CAASTRO
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FOR ALL-SKY ASTROPHYSICS

Reader's Digest

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Publication stories about current CAASTRO research

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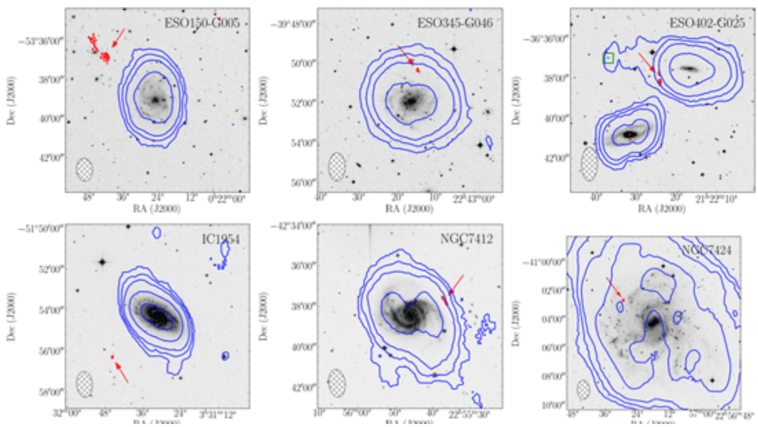
Pilot study data prepare astronomers for future blind HI surveys

Next-generation radio telescopes will make it possible to conduct the first large-scale HI absorption-line surveys, which will enable us to study the evolution of neutral gas in galaxies over a large range of cosmic time. However, we don't currently have the understanding to derive physical galaxy properties from absorption-line data alone.

To gain this understanding, we need to start by knowing the expected detection rate of intervening HI absorption. Previous studies have suggested that the detection rate is around 50% for sightlines bypassing the galaxy at distances of 20 kpc or less. However, these studies have typically targeted sightlines to quasars which provide very bright, compact radio sources ideal for detecting HI absorption against. Since only around 10% of all radio sources are quasars, it is therefore possible that such studies will have over-estimated the detection rate, compared to what future blind surveys might expect to find.



In a new study, CAASTRO researcher Sarah Reeves (University of Sydney) and colleagues have investigated the detection rate of intervening absorption in an unbiased sample of radio sources. Importantly, they also obtained HI emission-line data, allowing them to map the distribution of HI gas in the target galaxies. This means that where they did not detect an absorption-line, they were able to pin-point the reason for the non-detection, i.e. whether the lack of absorption was due to the sightline not intersecting the HI disk of the galaxy or due to the properties of the background radio source (e.g. too dim) – or some other reason.

This publication presents observations and results from the pilot sample (six of an eventual 16 sources). In this pilot sample, no intervening absorption-lines were detected. While observations for the full sample are required to better establish the detection rate, this preliminary result suggests that the detection rate is considerably lower than estimated by previous studies – perhaps around 5-10%. The team found that most of their sightlines did intersect the HI disk of the target galaxies, meaning that the low detection rate must be due to properties of the background sources. They found that many of the background sources resolved into multiple components at higher resolution, lowering the flux and reducing the absorption-line sensitivity. These results show that source type and structure can significantly affect the detection rate of absorption-line surveys, and help astronomers to better prepare for future large surveys, such as FLASH ("The First Large Absorption Survey in HI").

Publication details:

Sarah Reeves, Elaine Sadler, James Allison et al. in the Monthly Notices of the Royal Astronomical Society (2015) "*HI emission and absorption in nearby, gas-rich galaxies*"

Escaping photons affect galaxy formation but supernovae dominant

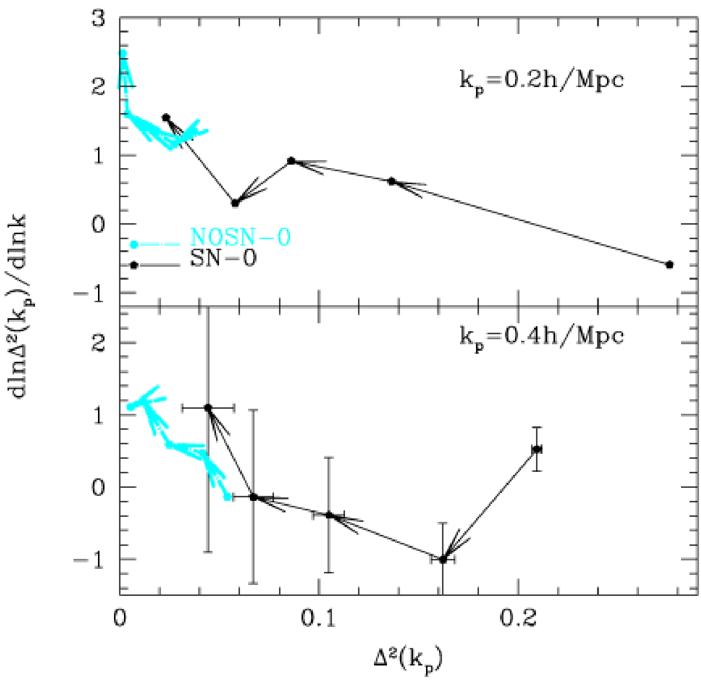
The new generation of low-frequency radio telescopes, including MWA (Murchison Widefield Array), LOFAR (LOw Frequency Array), PAPER (Precision Array for Probing the Epoch of Reionisation) and SKA (Square Kilometre array), will enable us to observe the evolution of neutral hydrogen during the reionisation of the Universe. The resulting measurements of the timing and structure of reionisation promise to probe the properties of the first galaxies.

In recent years though – while gearing up to using these new instruments – a great deal of attention has focused on theoretical modelling the effect of galaxies on the reionisation of the intergalactic medium (IGM). Large modern simulations commonly begin with an N-body simulation to generate a distribution of dark matter haloes, followed by relating dark matter halo mass to ionising luminosity. Radiative transfer methods (usually ray-tracing algorithms) then model the generation of ionised structure on large scales which is often run with lower resolution than the N-body code for computational efficiency.

One of main limitations in modelling of reionisation is the physics of the ionising sources. In their 2013 publication, however, CAASTRO Affiliate Dr Hansik Kim and his colleagues at the Universities of Melbourne and Durham overcame this limitation. They combined the semi-analytic galaxy formation model, as implemented in the Millennium-II dark matter simulation, with a semi-numerical scheme to describe the resulting ionisation structure. The researchers further had to account for the most important unknowns for the reionisation history: the fraction of ionising photons that escape from their host galaxies.

Observational estimates show a broad range of escape fraction values from a few per cent in the local Universe to possibly a few tens per cent at redshift z = 1~3. However, there are no observational constraints on the escape fraction during the Epoch of Reionisation.

Dr Kim and his team decided to incorporate a variable escape fraction for ionising photons and were able to predict the redshifted 21-cm power spectrum for the resulting reionisation histories. They not only modelled dependencies of the escape fraction with halo mass and redshift, according to the default semi-analytic galaxy formation model that includes supernova feedback, but also the halo mass dependency of escape fraction without supernova feedback. The importance of SN feedback during reionisation is not constrained by current observations.



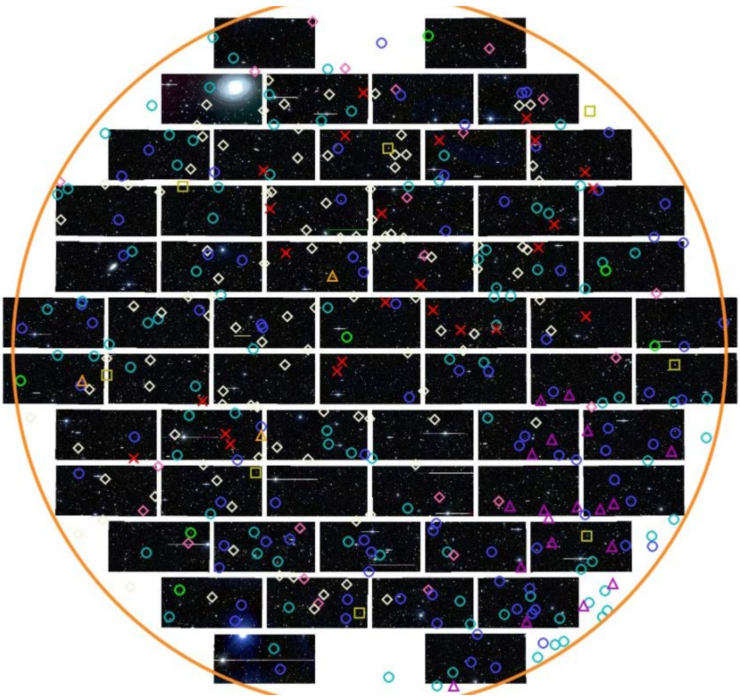
Their results show that an escape fraction which varies with host dark matter halo mass and redshift does in fact influence the structure of reionisation. However, the effect is smaller than the dominant astrophysical influence of SN feedback.

Publication details:

Han-Seek Kim, Stuart Wyithe et al. in the Monthly Notices of the Royal Astronomical Society (2013) "*Variation in the escape fraction of ionising photons from galaxies and the redshifted 21-cm power spectrum during reionization*"

First year of Australia hunting for Black Holes and Dark Energy

Type Ia supernovae provided some of the first evidence for the accelerating Universe and remain among the most import tools for cosmology. The Dark Energy Survey (DES) Supernova Search is a new generation experiment that will discover more than 3000 Type Ia supernovae. This will be the largest coherent sample to date and used to make the best ever measurement of the Universe's expansion history. Traditionally, spectroscopy of a live supernova within a few weeks of maximum light serves the dual purpose of "typing" the transient (i.e. determining whether it is a Type Ia supernova) and measuring its redshift, both of which parameters are critical for putting the supernova onto a Hubble diagram. However, this method requires an unrealistically large amount of resources for a large number of supernovae such as DES will collect. Alternatively, redshifts can be measured by observing supernova host galaxies at any time after the supernova discoveries. With the help of these redshifts, light curves can be used to reliably identify Type Ia supernovae.



The Australian Dark Energy Survey (OzDES) is a five-year, 100-night program that will use the 400 fibre 2dF system and AAOmega spectrograph on the Anglo-Australian Telescope to measure redshifts of 2,500 Type Ia supernovae host galaxies from DES. Bringing together the power of multi-fibre spectrograph and time series observations (roughly monthly during the DES season), OzDES will also monitor more than 500 Active Galactic Nuclei and quasars to measure their black hole masses, classify live DES transients and provide calibration data for other DES programs probing the Universe's structure and evolution.

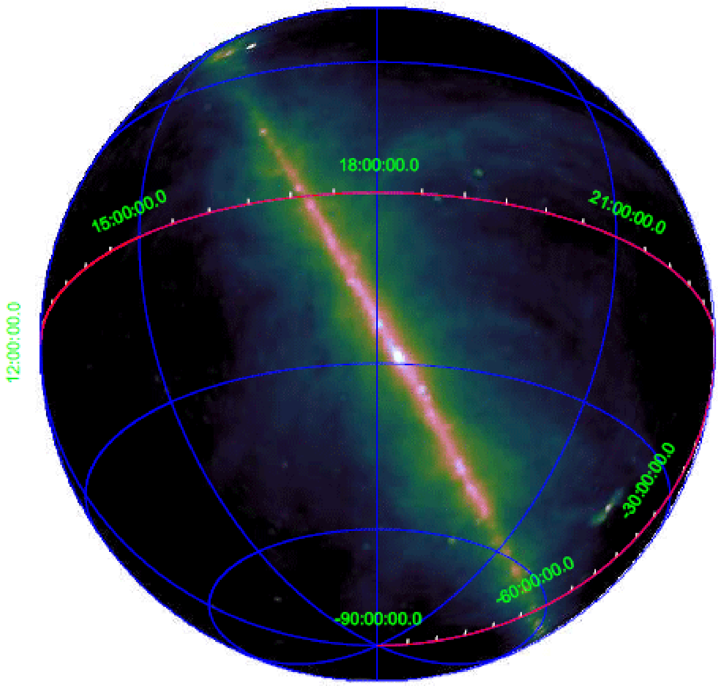
In the first paper by the OzDES collaboration – led by CAASTRO researcher Dr Fang Yuan (ANU) – they present an overview of the OzDES program and results from its first year of operation. In the first year, OzDES observed over 10,000 objects and measured more than 6,000 redshifts. They were achieving goals in terms of efficiency, redshift reliability and precision while continuing to improve data quality. The large number of spectra taken by OzDES also guarantees discoveries of rare events or objects. The researchers highlight a few cases that stand out, including some galaxy-galaxy lens candidates.

Publication details:

Fang Yuan, Chris Lidman, Tamara Davis, Michael Childress et al. in the Monthly Notices of the Royal Astronomical Society (2015) "*OzDES multi-fibre spectroscopy for the Dark Energy Survey: first-year operation and results*"

MWA survey opens new window into the low-frequency radio sky

The Murchison Widefield Array (MWA) radio telescope has completed observations for a 2-year observing program to survey the entire radio sky accessible to the MWA. The GaLactic and Extragalactic All-sky MWA (GLEAM) survey – led by ICRAR-Curtin – was designed to meet the observational requirements of over 30 individual science programs that aim to study a diverse range of astrophysical sources and phenomena ranging from the most distant known quasars to nearby gas and magnetic fields in our Milky Way galaxy.



The GLEAM survey covers the entire sky south of declination +25 degs, including the galactic plane. ObMWA survey opens new window into the low-frequency radio skyservations were performed with almost continuous frequency coverage between 73 and 231 MHz with 10 or 40 kHz frequency resolution. The broad frequency coverage and fine frequency resolution enables the data to be used for many scientific applications. As well as broad frequency coverage, the GLEAM survey is unique in being sensitive to radio emission from both compact and large diffuse radio sources up to tens of degrees in angular size. This capability is enabled by the many different length "baselines" (distances between all combinations of pairs of the MWA's 128 antenna tiles) comprising the MWA.

The angular resolution of images in the mid frequency range (155 MHz) is approximately 2 arcmin, which is comparable to or better than other radio sky surveys covering a large part of the southern sky. This provides the opportunity for scientists to add new data to the study of known radio sources and to search for new or rare objects that do not appear in other radio surveys.

GLEAM will form a significant legacy dataset from the MWA, both in terms of the raw data (which can be re-processed by future scientists) and from the tabulated source catalogues that are being generated by processing the data now. Sky surveys are typically highly valuable scientific products and are often used for studies well beyond what the original proposers envisaged. GLEAM data products, including an extragalactic compact source catalogue and a catalogue of supernova remnants in the galaxy, are in preparation and expected in the latter half of 2015.

Publication Details:

Randall Wayth, Emil Lenc, Martin Bell, Joe Callingham et al. in the Publications of the Astronomical Society of Australia (2015) "*GLEAM: The GaLactic and Extragalactic All-sky MWA survey*"

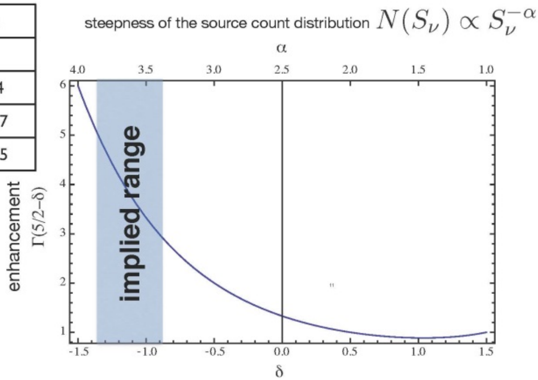
Solution to FRB conundrum also reveals clues about their origin

Since first reported in 2007, the origin of the bright, millisecond-duration pulses known as Fast Radio Bursts (FRBs) has remained a mystery to astronomers. There have been more theories proposed to explain them than the 17 events so far detected. Where do they come from – our Solar System, our galaxy, or beyond? The dispersion sweeps of FRBs (the delay of the pulse arrival time with wavelength caused by propagating through plasma in space) indicate that they have travelled through so much material on their way to Earth that they must be cosmological in origin. There just is not enough plasma in the interstellar medium of the Milky Way to explain their long dispersion sweeps.

Adding to the mystery, CAASTRO PhD student Emily Petroff (Swinburne University, now at ASTRON in the Netherlands) and colleagues analysed the distribution of FRB detections across the sky and reported in their 2014 paper that their rate is about four times higher at high galactic latitudes than close to the galactic plane. This result is doubly puzzling because (a) the distribution of extragalactic pulses should not be related to their position with respect to the galactic disk and (b) the rate of pulses of galactic origin should be higher closer to the galactic plane, the exact opposite of what is observed.

disparity	α
2:1	3
3:1	3.4
4:1	3.67
5:1	3.85

likely range: 3:1 – 5:1



CAASTRO members Dr Jean-Pierre Macquart (ICRAR-Curtin) and Prof Simon Johnston (CSIRO) now provide an explanation in their recent publication. Radio pulses received at the Earth have propagated through the turbulent interstellar medium of our own galaxy irrespective of whether they were generated inside or outside of it. The density fluctuations in this medium can randomly amplify the amplitude of a pulse. This effect is equivalent to the Earth's atmosphere causing an apparent twinkling of stars.

The intensity fluctuations change both with time and with observing frequency; and the more material, the more quickly they change with frequency. At low galactic latitudes, FRBs propagate through so much turbulent galactic material that the intensity fluctuations change very rapidly with frequency – so much so that radio telescopes average over many tens to hundreds of intensity fluctuations over the observing band. When averaged across the bandwidth of the telescope, the intensity is very close to the mean intensity of the pulse. However, at high galactic latitudes the FRB radiation is subject to only one or two intensity fluctuations across the telescope observing band, and the observed radiation can be either greatly diminished or enhanced.

The extent to which this matters for FRBs depends on their brightness distribution – the ratio of intrinsically bright and faint pulses. If the distribution is steep, many more faint events will be enhanced to become apparently bright than bright events will be diminished to become faint. The net result is that many faint events which would otherwise have been undetectable are rendered detectable. Thus, there is a direct connection between the brightness distribution of FRBs and the degree to which interstellar scintillation enhances their apparent event rate at high galactic latitudes.

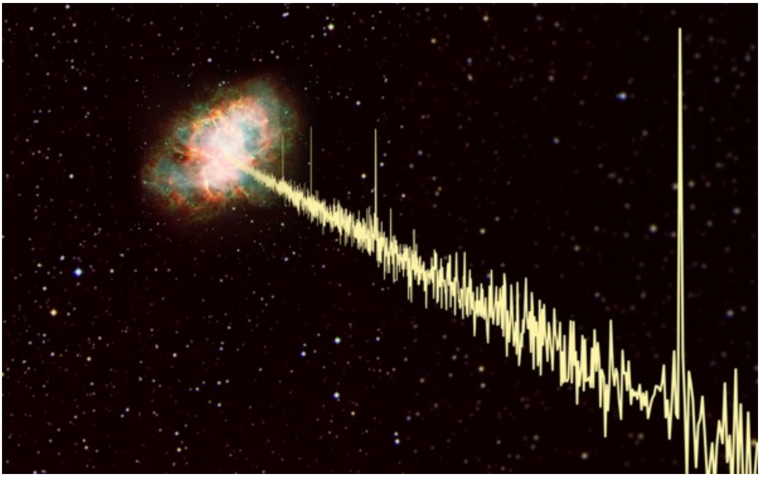
The researchers used the difference in event rates at high and low galactic latitudes to infer the steepness of the FRB brightness distribution. Their results show that the distribution is significantly steeper than expected from homogenously distributed events, and this in turn rules out many of the proposed models in which FRBs originate from the nearby Universe. By far the most likely interpretation is that the population of FRBs occurs at cosmological distances and that their abundance has changed throughout cosmic history.

Publication Details:

Jean-Pierre Macquart & Simon Johnston in the Monthly Notices of the Royal Astronomical Society (2015) "*On the paucity of Fast Radio Bursts at low galactic latitudes*"

MWA and Parkes data confirm broadband nature of giant pulses

The Crab pulsar is a relatively young pulsar situated in the central region of the Crab nebula. Its giant pulses are short duration radio bursts consisting of complex superpositions of nanosecond- and microsecond-scale bursts, occurring only at the main-pulse and the inter-pulse phases of the pulsar rotation. Their short duration implies broadband emission but although simultaneous observations had been performed in the past to ascertain the validity this assumption, the emission bandwidth was poorly determined – until recently.



In a new publication by CAASTRO student Samuel Oronsaye and the pulsar team at ICRAR-Curtin, the researchers report on their simultaneous observations of the Crab pulsar giant pulses with the Murchison Widefield Array (MWA), operating at 193 MHz, and the CSIRO Parkes radio telescope, operating at 1382 MHz. In a single hour, the MWA detected 55 giant pulses while 2075 giant pulses were observed at Parkes. The authors estimated a power-law index of $\beta = -3.35 \pm 0.35$ and -2.85 ± 0.05 for the giant pulse fluence (i.e. time integrated flux density) distribution observed at the MWA andParkes, respectively, by using a new approach which removes any bias from the power-law index determination.

The team detected 51% of the MWA giant pulses at Parkes, with spectra indices in the range of $-3.6 > \alpha > -4.9$. This range is much narrower than previously reported. Ideally, if the giant pulses were broadband, all pulses observed at the MWA frequency would also be observed at the Parkes frequency. The researchers performed a Monte Carlo analysis to investigate the less-than-100% correlation between the MWA and Parkes observations. Their analysis supports the initial assumption that the giant pulse emission in the Crab is intrinsically broadband, with the less-than-100% correlation being due to the relative sensitivities of the two instruments and the width of the spectral index distribution. These results are therefore consistent with the hypothesis that the spectral index of giant pulses is drawn from normal distribution of standard deviation 0.6 but with a mean that displays an evolution with frequency from -3.00 at 1382 MHz to -2.85 at 192 MHz.

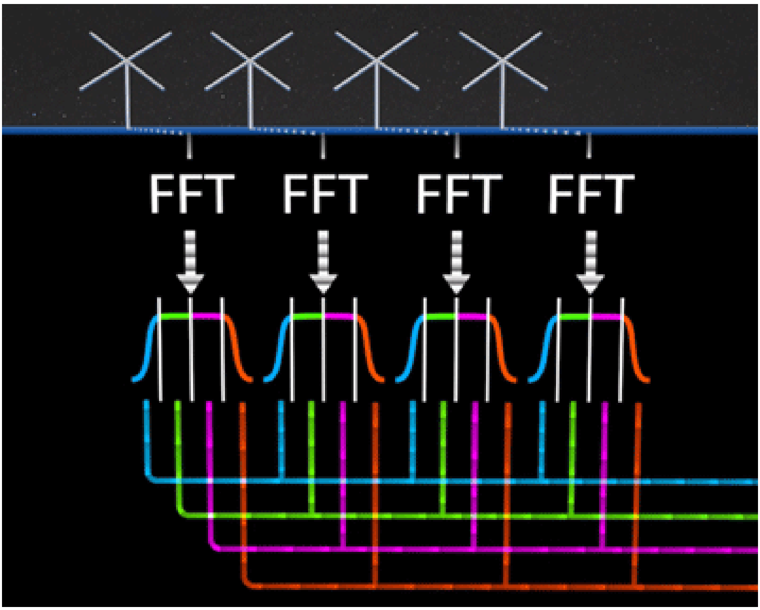
Publication details:

Samuel Oronsaye, Stephen Ord, Ramesh Bhat, Steven Tremblay, Samuel McSweeney, Steven Tingay, Willem van Straten, Andrew Jameson et al. in the Astrophysical Journal (2015) "*Simultaneous Observations of Giant Pulses from the Crab Pulsar, with the Murchison Widefield Array and Parkes Radio Telescope: Implications for the Giant Pulse Emission Mechanism*"

Gaming technology makes new telescopes flexible, cheap and fast

Computer gamers will be familiar with the technology of Graphics Processing Units (GPUs): they power the ultra-fast, ultra-realistic graphics for modern computer games. Out of this mass market for incredibly high performance rendering of graphics in gaming, GPUs have emerged as a very serious technology for a wide range of complex high performance computing problems in science and engineering.

CAASTRO Associate Investigator Dr Stephen Ord (ICRAR-Curtin University) and the Murchison Widefield Array (MWA) team have placed GPUs at the heart of the SKA precursor. Just as a GPU has to rearrange, process and output data in real time for computer games, the MWA system uses GPUs to correlate the signals from 128 antennas scattered over several kilometres in real time, then send the visibilities 800km to the Pawsey Supercomputing Centre in Perth for storage and further (offline) processing. Other processing stages are being performed by bespoke hardware based on Field Programmable Gate Arrays (FPGAs), both of which are housed in general purpose rack mounted servers. This hybrid approach to the correlation task is required to handle approximately 8 TFLOPS (Tera FLoating point Operations Per Second). The MWA correlator currently generates 8.3 TB of data per day. Its design, signal path and processing elements are being described in a recent publication.



Projects such as the MWA and the SKA will be more flexible, cheaper and faster to develop because of these technologies. The Australian Government is funding Dr Ord to help design the SKA during its pre-construction phase, to scale the MWA GPU solution up by a factor of over 100 and meet the SKA data processing challenge. He works closely with global technology companies NVIDIA (GPUs), IBM (computing) and CISCO (networking), as well as international partners in Canada, Europe, the UK and India.

Publication details:

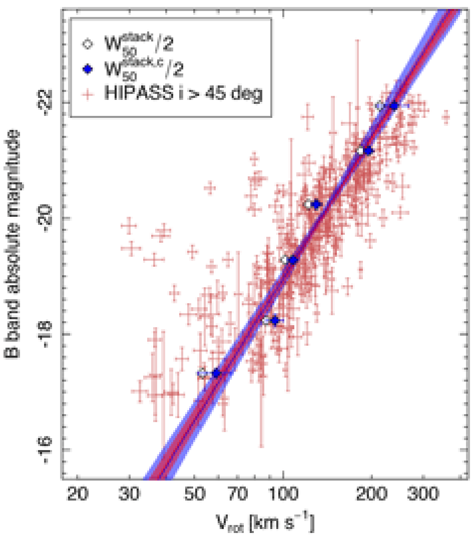
Stephen Ord et al. in the Publications of the Astronomical Society of Australia (2015) "*The Murchison Widefield Array Correlator*"

Novel trick draws fundamental scaling relation to high redshifts

Galactic scaling relations are an important part of extragalactic research as they are tracers of galaxy evolution processes and are also quite often useful observational tools. The Tully-Fisher Relation (TFR) is one such scaling relation linking the mass (using luminosity as a proxy) and rotation velocity (using the HI emission line width as a proxy) of spiral galaxies. The TFR not only serves as an important cosmological distance tool but also describes the baryonic and dark matter components of galaxies at a given distance, or redshift (z). Measuring the TFR over a range of redshifts therefore allows a glimpse into galaxy evolution.

Probing the rotation velocity of galaxies is a difficult job though: using the optical light, galaxies appear limited to their stellar component. Measuring rotation velocities from optical data is a bit like trying to measure how fast a ballerina's arms are spinning by measuring how fast their torso is spinning: you get a very different answer depending on if their arms are tucked in or extended. A more favourable method is to measure the rotation of the neutral Hydrogen gas (HI) in galaxies as it also extends out to the edge of galaxies.

This gas has a spectral line feature at 1420.4 MHz (about 21cm), and its width is a direct measurement of the maximum velocity that the gas is rotating at in the galaxy. This 21cm emission is a very faint signal though and quite difficult to measure at a distance, and hence the TFR is poorly constrained beyond the very nearby Universe ($z < 0.1$).



CAASTRO PhD student Scott Meyer (ICRAR-UWA) and his CAASTRO colleagues have now used a technique called HI stacking that involves co-adding the signal from multiple galaxies to create a statistical signal with lower noise properties. HI stacking had previously been used to extend the redshift range accessible for astronomers to study the neutral gas content of the Universe. The researchers applied this technique by stacking galaxies with similar absolute magnitudes and measuring the width of the resulting stacked HI emission lines. They could use the measured widths from these signals to determine average rotation velocities for the absolute magnitude ranges these galaxies come from.

For calibration purposes, the team first used simulated galaxies from the S3-SAX simulation, then galaxies detected with the HI Parkes All-Sky Survey (HIPASS), and they also demonstrate its utility with noisy spectra. Using the stacking technique in this novel way, the spectral line features of the galaxies do not need to be detectable above the noise, such that more galaxies – of lower mass and much more distant than currently possible – can be studied. Even when including galaxy spectra that had not been corrected for inclination or dispersion, the researchers found that the width of the resulting stacked spectrum traces the average width of the corrected galaxies with only a small (~7%) systematic error.

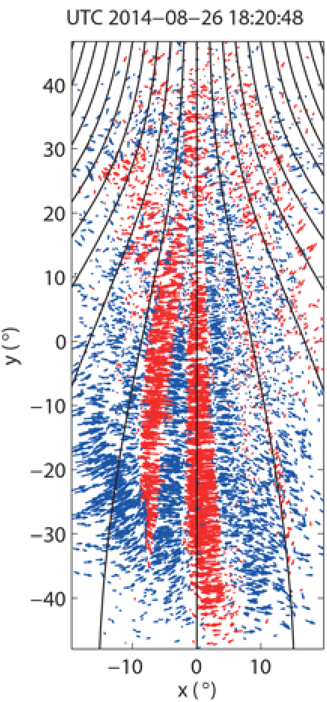
Publication details:

Scott Meyer, Martin Meyer, Danail Obreschkow & Lister Staveley-Smith in the Monthly Notices of the Royal Astronomical Society (2015) "*Extended Tully-Fisher Relations using HI Stacking*"

Lessons about the ionosphere from the MWA Transients Survey

Over the past two years, the Murchison Widefield Array (MWA) radio telescope has been used to conduct a general survey for transient and variable radio sources, the MWA Transients Survey (MWATS). Although the MWA's large field of view alone gives it impressive survey speeds, capitalising on the fact that it can be repointed almost instantaneously in any direction lets us take this to a whole new level. In MWATS, the instrument cycles swiftly between three different pointings, gaining rapid coverage of the sky as the Earth rotates. Effectively, the telescope is used like a raster scanner, greatly expanding its angular coverage.

The low frequencies of operation mean that the MWA is highly sensitive to refractive distortions caused by the ionosphere. Combining all these properties makes the MWA useful for characterising ionospheric fluctuations over large expanses of sky, a task important for understanding what the future Square Kilometre Array will experience. Gradients of electron density in the ionosphere produce displacements of point sources as a function of angular position and time, potentially affecting automated source extraction and association algorithms. Apparent brightnesses can also change, impacting how accurately radio light curves can be measured.



Former CAASTRO Honours student Cleo Loi (University of Sydney, now PhD student at the University of Cambridge, UK) and colleagues statistically analysed about 51 hours of MWATS data and revealed that at the MWATS observing frequency of 154 MHz, refractive displacements are typically 10-20 arcsec, consistent with the density gradients associated with atmospheric waves. This is several times smaller than the resolution of the telescope, and so is unlikely to affect spatial cross-matching. An upper bound on brightness fluctuations of ionospheric origin was placed at 1-3%, smaller than the contribution from other sources of noise under typical circumstances. The authors conclude that these results reassuringly suggest that the ionosphere is not a significant impediment to the goals of MWATS and other time-domain studies with the MWA at these frequencies.

In another publication, the same analyses used to extract ionospheric fluctuations uncovered an interesting event on the night of the 26th of August 2014. A large-amplitude travelling ionospheric disturbance, observed over a huge angular field of view, was seen to pass overhead, triggering the formation of a collection of density ducts in its wake. The event also evidences one possible mechanism for the formation of density ducts in the ionosphere: that they may be triggered by propagating disturbances. The ducts were aligned along the Earth's magnetic field lines, a property expected for plasma density structures high in the atmosphere. Notably, geomagnetic conditions were very quiet at the time. This suggests that ionospheric activity does not necessarily correlate with global geomagnetic activity, making ionospheric forecasting potentially difficult.

Overall, what these results have demonstrated is that studying ionospheric structure can be a fully commensal application of an instrument like the MWA alongside astronomical research. A general-purpose low-frequency survey like MWATS can reveal fascinating events happening high up in the Earth's atmosphere. Ultimately, harnessing the MWA's dual-purpose capabilities as an astronomical telescope and a geospace probe will allow it to realise its full scientific potential.

Publication details:

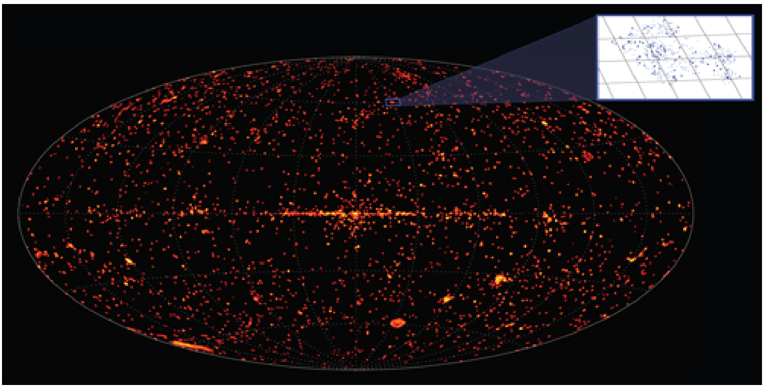
Shyeh Tjing Loi, Tara Murphy, Martin Bell et al. in the Monthly Notices of the Royal Astronomical Society (2015) "*Quantifying ionospheric effects on time-domain astrophysics with the Murchison Widefield Array*"

Shyeh Tjing Loi, Iver Cairns, Tara Murphy et al. in the Journal of Geophysical Research (2016) "*Density duct formation triggered by a travelling ionospheric disturbance: Murchison Widefield Array observations*"

Classifying serendipitous X-ray sources with Machine Learning

The instruments of modern day observational astronomy have been steadily moving towards bigger telescopes and deeper surveys. A number of facilities have recently been (or will soon be) commissioned to survey the sky in unprecedented detail: at radio wavelengths, the upcoming Square Kilometre Array (SKA) telescope and its operational Australian precursors, the Murchison Widefield Array (MWA) and Australia Square Kilometre Array Pathfinder (ASKAP); in the visible bands, the Large Synoptic Survey Telescope (LSST) and SkyMapper; at higher energies, the soon-to-be-launched Spectrum Roentgen Gamma (SRG) space telescope. These facilities represent a dramatic increase in the amount of data collected that will be immensely challenging to process and utilise in real time.

Novel methods to quickly and accurately identify astrophysical sources and to flag objects of particular rarity are needed to meet this challenge. In the 2014 publication by former CAASTRO PhD student Kitty Lo and colleagues, the Random Forest supervised ensemble machine learning algorithm was applied to classify the variable X-ray sources in the second XMM-Newton Serendipitous Source catalogue (2XMM). Building on this work, CAASTRO Affiliate Dr Sean Farrell (University of Sydney) led the team that applied the same method to the 3XMM catalogue, the largest X-ray source catalogue ever produced (representing a 40% increase over 2XMM with 372,728 unique sources of which 3,696 are flagged as variable). The variable X-ray sources were classified into six distinct categories of object:



Active Galactic Nuclei (AGN), Cataclysmic Variables (CVs), Gamma Ray Bursts (GRBs), stars, Ultraluminous X-ray Sources (ULXs) and X-ray Binaries (XRBs), with a classification accuracy of ~92%. The Random Forest algorithm was also applied for the first time to data quality control and was used to identify spurious detections with an accuracy of ~95%. Quality control is one of the areas in astronomy surveys that is most demanding of human inspection, making this result particularly significant.

In addition to classifying the entire variable source component of 3XMM, a number of exotic outlier sources were discovered that may be representative of entirely new classes of objects. Three particularly interesting objects were identified including a new candidate supergiant fast X-ray transient (SFXT), a 400 second period X-ray pulsar and an eclipsing binary system with a 5-hour orbital period coincident with a known Cepheid variable star. All these objects are very rare and could provide unique insight into the most extreme physical processes known, highlighting the effectiveness of the Random Forest technique. In the era of large surveys, machine learning appears to be rapidly becoming an invaluable tool for the modern day astronomer.

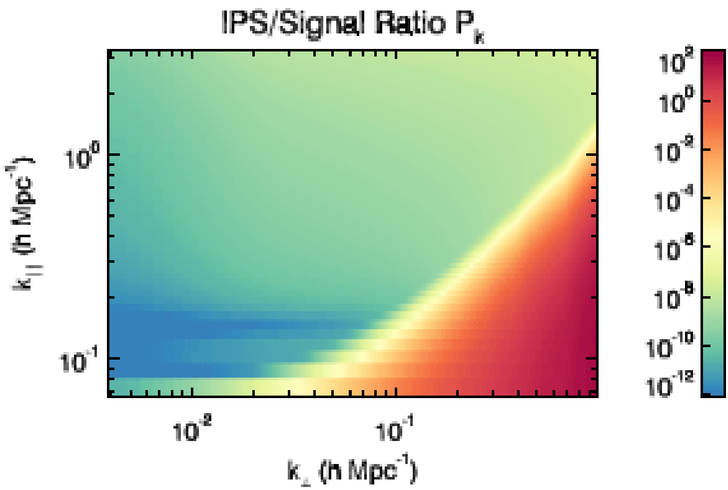
Publication details:

Sean Farrell, Tara Murphy & Kitty Lo in the Astrophysical Journal (2015) "*Autoclassification of the Variable 3XMM Sources Using the Random Forest Machine Learning Algorithm*"

Interplanetary scintillation found to contaminate the EoR signal

The Epoch of Reionisation (EoR) is a period in the early Universe when the first stars and galaxies began radiating. Before this time, the Universe existed in the Dark Ages, a time marked by a lack of radiating sources and a neutral hydrogen intergalactic medium. During the EoR, the ionising radiation from these first sources stripped the electrons from these hydrogen atoms, transitioning the Universe from dark and neutral to bright and ionised. The details of this transition promise to provide a wealth of information about structure formation in the Universe but the radio signal we are trying to detect to trace it is extremely weak. Much more prominent in the radio sky are the numerous foreground sources, such as Active Galactic Nuclei and radio galaxies that "contaminate" our signal. In the EoR experiments with the Murchison Widefield Array (MWA), and others, we use our knowledge of these bright foregrounds, along with some signal processing tricks, to discriminate the EoR signal from the contaminants. However, if the contaminants differ from our expectations, then residual signal may affect our ability to observe the early Universe. Interplanetary scintillation (IPS) is a potential candidate to create this kind of issue.

IPS is typically observed as the twinkling of radio sources due to their light interacting with solar plasma before reaching our telescopes. Electrons and other ionised particles (plasma) flowing in the solar wind interact with the light from distant objects, distorting and refracting the wavefronts. The constructive and destructive interference of these wavefront distortions, as seen by the telescope, apparently increases or decreases the strength of the signal, compared



with expectations. Such behaviour has the potential to add unexpected and time-dependent power to the EoR data and to further contaminate the signal. Following the measurement of IPS in two bright radio sources in the MWA EoR field by Kaplan et al. (2015), ICRAR-Curtin based CAASTRO members Dr Cathryn Trott and Prof Steven Tingay explored the importance of considering IPS contamination for EoR experiments in their recent publication.

Taking a statistical approach, they took the measured spatial and temporal properties of IPS from results in the literature spanning 50 years and imprinted this signature on the expected, static properties of foreground radio sources in EoR data. The researchers found that IPS has different spatial and spectral properties to the static radio sources themselves, producing a unique, but low-level, signature in the EoR data. Having considered normal IPS conditions, they concluded that IPS would not be a major contributor to EoR contamination but that it should be considered in the modelling due to its distinct behaviour to avoid bias in the final results. This conclusion has potential implications for future, large-scale EoR experiments, such as with the Square Kilometre Array (SKA).

<u>Publication details:</u>

Cathryn Trott & Steven Tingay in the Astrophysical Journal (2015) "*The Effect of Interplanetary Scintillation on Epoch of Reionisation Power Spectra*"

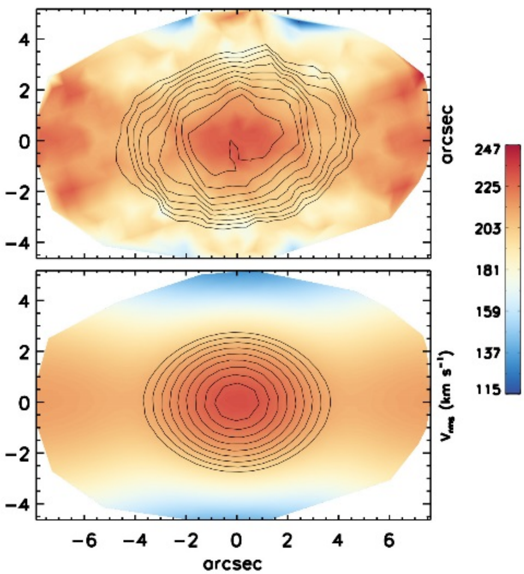
Weighing galaxies to find a more Fundamental Plane

Early-type galaxies are thought to have a very simple structure, and therefore their properties ought to follow well-defined scaling relations. The most prominent of these is the Fundamental Plane. Under the assumption that galaxies are dynamically relaxed systems, the mass of a galaxy should be proportional to its radius and the square of the velocity dispersion of the stars.

However, the observed relation did not quite match the theory – the observed Plane was tilted with respect to the theoretical prediction. One possible explanation for this discrepancy is that the theoretical prediction refers to galaxy mass, whereas most observations have relied on galaxy luminosity as a proxy for mass. Directly measuring the galaxy mass may remove this; however, measuring galaxy mass is much more challenging than measuring luminosity.

One approach to measuring galaxy mass is to use 3D, integral field spectroscopy. CAASTRO researcher Dr Nicholas Scott (University of Sydney) and members of the SAMI Pilot Survey obtained spatially resolved spectroscopy of 106 galaxies in three nearby clusters. From these observations they were able to produce maps of the velocities and velocity dispersions within each galaxy. From these maps they can then use a dynamical modelling technique to measure the total mass (stars, gas and dark matter) of each galaxy.

While other studies have used this approach for very nearby galaxies, the SAMI Pilot team was the first to apply this to a large sample of galaxies in clusters. Galaxies in clusters are particularly well suited to this work because we know they are all at the same distance, removing the most significant source of uncertainty when measuring the Fundamental Plane. Using



these mass measurements, the researchers were able to construct Fundamental Planes for the galaxies in each of the three clusters. All three galaxy mass planes were consistent with the theoretical prediction, confirming that the difference between galaxy light and mass was responsible for the previously tilted plane.

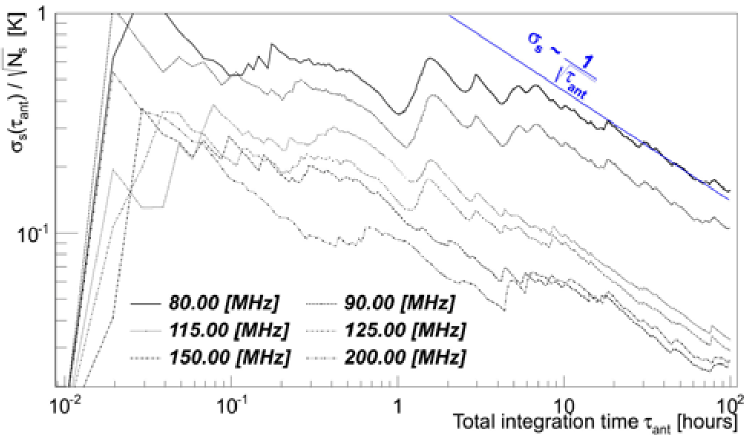
<u>Publication details:</u>

Nicholas Scott, Lisa Fogarty et al. in the Monthly Notices of the Royal Astronomical Society (2015) "*The SAMI Pilot Survey: The Fundamental and Mass Planes in Three Low-Redshift Clusters*"

Ionospheric effects not detrimental to EoR detection from ground

The Epoch of Reionisation (EoR) is the time in the early Universe when the first stars and galaxies formed and re-ionised the neutral hydrogen. Indirect information about the EoR has been obtained from the Cosmic Microwave Background and spectra of the distant quasars. However, the bulk of information about the physical parameters of the EoR is encoded in the 21cm line (1420 MHz) from neutral hydrogen redshifted into the low radio frequency range 200 – 50 MHz, for redshifts of $6 < z < 30$.

The observational approaches range from large interferometer arrays to single antenna experiments. The latter, so-called global EoR experiments, spatially average the signal from the entire visible sky and try to identify the tiny signature of the EoR (of order 100 milliKelvin, which is a few orders of magnitude smaller than the galactic foregrounds) in the sky-averaged spectrum. This extremely challenging precision requires very long observations (hundreds of hours) to achieve a sufficiently high signal-to-noise ratio. Moreover, ground-based global EoR experiments are affected by frequency-dependent effects (i.e. absorption and refraction) due to the propagation of radio-waves in the Earth's ionosphere. The amplitude of these effects changes in time. There has therefore been an ongoing discussion in the literature on the importance of ionospheric effects and whether the global EoR signature can feasibly be detected from the ground.



The team of CAASTRO researches at ICRAR-Curtin, led by Dr Marcin Sokolowski, used three months' worth of 2014/2015 data collected with the BIGHORNS system with a conical log-spiral antenna deployed at the Murchison Radio-astronomy Observatory to study the impact of the ionosphere on its capability to detect the global EoR signal. Comparison of data collected on different days at the same sidereal time enabled the researchers to infer some properties of the ionosphere, such as electron temperature ($T_e \approx 470$ K at night-time) and amplitude and variability of ionospheric absorption of radio waves. Furthermore, the data sample shows that the sky-averaged spectrum indeed varies in time due to fluctuations of these ionospheric properties. Nevertheless, the data analysis indicates that averaging over very long observations (several days or even several weeks) suppresses the noise and leads to an improved signal-to-noise ratio. Therefore, the ionospheric effects and fluctuations are not fundamental impediments that prevent ground-based instruments, such as BIGHORNS, from integrating down to the precision required for global EoR experiments, provided that the ionospheric contribution is properly accounted for in the data analysis.

Publication details:

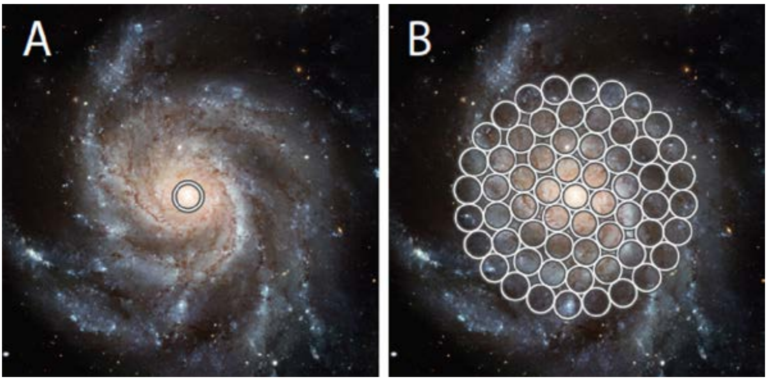
Marcin Sokolowski, Randall Wayth, Steven Tremblay, Steven Tingay et al. in the Astrophysical Journal (2015) "*The impact of the ionosphere on ground-based detection of the global Epoch of Reionisation signal*"

SAMI hexabundles probe biases in local star formation rates

Over the past few decades, studies into the evolution of galaxies have been reliant on data that has come from observing galaxies with individual fibre optics. The light from a galaxy travels down the fibre into a spectrograph where it is split into all of its wavelengths (from blue to red like a rainbow). This spectrum contains a wealth of information about the workings of the galaxy: how far away it is, how fast it is rotating, how many stars are being born etc.

There is a problem with this method though: "local galaxies" are close enough that the single fibre optic only covers the central part of the galaxy, so the data that astronomers use from this method is incomplete. The SAMI Galaxy Survey (using the "Sydney-AAO Integral-field Spectrograph" on the Anglo-Australian Telescope) is a major part of CAASTRO's Evolving Universe research theme and instead uses a device called "hexabundle" to solve this problem and to observe the entire galaxy with many fibres instead of just one.

Before SAMI, elaborate methods ("aperture corrections") had been developed to deal with the bias of estimating a galaxy's star formation rate from using single fibre optics. CAASTRO PhD student Samuel Richards (University of Sydney) and colleagues have now tested these aperture correction methods using the full data of 1212 different galaxies observed with SAMI.



They scrutinised two of the most commonly used aperture corrections, by first comparing their estimated total star formation rates, against the SAMI observed total star formation rates. With the ability to actually probe the assumptions in the aperture corrections, the researchers were able to establish that biases arise when assuming that instantaneous star formation can be traced by broadband optical images (Hopkins et al. 2003, GAMA) and when the aperture correction is built only from spectra from the centre of galaxies (Brinchmann et al. 2004, SDSS). These biases can be significant depending on what types of galaxies are being observed. Understanding the sensitivities of these aperture corrections is essential for correct handling of errors in galaxy evolution studies.

Publication details:

Samuel Richards, Julia Bryant, Scott Croom, Andrew Hopkins, Adam Schaefer, Joss Bland-Hawthorn, James Allen et al. in the Monthly Notices of the Royal Astronomical Society (2015) "*The SAMI Galaxy Survey: Can we trust aperture corrections to predict star formation?*"

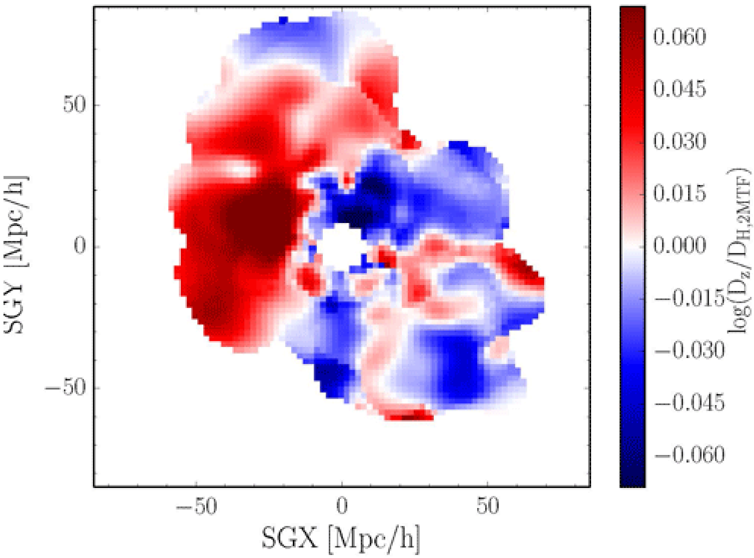
Large scale galaxy motions match expectations for dark matter

For nearly a century, astronomers have known that the Universe is expanding – most galaxies are moving away from each other. When we measure the motion of a distant galaxy, the overall expansion of the Universe is, in most cases, by far the dominant contributor to that galaxy's movement. However, astronomers have long been fascinated by a secondary contributor to galaxy motions: the gravitational attraction of nearby matter. By studying the motions of galaxies, we can measure the distribution of all matter in the nearby Universe, including dark matter.

One important statistic that can be used to understand the large scale motions of galaxies is the "bulk flow". It is the average motion of all galaxies within a large region of the Universe. The faster the bulk flow, the stronger the gravitational attraction of nearby matter on large scales. Two studies of galaxy motions presented this month by researchers in the CAASTRO Dark Universe research theme show that this bulk flow is consistent with our expectations.

Dr Morag Scrimgeour, a former CAASTRO PhD student at ICRAR-UWA, and the 6dF Galaxy Survey team measured the bulk flow of galaxies in the 6dF Galaxy Survey. They found that the bulk flow of

galaxies in the southern sky out to a depth of 300 million light-years is 243 +/- 58 km/s. This is within the range of theoretical predictions for the bulk flow taken from the standard model for the Universe, albeit on the high end of that range. The analysis concluded that the galaxies



covering this large volume are collectively moving in a direction that aims roughly towards the Shapley Supercluster, an extremely massive supercluster of galaxies about 600 million light-years away.

This study shows that the bulk flow is consistent with theoretical expectations drawn from the "standard model" of the Universe, and now another study from the CAASTRO Dark Universe research theme suggests that the bulk flow is also consistent with expectations relating to the specific geometry of the galaxies that we see in the nearby Universe. Dr Christopher Springob (ICRAR-UWA) and collaborators took the bulk flow as measured for the 2MASS Tully-Fisher Survey and compared it to what we would expect it to be if the dark matter is distributed across the nearby Universe in the same pattern that we observe for the galaxies themselves. Again, the model and our measurements are largely in agreement. Assuming that dark matter is more heavily concentrated wherever galaxies are more heavily concentrated (such as the Shapley Supercluster) gives a prediction for the bulk flow that is consistent with what we actually observe.

Publication details:

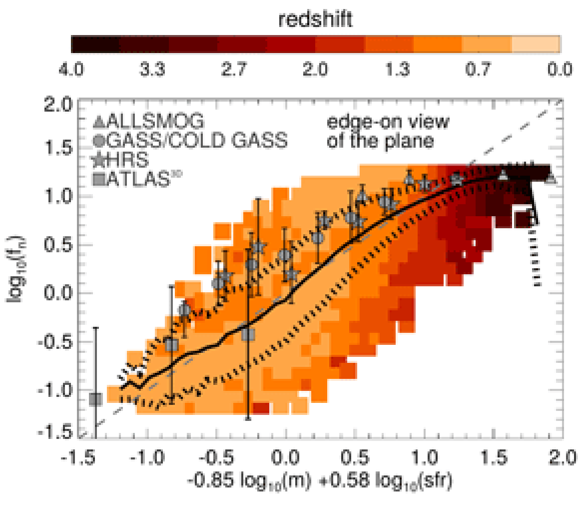
Morag Scrimgeour, Tamara Davis, Chris Blake, Lister Staveley-Smith, Christina Magoulas, Christopher Springob et al. in the Monthly Notices of the Royal Astronomical Society (2015) "*The 6dF Galaxy Survey: Bulk Flows on* $50-70h^{-1}$ *Mpc scales*"

Christopher Springob, Tao Hong, Lister Staveley-Smith et al. in the Monthly Notices of the Royal Astronomical Society (2015) "*2MTF V. Cosmography, Beta, and the residual bulk flow*"

Simulations first to reveal fundamental plane of star formation

Galaxy formation involves many inter-linked physical processes at any given time: the rate at which the galaxy's halo accretes mass from the intergalactic medium, the rate of shocking and cooling of this gas onto the galaxy, and the conversion of gas in the interstellar medium into stars. The complexity and non-linearity of these processes make it difficult to understand which processes dominate, and if and how this changes over time. The identification of scaling relations, that is the tight correlation between certain physical galaxy properties, can therefore be very valuable to reduce the number of properties in galaxy formation models and to formulate simple relations that capture the dominant paths along which galaxies evolve. While helpful for this reason, these relations cannot ultimately distinguish between cause and effect though. Cosmological simulations of galaxy formation are excellent testbeds as they allow examining causality directly. If reproducing the observed scaling relations adequately, these simulations can be used to better understand how galaxies evolve and to predict how scaling relations are established, how they evolve, and which processes determine the scatter around the main trends.

In their current publication, the research team around CAASTRO member Dr Claudia Lagos (ICRAR-UWA) investigated the correlations between different physical properties of star-forming galaxies in the "Evolution and Assembly of GaLaxies and their Environments" (EAGLE) cosmological hydrodynamical simulation suite over the redshift range 0 < z < 4.5. Their careful statistical analysis revealed that the neutral gas fraction, stellar mass and star formation rate account for most of the variance seen in the population of galaxies at all times. Galaxies trace a two-dimensional, nearly flat surface in the three-dimensional space of the properties above which the team names "Fundamental plane of star



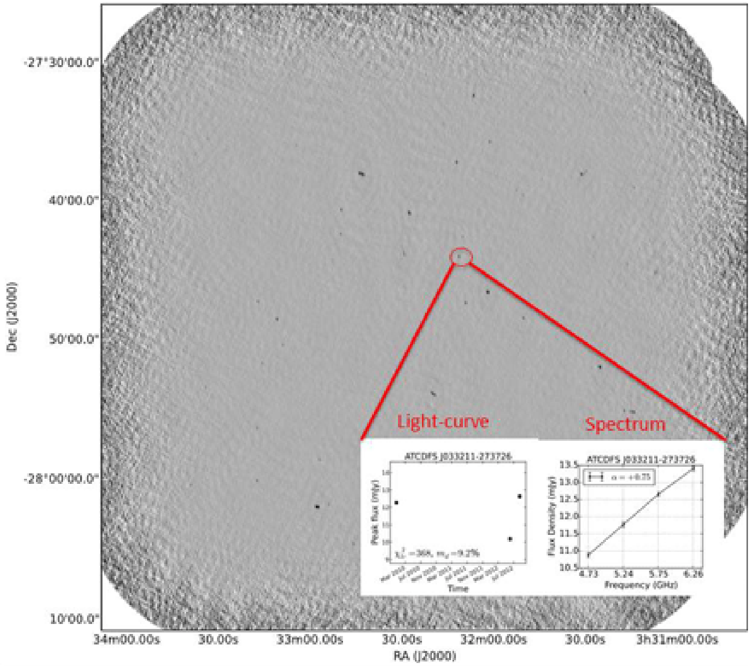
formation". The location of this plane varies little in time, whereas galaxies themselves move along the plane as their gas fraction and star formation rate decrease over time. The existence of this "fundamental plane of star formation" is a consequence of the self-regulation of galaxies in which the accretion of newly cooled gas and feedback outflows from stars and Active Galactic Nuclei balance each other out: the rate at which gas flows into and out from the galaxy are similar. Excitingly, using the insights from their simulations, the researchers found that real galaxies follow the same plane, based on a large compilation of observations spanning the redshift range $0 < z < 2.5$. This is the first time that the existence of such a plane was initially established in simulations and then confirmed in observations.

Publication details:

Claudia Lagos et al. in the Monthly Notices of the Royal Astronomical Society (2015) "*The fundamental plane of star formation in galaxies revealed by the EAGLE hydrodynamical simulations*"

Variability of radio sources due to black hole activity

The Universe is a violent and dynamic environment – dramatic changes in the brightness of an object on a variety of timescales are often an indicator that extreme astrophysical processes are taking place, or that the intervening medium is severely affecting the propagation of the electromagnetic waves. In either case, measuring temporal variations enables us to investigate the changes in density, temperature, pressure, velocity and gravitational/magnetic fields experienced in these environments which are often an excellent probe of "extreme physics". A variety of exciting astronomical objects detectable at radio wavelengths fall into the variable classification such as: Active Galactic Nuclei (AGN), Black Hole X-ray Binaries, flare stars, Gamma-Ray Bursts afterglows, pulsars and Radio Supernovae, to name a few.



The Chandra Deep Field South (CDFS) is a region of the sky that has been observed extensively and to very deep depth with a plethora of telescopes across the electromagnetic spectrum. It covers ~0.3 square degrees of the sky, and the majority of the objects within this region have been classified and studied in great detail. In a recent paper, CAASTRO Affiliate Dr Martin Bell (CSIRO) and his colleagues revisited this particular region of sky – two years after their first intense survey at radio wavelengths (Huynh et al. 2012) – to study how the objects had changed and to search for new objects that had "appeared" or become transient in the intervening time. The team again used the Australia Telescope Compact Array at a frequency of 5.5 GHz. Choosing the CDFS, instead of another region of the sky that was not so well studied, ensured that identification of objects of interest was easy and did not require additional telescope observations at different frequencies.

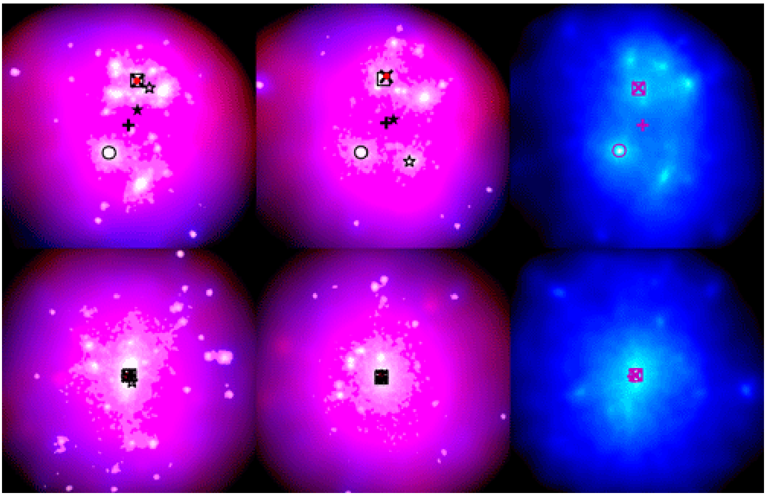
Within the CDFS, the researchers identified four highly variable radio sources out of a total of 124 objects. Using the multi-wavelength data available, they identified these objects as AGN and concluded that the variability was driven by accretion onto a supermassive Black Hole. The radio emission traces the after-effect of the accretion process via collimated relativistic "jets" of material. These jets respond to increases and decreases in the amount of material plummeting into the Black Hole and are hence time variable. The remarkable thing about these variable AGN is that they all had inverted radio spectra. Such spectra are a hall mark of potentially young objects that have "knots" within their compact radio jets.

Publication details:

Martin Bell, Minh Huynh, Paul Hancock, Tara Murphy, Bryan Gaensler, Davide Burlon, Cathryn Trott & Keith Bannister in the Monthly Notices of the Royal Astronomical Society (2015) "*A search for variable and transient radio sources in the extended Chandra Deep Field South at 5.5 GHz*"

Simulated galaxy clusters show complexity of identifying centre

Cosmological structure formation models assume lower mass systems to merge to form more massive structures, with galaxy clusters representing the final state of this process. These clusters are not only good cosmological probes but also valuable laboratories for testing models of gravitational structure formation, galaxy evolution, thermodynamics of the intergalactic medium and plasma physics. Observationally, galaxy clusters are usually identified through optical images, X-ray observations or gravitational lensing. A fundamental step in any of these procedures is the identification of the cluster centre though, and the preferred measures depend on the signal used. For instance, the minimum of the gravitational potential (which expects to define the centre if the cluster is in dynamical equilibrium) is usually adopted when using strong and weak lensing, whereas luminosity peaks are common measures when using optical and X-ray images. In a new publication by CAASTRO members Dr Weiguang Cui and Prof Chris Power (both at ICRAR-UWA) and colleagues, the researchers employed simulations to determine the difference in the estimation of the centre of a galaxy cluster when assuming different mass distribution and physical processes.



They created a statistical sample of clusters drawn from a suite of cosmological simulations in which they explored a range of galaxy formation models: Dark Matter only, CSF (hydrodynamical models that include gas cooling, star formation and supernova feedback) and AGN (feedback from supermassive Black Holes included in addition to CSF). The team investigated how the location of the galaxy cluster centre was affected by the choice of these observables. What they found was that the "brightest cluster galaxy position" from the optical images correlated more strongly with the minimum of the gravitational potential than the X-ray defined centres. The feedback from supermassive Black Holes, on the other hand, significantly enhanced the offset between the peak X-ray luminosity and the minimum gravitational potential. These results highlight the importance of identifying the cluster centre when interpreting cluster observations, in particular when comparing theoretical predictions and observational data.

Publication details:

Weiguang Cui, Chris Power et al. in the Monthly Notices of the Royal Astronomical Society (2015) "*How does our choice of observable influence our estimation of the centre of a galaxy cluster? Insights from cosmological simulations*"