sensitive VLBI array in the world, thanks to the collection of extremely large telescopes that contribute to the network. An SKA pathfinder in its own right, the EVN also includes several individual pathfinders: Arecibo in Puerto Rico, the Effelsberg 100m telescope in Germany, the Westerbork Synthesis Radio Telescope in the Netherlands and several of the UK's e-MERLIN telescopes.

Among the EVN's stations are two operated by INAF in Italy: Noto, in Sicily, and Medicina near Bologna. These telescopes contributed to the observation of an event depicted in this artist's impression (image 1). It shows a jet emerging from the dense material ejected by the merger of two neutron stars that produced the first gravitational wave signal with an electromagnetic counterpart, namely GW/GRB170817. The global VLBI observation, obtained with 33 radio telescopes distributed in five continents 207 days after the event, shows a compact radio source which best matches the simulation of a jet which successfully emerged from the dense material.

An international group of scientists led by Spanish researchers at the IAA-CSIC used the EVN, including the 40m antenna in Yebes, Spain, to observe one of the nuclear regions of the merging galaxy system Arp299 (image 2). The image is the result of stacking multiple EVN images at an observing wavelength of 6 cm, and shows a region of about 400 light years in radius. The small white blobs correspond to young supernovae and supernova remnants, adding up to almost 30 discovered, and imply a rate of star-formation 50 to 100 times larger than for our galaxy.

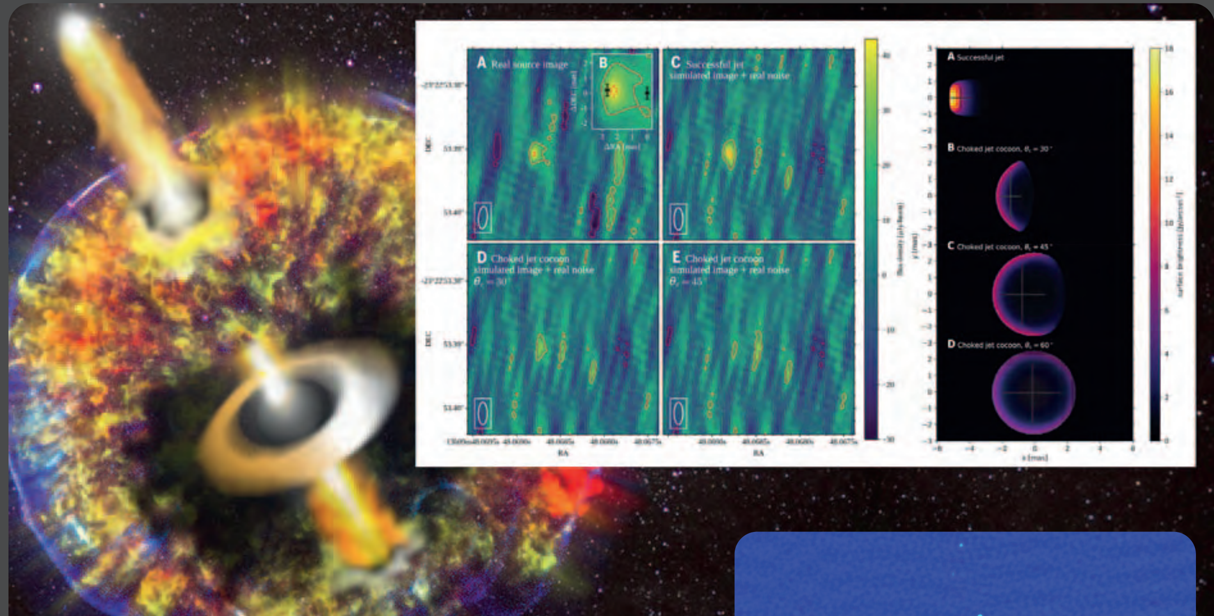

Image 1. Credits: Artist's impression by O. S. Salafia and G. Ghirlanda (based on NASA/CXC/GSFC/B.Williams et al., www.flickr.com/people/sagesolar/). Scientific images: Ghirlanda et al. 2019, "Compact radio emission indicates a structured jet was produced by a binary neutron star merger", Science, 363, 6430, 968.

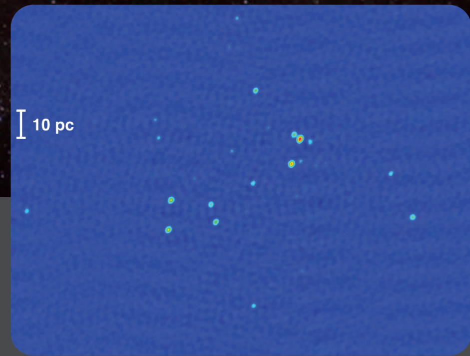

Image 2. Credits: Copyright: Miguel Pérez-Torres. Based on images published in Pérez-Torres et al. 2009 (Astronomy and Astrophysics, 507, L17) and Bondi, Pérez-Torres et al. 2012 (Astronomy and Astrophysics, 539, 134).

JULY

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enhanced Multi Element Remotely Linked Interferometer Network (e-MERLIN)

e-MERLIN consists of an array of seven radio telescopes including the iconic Lovell Telescope, and spans 220 km across the UK. With an angular resolution comparable to that of the Hubble Space Telescope, and carrying out centimetre wavelength radio astronomy with micro-Jansky sensitivities, e-MERLIN provides a unique facility to address a broad range of scientific questions. e-MERLIN is a National Facility operated by the University of Manchester at Jodrell Bank Observatory on behalf of the UK Research and Innovation's Science and Technology Facilities Council (STFC).

e-MERGE is an e-MERLIN Legacy deep survey to image thousands of faint radio sources in a region of the sky known as the GOODS-N field.

Led by the University of Manchester, University of Durham and University of Southampton and involving scientists from around eight countries, the survey will trace in detail the distribution of star-formation and active galactic nuclei (AGN) activity in galaxies out to a redshift of 3*. Characterising this micro-Jansky radio source population is a major science goal for deep SKA imaging.

Results from the survey have been overlaid with Hubble images, including (image 1) contours showing the radio emission across the face of a massive spheroidal galaxy at a redshift of 0.503 and (image 2) contours showing the radio emission from recent supernovae tracing current star formation activity from the dusty nuclei of merging galaxies at a redshift of 1.22.

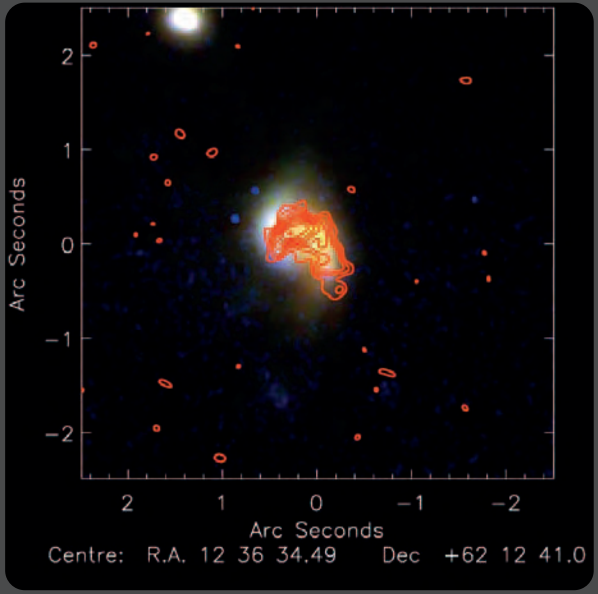

Image 1. Contours showing the radio emission from recent supernovae tracing current star formation activity from the dusty nuclei of merging galaxies at a redshift of 1.22, overlaid on an image taken with the Hubble Space Telescope. Credit: University of Manchester and the e-MERGE team.

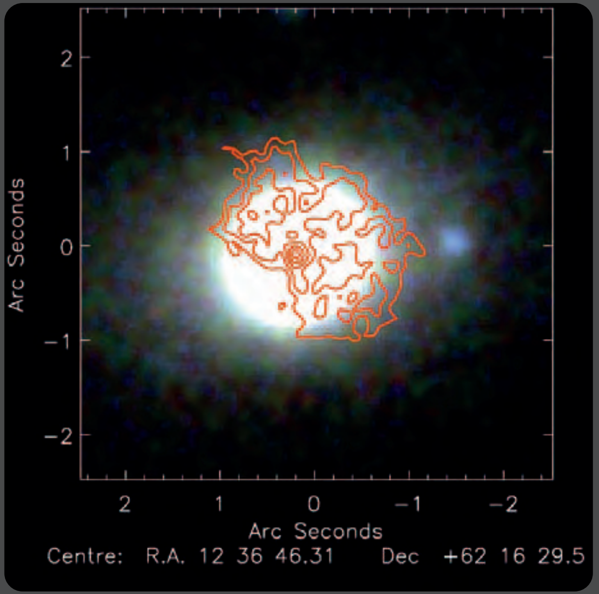

Image 2. Contours showing the radio emission across the face of a massive spheroidal galaxy at a redshift of 0.503, overlaid on an image taken with the Hubble Space Telescope.
Credit: University of Manchester and the e-MERGE team.

* The higher the redshift, the younger the age of the Universe at that point. A redshift of 3 means we're seeing objects from when the Universe was only 2.2bn years old. Redshift 0.5 is much more recent in the Universe's history, at an age of 8.6bn years.

AUGUST

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MeerKAT

South Africa's MeerKAT telescope, inaugurated in July 2018, has already broken new ground for radio astronomy, creating some of the most visually stunning images in the field. Operated by the South African Radio Astronomy Observatory, a facility of the National Research Foundation, it is the most powerful radio telescope of its kind.

MeerKAT observations have provided us with the clearest view yet of the central regions of our galaxy (image 1). At the distance of the galactic centre (located within the white area near image centre), this 2 degree by 1 degree panorama corresponds to an area of approximately 1,000 light-years by 500 light-years. This image shows a wealth of never before seen features, as well as a clearer view of previously known supernova remnants, star-forming regions, and radio filaments.

In another view of the central portions of the Milky Way galaxy (image 2), MeerKAT revealed radio bubbles extending vertically above and below the plane of the galaxy. Many magnetised filaments can be seen running parallel to the bubbles.

Researchers from INAF used MeerKAT to observe the galaxy Fornax A and its environment at 1.4 GHz (image 3). Orange shades represent synchrotron radiation from relativistic electrons, while blue shades represent radio emission from neutral hydrogen atoms. Among the most notable features are the giant synchrotron lobes of Fornax A, generated during a recent phase of activity of its central super-massive black hole.

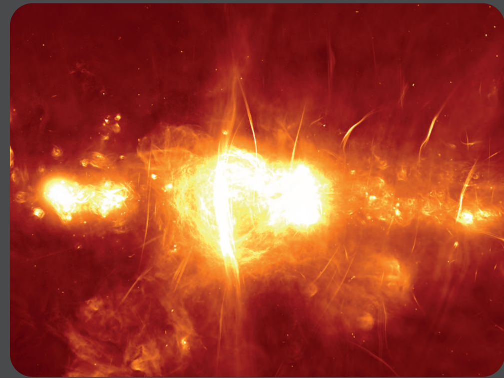

Image 1. MeerKAT Galactic centre of the Milky Way. Credit: SARAO (South African Radio Astronomy Observatory).

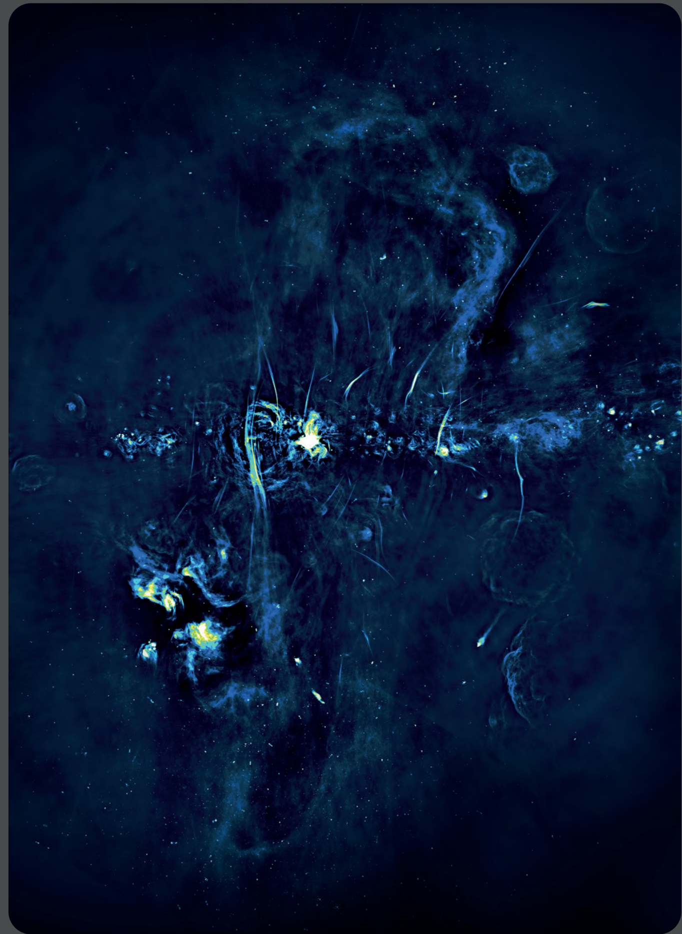

Image 2. (Adapted from results published in Heywood et al. 2019.). Credit: SARAO (South African Radio Astronomy Observatory)

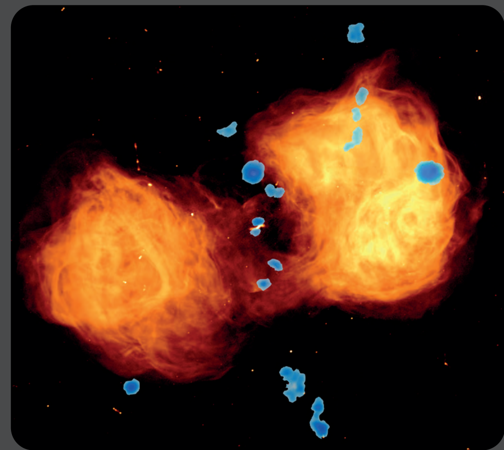

Image 3. Fornax (Serra et al. 2019, Maccagni et al. A&A, in press, arXiv:1911.09424)

SEPTEMBER

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Australian SKA Pathfinder (ASKAP)

CSIRO's Australian Square Kilometre Array Pathfinder (ASKAP) is a 36-dish radio telescope, located in Western Australia. Its cutting-edge technologies enable it to rapidly survey the sky at GHz frequencies. Ten large international science projects will use ASKAP's wide field-of-view and fast survey speed to explore the structure and evolution of the Universe.

Image 1 & 2: The CRAFT (Commensal Real-time ASKAP Fast Transients) project, an international collaboration led by CSIRO, ICRAR and Swinburne University, aims to detect and study Fast Radio Bursts (FRBs), millisecond flashes of radio waves. ASKAP detected FRB180924 within 0.5 seconds of the burst being received by the antennas and subsequently localised the burst with a precision of 0.1 arcseconds, placing it in the outskirts of a distant galaxy. FRB180924 is the first one-off FRB to ever be accurately localised. The galaxy was then imaged by three optical telescopes – Keck, Gemini South and ESO's Very Large Telescope (the VLT image is shown in image 2) – showing that the burst originated in a Milky Way-sized galaxy about 3.6 billion light-years away.

Image 3: Another ASKAP survey is DINGO (Deep Investigations of Neutral Gas Origins), led by scientists from ICRAR. DINGO aims to investigate the evolution of galaxies and the gas-rich Universe from up to 4.2 billion years ago. Here, early ASKAP observations for the DINGO project show the average HI content of 863 blue galaxies, co-added together using the location of optical galaxies.

Image 4: EMU (the Evolutionary Map of the Universe), a large international collaboration led by scientists from Western Sydney University and CSIRO, is the main ASKAP radio continuum survey that will survey the entire sky. EMU scientists from INAF produced this glimpse of the Galactic plane in the SCORPIO field, from ASKAP observations spanning its full 0.7-1.8GHz bandwidth.

Australia's national science agency, CSIRO, operates ASKAP at the Murchison Radio-astronomy Observatory and acknowledges the Wajarri Yamaji as the traditional owners of the site.

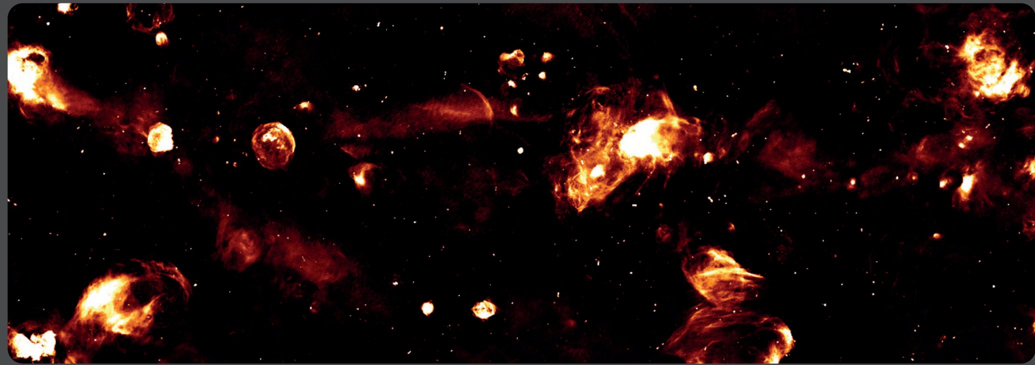

Image 4. Credit: The INAF SCORPIO team

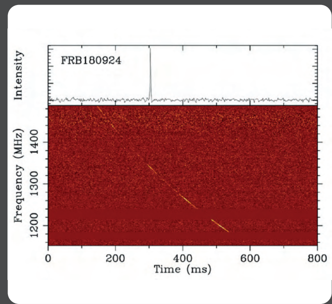

Image 1. Credit: Keith Bannister, CSIRO and the ASKAP CRAFT team

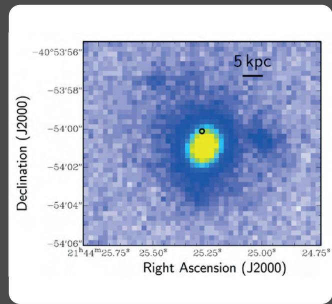

Image 2. False colour image of DES J514425.25-405400.81, the host galaxy of FRB 180924. This image was taken with the Very Large Telescope (VLT). FRB180924 came from somewhere inside the black circle, roughly 4 kiloparsecs from the center of the galaxy. Credit: VLT

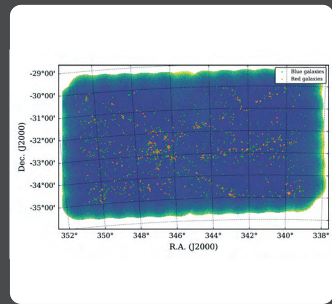

Image 3. Martin Meyer and Jonghwan Rhee DINGO HI stacking using ASKAP Credit: M.Meyer & J.Rhee (ICRAR)

OCTOBER

MON	TUE	WED	THUR	FRI	SAT	SUN	MON	TUE	WED	THUR	FRI	SAT	SUN
										01	02	03	04
05	06	07	08	09	10	11	12	13	14	15	16	17	18
19	20	21	22	23	24	25	26	27	28	29	30	31	

Murchison Widefield Array (MWA)

The Murchison Widefield Array (MWA), located at the Murchison Radio-astronomy Observatory in Western Australia, is one of the two SKA precursor instruments at the future SKA-Low site. Developed by an international collaboration, the telescope is maintained and remotely operated by a team at the Curtin Institute of Radio Astronomy.

MWA has a very wide field of view, high angular resolution, wide frequency range with flexible tuning, and extreme (digital) pointing agility. Since mid-2013, when it began scanning the Earth's southern skies, the project has supported a trove of scientific achievements, including the creation of a catalogue of 300,000 galaxies and the first radio-colour panorama of the Universe in the GLEAM all-sky survey. An ICRAR team used MWA to create this brand-new view of the Milky Way (image 1). The colours from red to blue cover 72 - 231 MHz, which will also be observed by SKA-Low; the images reveal cosmic magnetic fields and the remains of exploded stars.

ICRAR scientists have also been using the MWA to look 12.5 billion years back in time to discover the Epoch of Reionisation (image 2 & 3). Time and time again, they have reduced the upper limit for detection of the EoR signal, leading us closer to discovering the first stars in the Universe.

Indian scientists using MWA have detected very faint radio emission from the Sun coming from the plasma expelled during explosive events (image 4). This is an important step towards our ability to understand and eventually predict space weather, which can have an enormous societal impact.

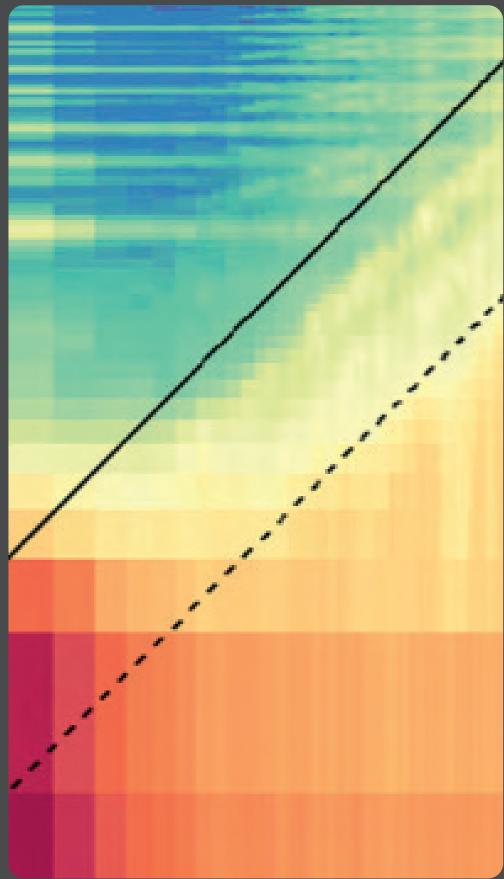

Image 2. Credit: A/Prof C.Trott (ICRAR)

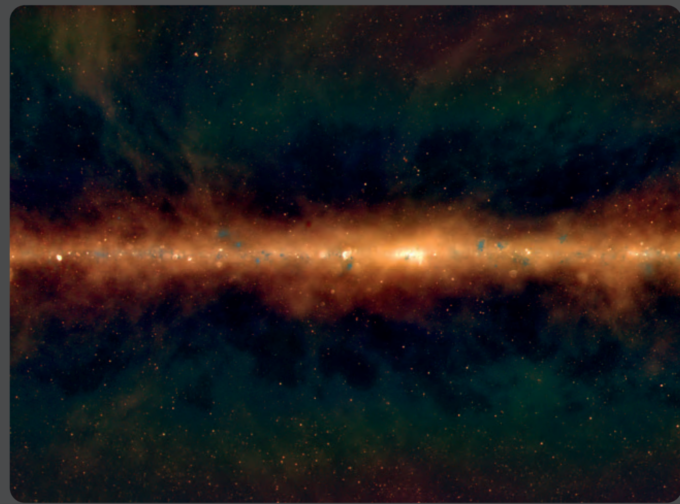

Image 1. Credit: Dr N.Hurley-Walker (ICRAR)

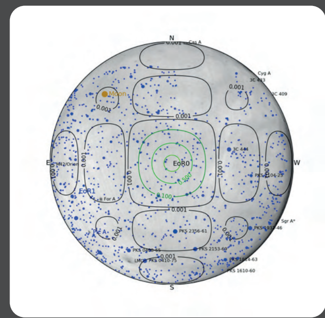

Image 3. Credit: A/Prof C.Trott (ICRAR)

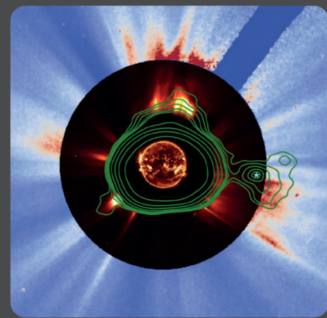

Image 4. Green radio contours superposed on white light images of electron density in the corona, with an EUV image of the Sun at the centre. Credit: D. Kansabanik, S. Mondal and D.Oberoi

NOVEMBER

MON	TUE	WED	THUR	FRI	SAT	SUN	MON	TUE	WED	THUR	FRI	SAT	SUN
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09	10	11	12	13	14	15	16	17	18	19	20	21	22
23	24	25	26	27	28	29	30						

Effelsberg 100m Radio Telescope

Effelsberg's 100m diameter makes it one of the largest fully steerable radio telescopes on Earth. It has been continually upgraded since starting operations in 1972, with a new collecting surface for the antenna-dish, better reception of high-quality data and extremely low noise electronics, all of which makes it one of the most advanced modern telescopes worldwide.

The telescope, operated by Germany's Max Planck Institute for Radio Astronomy, observes pulsars, cold gas- and dust clusters, the sites of star formation, jets of matter emitted by black holes and the nuclei of distant far-off galaxies, and also radio emission and magnetic fields in our Milky Way and nearby galaxies. Effelsberg is also an important part of the European VLBI Network (EVN) of radio telescopes.

The magnetic field structure of galaxy NGC 628 (image 1) is based on radio observations with both the Effelsberg telescope and the Jansky Very Large Array (JVLA) in the United States, superposed onto an optical image of the galaxy. Effelsberg alone created the radio image of the Andromeda galaxy M321 (image 2), a false-colour radio map of that galaxy at 6cm wavelength.

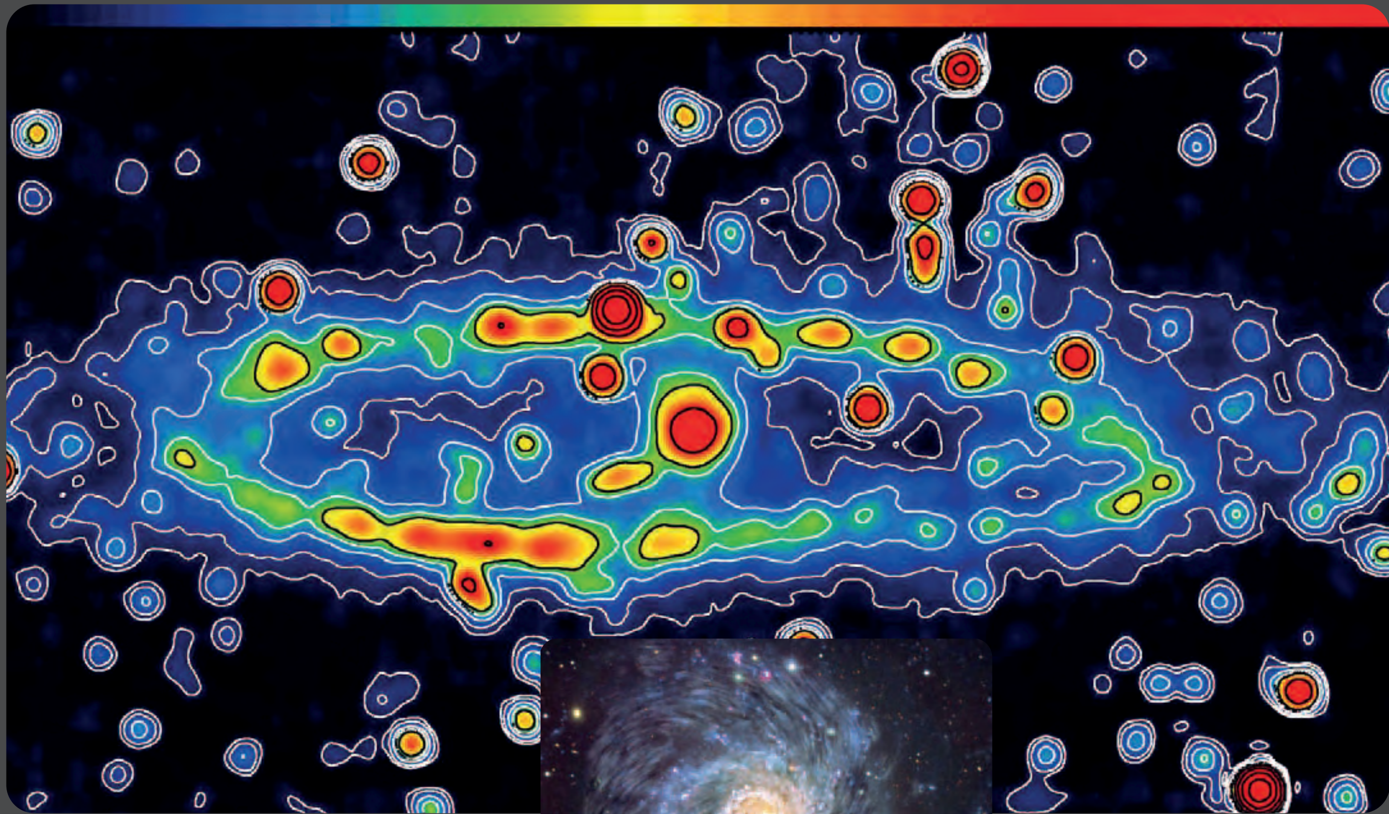

Image 2. Radio image of the Andromeda Galaxy M321. Credit: Rainer Beck, MPIfR

Image 1. The magnetic field structure of galaxy NGC 628 superposed onto an optical image of the galaxy.
Credit: Steve Mazlin and Vincent Peris (at Calar Alto observatory)

DECEMBER

MON	TUE	WED	THUR	FRI	SAT	SUN	MON	TUE	WED	THUR	FRI	SAT	SUN
								01	02	03	04	05	06
07	08	09	10	11	12	13	14	15	16	17	18	19	20
21	22	23	24	25	26	27	28	29	30	31			