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FOR ALL-SKY ASTROPHYSICS

Reader's Digest

Publication stories about recent CAASTRO research

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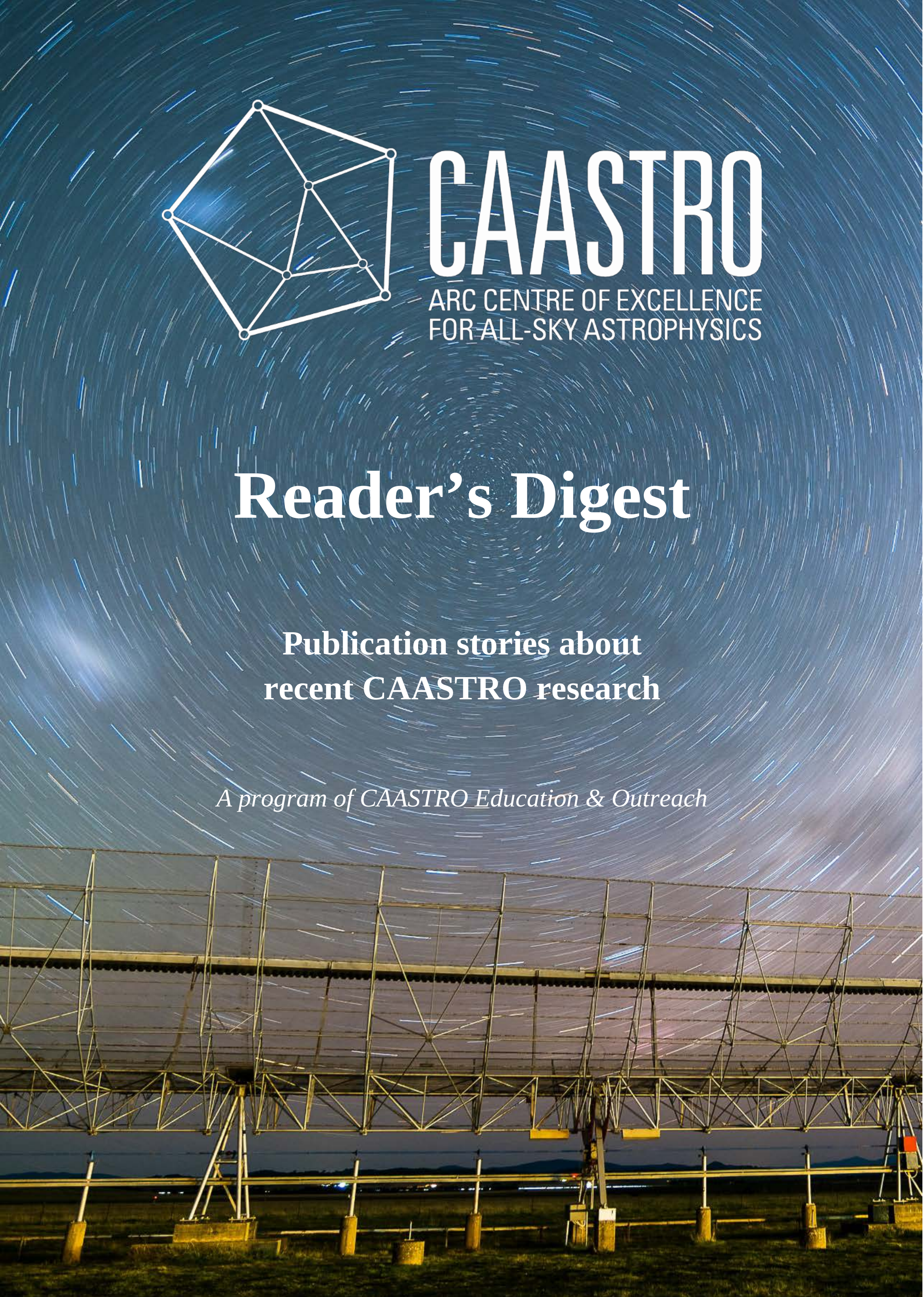

Cover image by Fabian Jankowski (Swinburne University)

These stories were written by the leading
CAASTRO author in collaboration with
Dr Wiebke Ebeling,
CAASTRO Education & Outreach.

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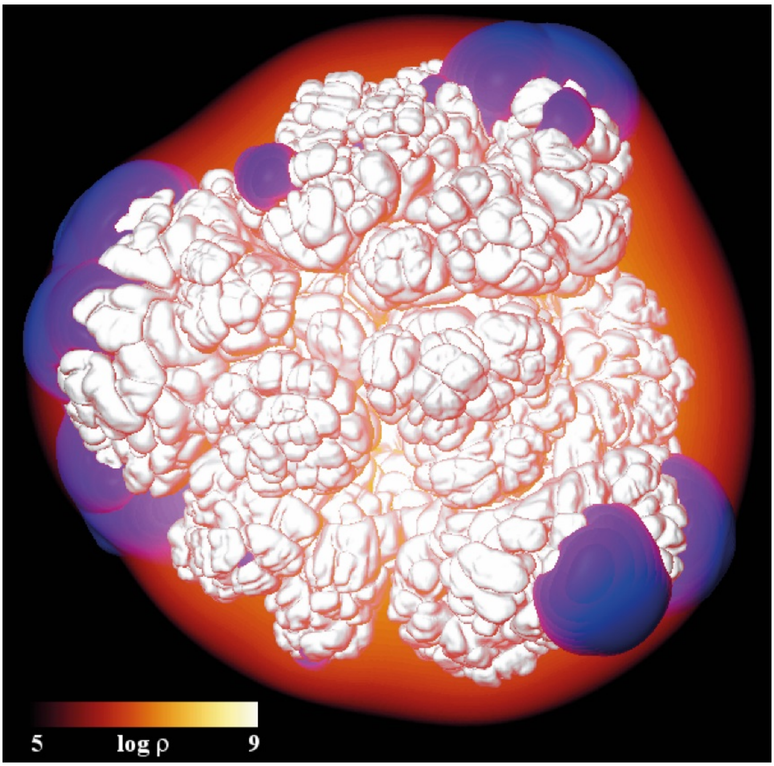
Simulated supernovae match many observations but lack diversity

Supernovae are dramatic explosions that occur at the end of the lives of certain types of star. These events are intensely energetic, ejecting debris with speeds of tens-of-thousands of kilometers per second and radiating, albeit briefly, with luminosities billions of times greater than our Sun. The energy and material ejected by supernovae have a key role in the evolution and chemical history of galaxies, and the brightness of supernovae means that it is feasible to observe them at great distances and use them to probe the expansion history of our Universe. However, we still lack a complete understanding of the nature of supernovae: which stars explode, and why? In an ongoing attempt to answer such questions, astronomers within CAASTRO, and around the world, are studying supernovae using a combination of observational campaigns, such as the SkyMapper supernova survey, and theoretical simulations of explosion physics.



As part of an international research team, Dr Stuart Sim (CAASTRO Associate Investigator, Queen's University Belfast) and Dr Ivo Seitenzahl (CAASTRO Associate Investigator, ANU) led two studies that help make the link between theoretical ideas and observed properties of supernovae. Their work focuses on so-called "Type Ia" supernovae.

These supernovae are thought to result from the explosion of white dwarf stars, but the means by which the explosion is triggered is widely debated. One of the leading models for Type Ia supernovae is the "Chandrasekhar mass delayed-detonation" scenario in which explosion occurs as a result of a white dwarf star increasing in mass due to transfer of material from a main-sequence (or giant) companion star in a binary system. In their publications, the team (also including CAASTRO Associate Investigator Dr Ashley Ruiter, ANU) presents the first set of theoretical predictions for light curves and spectra from a set of full three-dimensional hydrodynamical simulations of the delayed-detonation model. These synthetic observables can be compared to real data to judge the success of the theoretical models.

The researchers found that the full explosion models are remarkably successful in explaining many observed properties: although imperfect, the match to many observed features in the optical spectra of real supernovae is remarkable, and variations due to the orientation from which the supernova is observed can explain some of the observed differences between supernovae. However, the set of models considered do not yet account for the full range of observed properties of Type Ia supernovae. Building on this work, the team is now focused on extending their studies to alternative theoretical models and identifying the best way to use modern observations to distinguish between models.

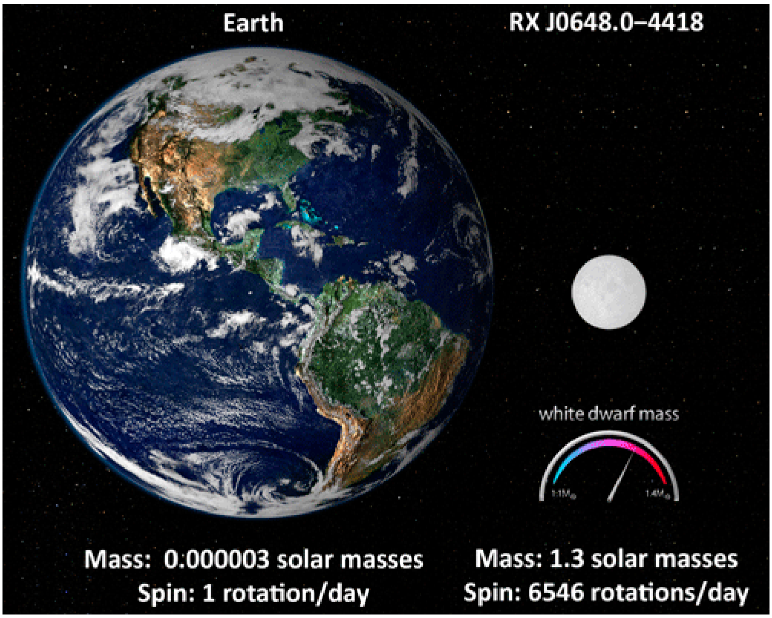
Publication details:

Stuart Sim, Ivo Seitenzahl et al. in the Monthly Notices of the Royal Astronomical Society (2013) "*Synthetic light curves and spectra for three-dimensional delayed-detonation models of Type Ia supernovae*"

Ivo Seitenzahl et al. in the Monthly Notices of the Royal Astronomical Society (2013) "*Three-dimensional delayed-detonation models with nucleosynthesis for Type Ia supernovae*"

The fastest spinning White Dwarf?

The fastest spinning known pulsar rotates at a rate of 716 Hz (i.e. 716 rotations per second), the slowest takes 8.5 seconds to complete one rotation. Rotating White Dwarfs are much slower, AE Aqr being the fastest and taking 33 seconds for one rotation, while the rest are even slower. Then there is RX J0648.0-4418, a nearby (~650 parsec) compact star in a 1.5-day binary with a rather unremarkable sub-dwarf star. It is unclear what RX J0648.0-4418 is but it is an intriguing and extreme case. The star is seen as an X-ray source with a temperature of about 450,000 Kelvin and black-body radius of only about 20 km. The X-ray emission varies periodically as the star rotates, with a period of 13.2 seconds.



The temperature and size tell us that it is either a massive (and therefore small) White Dwarf or a Neutron Star but the spin period does not point to a clear answer: it is either the fastest spinning White Dwarf known or a very slow Neutron Star. Studying the orbital dynamics, its mass was determined as 1.3 solar masses – which, again, does not solve the mystery. Neutron Stars can be stable well above 2 solar masses, whereas White Dwarfs are unstable to gravitational collapse beyond the Chandrasekhar limit of 1.4 solar masses. So if RX J0648.0-4418 is a White Dwarf, it is very close to the limit, which is uncommon (most are ten times lighter). If RX J0648.0-4418 is a Neutron Star, its temperature suggest that it is young and, therefore, that its pulsar mechanism is active.

With this in mind, CAASTRO Affiliate Dr Evan Keane (SKA Office, Manchester; previously postdoc at Swinburne University) devised an observational study to resolve the issue: is there pulsar emission or not?

Australia's prolific pulsar hunting telescope, the 64-m CSIRO Parkes Radio Telescope, was employed in one of the deepest searches for pulsar emission ever performed, sensitive to both steady periodic emission and sporadic bursts, but the study came up empty. So, it appears as if RX J0648.0-4418 is not a pulsar but rather the heaviest White Dwarf known and also the fastest spinning. It would not take much to push it over the edge towards supernova. But for now it seems stable and offers a unique chance to study this most extreme version of this extreme type of star.

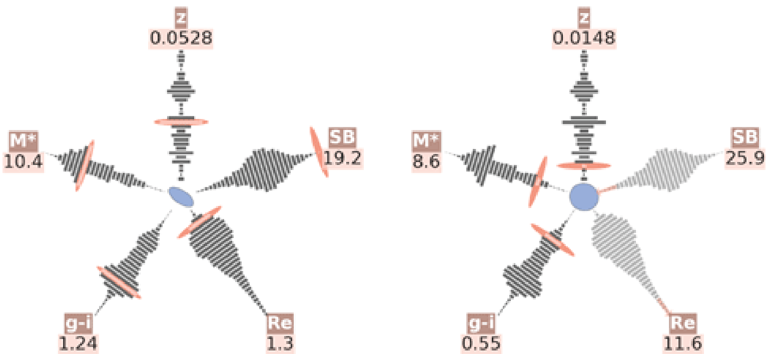
Publication details:

Evan Keane in the Monthly Notices of the Royal Astronomical Society (2015) "*A search for coherent radio emission from RX J0648.0-4418*"

Sports statistics inspired "Starfish" visualisation of SAMI data

Imagine you are a galaxy floating through space. You know more or less how luminous you are, how large, how massive. But how do you compare to your peers? Whether galaxies get status anxiety or not, this question is very interesting for astrophysicists, and the "Starfish" diagram now lets them know exactly how individual galaxies measure up with the Universe around them. The visualisation of individual targets and their properties is the "Where's Waldo?" challenge in the time and age of very large astronomical surveys.

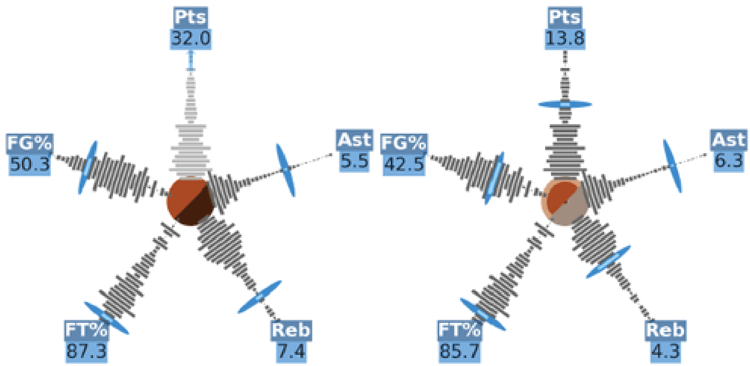
"Starfish" are, in essence, five-dimensional histograms. They plot a set of properties for an individual, along with the complete underlying statistical distribution of the sample from which these individuals are drawn. Each of the five histograms is pivoted about a central point of symmetry – this shape was decided to be optimal in user-testing. In that sense, "Starfish" approximate the function of violin plots but they extend the use case to precisely representing the place of the individual, rather than the distribution. The default option is to represent five attributes, but more can be accommodated.



The need for such a plotting technique came out of the SAMI Galaxy Survey, one of CAASTRO's flagship projects. When tasked with developing a data perusal interface, former CAASTRO Affiliate Dr Iraklis Konstantopoulos, at the Australian Astronomical Observatory (AAO), decided to rely solely on images, rather than text and numbers, to convey meaning. The user was invited to decide which galaxy dataset to download after perusing slices of hyper-spectral imaging.

As a second layer of screening, Dr Konstantopoulos and the SAMI team provided a "Starfish" diagram to place the galaxy and its properties (redshift, stellar mass, surface brightness, effective radius, colour excess) in the context of the survey: is the galaxy exceptional in any way or is it regular? The users could review and decide which galaxies fit their experiment best.

Astrophysics is not the entire ballpark for these "Starfish". The inspiration for the design actually came from the visualisation of sports statistics in 1990's video games. There, the aptitude of an athlete in a range of indicators, such as speed, agility, strength etc, was captured by way of partially filling circles and pentagons. The "Starfish" design adds a representation in that every other player's skill level is included in the sample distribution and the individuals' effective ranking among their peers is revealed at a glance.



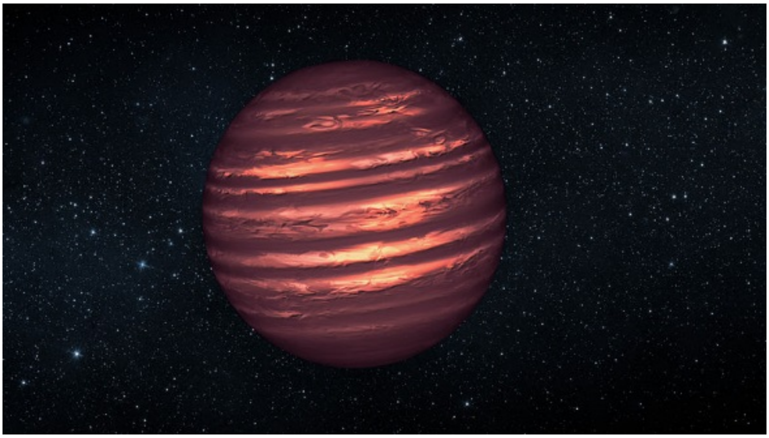
"Starfish" can be used to represent any sample-individual relationship in datasets where the place of an individual needs to be visually quantified.

<u>Publication details:</u>

Iraklis Konstantopoulos in Astronomy & Computing (2014) "*The Starfish Diagram: Visualising Data Within the Context of Survey Samples*"

Radio-loud ultracool dwarfs allow analysis of magnetic fields

The group of lowest mass stars and brown dwarfs are collectively called ultracool dwarfs. A number of these objects are sources of both burst and quiescent radio emission. The radio bursts are sometimes found to occur periodically on the timescale of the rotation of the ultracool dwarf or as isolated events. They are highly circularly polarised and occur over a timescale of a few minutes. Alternatively, the quiescent emission is observed to have very little variability and low circular polarisation. Both radio emission components are thought to be the result of magnetic processes and imply that ultracool dwarfs are able to generate and sustain strong magnetic fields. This is unexpected though, given their non-solar-like interior and the observed decline in the strength of magnetic activity tracers at other wavelengths.



Radio surveys of ultracool dwarfs have found that about 10% of these systems are radio luminous, with 21 currently known to have radio emission. Correlations between the presence of radio emission and other dwarf properties such as rotation are not well established. Furthermore, little is known about the magnetic environment responsible for the radio emission observed in ultracool dwarfs. To address these issues, CAASTRO members Dr Christene Lynch and Dr Tara Murphy (University of Sydney), with colleagues from Australia and overseas, carried out a survey of 15 ultracool dwarfs located in the Southern hemisphere using the Australia Telescope Compact Array. ATCA is able to simultaneously observe over a wide range of frequencies, providing detailed information on the time-frequency structure of radio bursts and quiescent emission. Such a characterisation is required if we want to constrain the magnetic properties of ultracool dwarfs.

The researchers detected radio emission from three of the 15 observed sources, including the detection of a new source, 2MASSW J0004348–

404405. The emission from these three sources showed no variability or burst emission and was consistent with emission from a gyrosynchrotron mechanism. To characterise the magnetic conditions responsible for the observed radio emission, the team constructed a simple stellar magnetospheric model consisting of mildly-relativistic electrons that spiralled in a uniform magnetic field. They found the observed quiescent emission to be consistent with radio emission expected from a magnetic environment with a field strength 10 – 230 G and electron density 104 – 108 cm-3. Additionally, they analysed the general trends of the radio emission for this sample of 15 sources and found that the radio activity increased for later spectral types and more rapidly rotating objects.

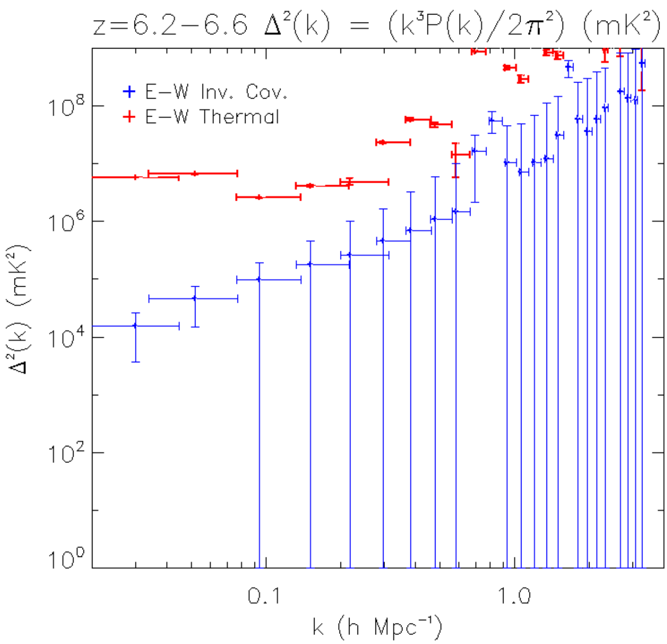
Publication Details:

Christene Lynch, Tara Murphy et al. in the Monthly Notices of the Royal Astronomical Society (2016) "*Radio detections of southern ultracool dwarfs*"

CHIPS: The Cosmological HI Power Spectrum Estimator

Exploring the neutral hydrogen from the first billion years of the Universe provides a wealth of information about the ionisation state, spatial structure and temperature of the intergalactic medium and the growth of the first stars, galaxies and black holes in the Universe. Neutral hydrogen is probed through its radio frequency emission line, observable from the early Universe with low-frequency radio telescopes. The Murchison Widefield Array (MWA) can detect 12 billion year-old hydrogen and provide a first glimpse into the evolution of the Universe at this early time – the Epoch of Reionisation (EoR).

As part of the MWA EoR project, CAASTRO Associate Investigator Dr Cathryn Trott (ICRAR-Curtin University) and colleagues have designed, built and launched a sophisticated data analysis tool to take the complex data from the telescope and extract the tiny EoR signal. CHIPS, the "Cosmological HI Power Spectrum Estimator", is based on signal detection theory and a sound knowledge of the characteristics of our telescope, to seek an optimised measurement of the EoR signal. As one of the two primary signal estimation pipelines for the MWA, it uses data calibrated through the MWA Real Time System (RTS), developed by CAASTRO members at the University of Melbourne, to extract the signal from the contaminated and noisy data.



In their recently-published paper, the researchers define the mathematical framework for the CHIPS Estimator and then apply it to three hours of test data from the MWA EoR experiment. As a small subset of the >1000 hours of the full experiment, this "golden set" of data is being used by multiple groups to test and refine their analysis methods. The CHIPS Estimator was demonstrated to produce the expected signals from this dataset and provides an upper limit on the strength of the early Universe signal.

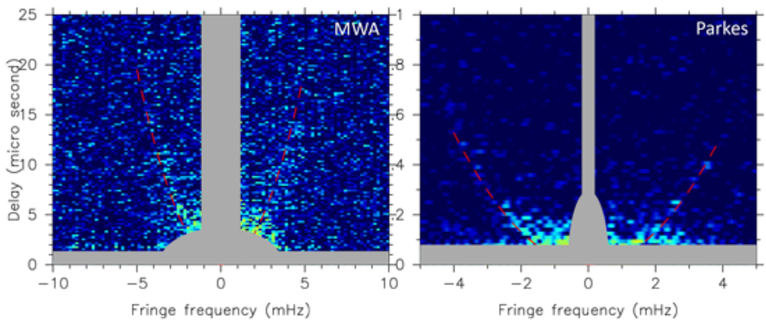
Publication Details:

Cathryn Trott, Bart Pindor, Pietro Procopio, Randall Wayth, Daniel Mitchell, Benjamin McKinley, Steven Tingay et al. in the Astrophysical Journal (2016) "*CHIPS: The Cosmological HI Power Spectrum Estimator*"

Detection of parabolic arc helps locate pulsar scattering screen

Millisecond pulsars are precise clocks provided by nature. By measuring pulse arrival times of many such pulsars distributed over the sky – a pulsar timing array (PTA) – astronomers are hoping to detect long-period gravitational waves, as produced in super-massive black hole mergers. This requires extremely high timing precisions: every possible source of error must be accounted for, including those arising from propagation effects in the interstellar medium (ISM). The ISM effects are strongest at the low frequencies that the Murchison Widefield Array (MWA) operates at.

An ICRAR-Curtin University based CAASTRO team led by Associate Investigator Dr Ramesh Bhat undertook MWA observations of PSR J0437–4715, a high-priority pulsar for the Parkes PTA experiment. The observations were made at a frequency of 192 MHz and exploited a brand new capability that they had recently developed for high time resolution science with the MWA: a tied-array beam processing pipeline which coherently combines voltage signals from all 128 antenna tiles. These signals were calibrated for the complex gains of individual tiles, as well as their polarimetric responses, yielding a ten-fold increase in sensitivity.



The turbulent ISM has denser regions that act as ‘scattering screens’ and produce thousands of images of the same pulsar, all at once. To an observer, interference between the scattered radiation – or scintillation – appears as brightening and dimming of the pulsar, the radio analogue of twinkling stars. This interference pattern can be captured by creating the ‘secondary spectrum’ (a two-dimensional Fourier transform of the dynamic spectrum that records the pulsar’s intensity as a function of time). The research team found faint, parabolic arc-like features in the secondary spectrum of PSR J0437–4715. These ‘scintillation arcs’ result from interference between the pulsar’s bright central core image and a ‘halo’ of images produced by the scattering screen. The curvature of the arcs critically depends on the distance to the scattering screen.

Adopting a technique based on Hough transform, which involves repeatedly fitting for the curve while summing the power along the curve segments, the researchers identified the curve with maximum power as the best fit. Based on this measurement, together with the distance and space velocity of PSR J0437-4715 from timing observations, they determined that the scattering screen lies at a distance of 115± 2 parsecs from Earth. This was independently verified using data from CSIRO’s Parkes telescope at a higher frequency, 732 MHz. The inferred location matches well with the estimated distance to the edge of the Local Bubble: a large, elongated cavity in the local ISM in which our Solar System resides.

The work demonstrates the MWA’s potential to play an important role in studying scattering delays in the signals of timing-array pulsars and the effect of the turbulent ISM in timing-array observations.

Publication details:

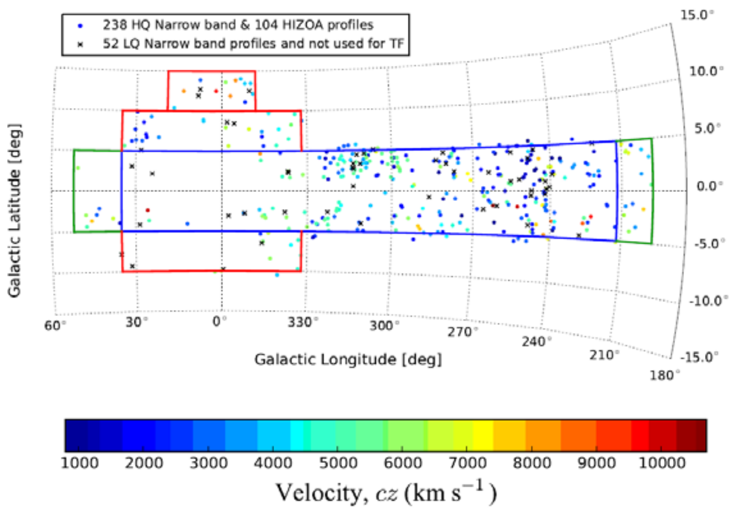
Ramesh Bhat, Stephen Ord, Steven Tremblay, Sammy McSweeney & Steven Tingay in the Astrophysical Journal (2016) "*Scintillation arcs in low-frequency observations of the timing-array millisecond pulsar PSR J0437−4715*"

Observing gas, mass and motions in the "Zone of Avoidance"

We are not living in a fixed rest frame on Earth: the Earth is orbiting around the Sun, the Sun is moving around the centre of our galaxy, and the galaxy itself is moving towards the nearest mass over-density around us, which is the nearest galaxy cluster in Virgo. Similar motions arise from even larger scales and larger mass densities, such as the gravitational anomaly "Great Attractor". To get a complete overview of these motions, we need a whole-sky map of the galaxies, together with these gravitationally induced motions.

A major stumbling block in these efforts is our own galaxy, which blocks the sky behind it from our view. Many of the large-scale structures are hidden behind the dust and stellar density of our Milky Way, notably the Great Attractor, Perseus-Pisces Supercluster, Puppis Cluster and the Local Void. This results in the so-called "Zone of Avoidance" (ZoA).

Contrarily to optical light though, radio waves travel unhindered through the galaxy. Researchers are therefore using the Parkes radio telescope to measure the gas in galaxies hidden behind the Milky Way. Combining these observations with near infrared (NIR) imaging allows measuring the distance and gravitationally induced peculiar velocity via a distance indicator called the Tully-Fisher (TF) relation.



CAASTRO PhD student Khaled Said, who is jointly supervised by researchers at the Astrophysics, Cosmology and Gravity Centre at the University of Cape Town, South Africa, and CAASTRO Deputy Director Prof Lister Staveley-Smith (ICRAR-UWA), recently published his analysis of 290 new galaxy observations with the Parkes Multibeam Receiver. The team also used 104 additional galaxies from the existing

HIZoA survey. The final sample contained 342 inclined spiral galaxies in the southern ZoA with adequate signal-to-noise and HI profiles suitable for their TF analysis.

The aim of this analysis was the development of a systematic processing pipeline for HI line spectra for future applications of the TF relation in the ZoA. Their current sample, in conjunction with their previously published newly calibrated TF relation and current NIR data, will be the first accurate determination of flow fields in the southern ZoA. Their results will be an important contribution to the forthcoming WALLABY survey (Widefield ASKAP L-band Legacy All-sky Blind surveY) and its northern hemisphere counterpart, the Westerbork Northern Sky HI Survey (WNSHS).

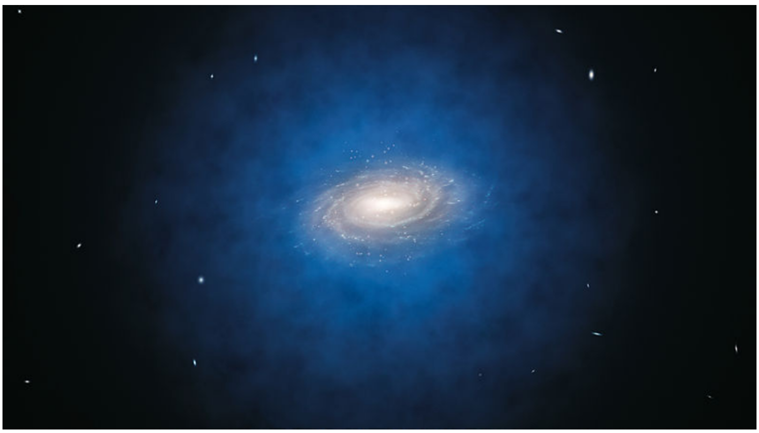
Publication details:

Khaled Said et al. in the Monthly Notices of the Royal Astronomical Society (2016) "*NIR Tully-Fisher in the Zone of Avoidance. - II. 21 cm HI-line spectra of southern ZOA galaxies*"

Suppression of low-mass galaxy formation during reionisation

The Universe experienced an "Epoch of Reionisation" (EoR) at redshift $z \geq 6$ during which the cosmic diffuse neutral hydrogen (HI) was "photo-ionised" by a background of ultraviolet (UV) and X-ray radiation. This radiation was produced by the first generation of stars and galaxies that formed from HI. Otherwise inefficient in their star formation, the gas from the shallow potential wells of low-mass dark matter haloes also got heated and expelled by this radiation. The questions remain whether there is a critical dark matter halo mass below which galaxy formation was suppressed during reionisation, and what the precise value of the halo circular velocity is.

A recent publication by CAASTRO members in the Evolving Universe theme, led by University of Melbourne Affiliate Dr Hansik Kim, used data from the HI Parkes All-Sky Survey (HIPASS) and Arecibo Legacy Fast ALFA Survey (ALFALFA) to estimate the HI mass function down to masses of a few times 10^6 h^{-2} Solar Masses in the local Universe. The researchers tried to reproduce the observed HI mass functions using the semi-analytic galaxy formation model GALFORM – previously developed by CAASTRO member Dr Claudia Lagos (ICRAR-UWA) – and to probe the physics of low-mass galaxy formation.



By default, GALFORM models the effect of photo-ionisation feedback by restricting galaxy formation in haloes of smaller effective circular velocities than a fixed value at redshifts following the end of reionisation. The predicted HI mass function from this model shows good agreement with observations for masses greater than ~ 108 h-2 Solar Masses but it does not explain the abundance of galaxies with HI masses between 10^6 h^{-2} and 10^8 h^{-2} Solar Masses. In the current study, the research team built on the default model by varying parameters such as supernova feedback, efficiency of star formation, the cosmological model, redshift and critical velocity of suppression of galaxy formation by photo-ionisation feedback. All of these effects failed to explain the shape and abundance of the low-mass end of HI mass function though.

They show that redshift-dependent modelling of feedback from photo-ionisation on low-mass galaxy formation was needed to match the shape and abundance of the observed HI mass function in the local Universe. They also found that the HI mass function was more sensitive to the redshift evolution of photo-ionisation feedback at high redshift. Future measurements of HI clustering in low-mass galaxies and the relation between the HI mass and the stellar mass of galaxies will further constrain the form of ionising feedback.

<u>Publication details:</u>

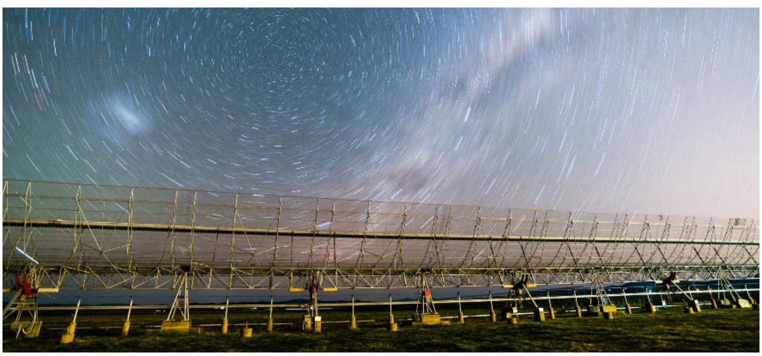
Han-Seek Kim, Stuart Wyithe, Chris Power et al. in the Monthly Notices of the Royal Astronomical Society (2016) "*The HI mass function as a probe of photoionisation feedback on low mass galaxy formation*"

Could Fast Radio Bursts be of cosmological origin?

High time resolution radio surveys over the last decade have discovered a population of millisecond-duration transient bursts called Fast Radio Bursts (FRBs) of unknown. Only 18 of these bursts have been detected to date, and their origin – whether extragalactic or at even cosmological distances – is still uncertain.

CAASTRO PhD student Manisha Caleb (ANU and Swinburne University) and colleagues have now scrutinised the FRB properties: energy distribution, spatial density as a function of redshift and properties of the Interstellar and Intergalactic Media. The researchers ran simulations to test whether a cosmological population is a feasible scenario and to compare their simulations to data from the High Time Resolution Universe survey that used the Effelsberg radio telescope in Germany and the 64-m Parkes radio telescope in Australia.

Their Monte Carlo simulations were based on two scenarios for the co-moving numbers of FRBs: a constant co-moving density model and a model in which the number of FRBs is proportional to the known cosmic star formation history (SFH). The most interesting property of the simulated events is their distribution of detections above some fluence (so-called logN-logF curves): if the sources have an even approximately typical luminosity (i.e. are standard candle-like), then the slope of this relation is a probe of their spatial distribution. For standard candles in the standard model of cosmology – LCDM – the slope varies smoothly from -3/2 for the nearby universe, gradually becoming flatter as further distances are probed. To illustrate, at a redshift of z ~0.7, which is typical of FRBs found to date, standard candles yield a relation with a slope of ~ -1. The observed slope of the logN-logF of the 9 FRBs analysed in this study is -0.9 +/- 0.3. The team's simulations were able, in both scenarios for the number density of the sources with redshift, to match this slope well, yielding -0.8 +/- 0.3 for the cosmic SFH and -0.7 +/- 0.2 for the constant density case. They concluded that the properties of the observed FRBs are generally consistent with arising from sources at cosmological distances.



The researchers also simulated FRB rates at the upgraded Molonglo telescope, UTMOST, and at Parkes for the Multibeam and the planned Phased Array Feed (PAF) receivers. They applied conservative assumptions about the spectral index of FRBs and the sensitivity of the instruments. According to those simulations, UTMOST has the capability, at full design sensitivity, to dominate the FRB detection rate. Uncertainty in the final PAF design sensitivity make predictions difficult for Parkes but its wide sky coverage has the potential to increase the FRB discovery rate close to the fluence limit. The fully sensitive UTMOST will dominate the event detection rate at all fluences.

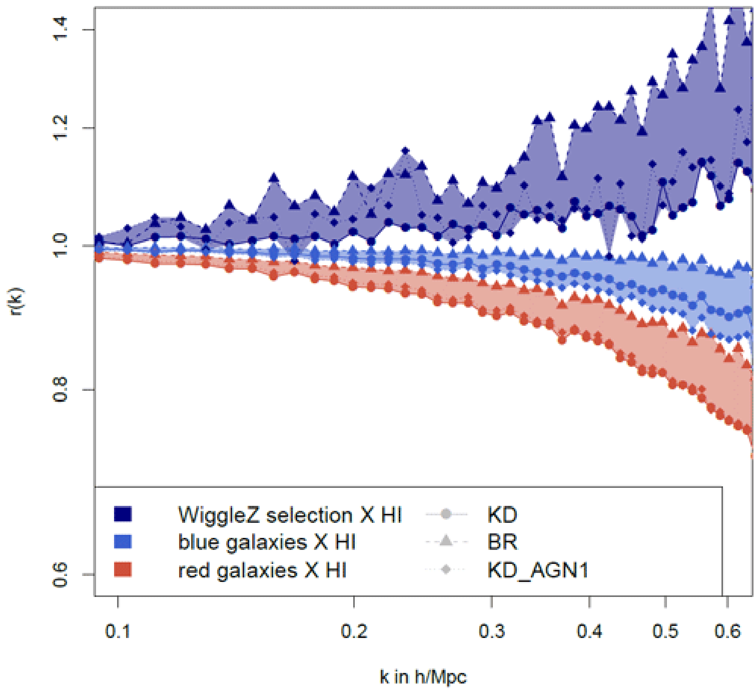
<u>Publication details:</u>

Manisha Caleb, Chris Flynn, Matthew Bailes, Ewan Barr et al. in the Monthly Notices of the Royal Astronomical Society (2016) "*Are the distributions of Fast Radio Burst properties consistent with a cosmological population?*"

Statistical tool beats radio telescopes in measuring distant gas

Intensity mapping is a novel technique that uses the Hydrogen emission at radio wavelengths of galaxies as a proxy for galaxy distribution on large scales. The statistical properties of this distribution help us understand the cosmological principles of our Universe. Hydrogen gas is the most abundant element in the Universe, and it is the main ingredient to fuel star-formation processes in galaxies and is thus driving galaxy evolution.

The individual detection of cold Hydrogen gas in distant galaxies is not yet feasible with radio telescopes. However, using intensity mapping, we observe the combined – or binned – emission of many galaxies through low-resolution maps and are able to observe the Cosmic Web over very large distance ranges.



The galaxy distribution is quantified by measuring the cosmological power spectrum. These power spectra contain information on the clustering strength of galaxies as a function of distance or scale. In recent analysis, the intensity mapping data was jointly analysed with optical data of the same regions to measure the cross-power spectrum, to eliminate foregrounds and instrumental noise contaminations in the maps.

As part of the CAASTRO intensity mapping project, CAASTRO post-doctoral fellow Dr Laura Wolz and colleagues at the University of Melbourne have theoretically investigated the signature of the cross-power spectrum of intensity maps with optical galaxy data. They modelled the intensity mapping signal using numerical simulations of the evolution of galaxies with cosmic time. In addition, they synthesised a mock galaxy catalogue of optical telescope observations based on the same simulation. In their study, the researchers show that the cross-power spectrum of intensity maps and optical galaxies has a different shape depending on how the optical galaxies were selected: blue galaxies, which are highly star-forming, show a much higher clustering signal on small scales than red galaxies, which are relatively passive. This proves that these signals can be linked back to the Hydrogen content of the optical galaxies as it correlates with the galaxy colour: blue galaxies are rich in cold gas while red galaxies are relatively gas poor.

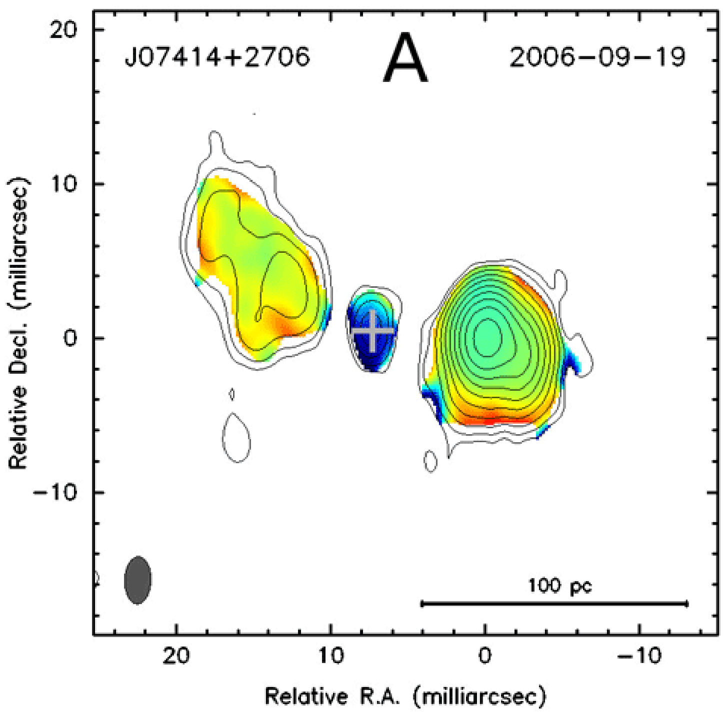
Intensity mapping in combination with optical galaxy measurements may therefore indirectly detect the Hydrogen gas content of the optical galaxies that were selected according to their colours. This theoretical study is the first proof of concept of this new Hydrogen detection technique, and the approach opens up new possibilities in understanding the gas content, and thus the star-formation activity, of very distant galaxies which are inaccessible to direct observations with our current generation of radio telescopes.

Publication details:

Laura Wolz, Chiara Tonini, Chris Blake & Stuart Wyithe in the Monthly Notices of the Royal Astronomical Society (2016) "*Intensity Mapping Cross-Correlations: Connecting the Largest Scales to Galaxy Evolution*"

A huge telescope looked closely at the smallest radio galaxies

Radio galaxies are twin-lobed structures visible in the radio portion of the electromagnetic spectrum which typically extend 100-1,000 kilo-parsecs end to end. The lobes are the result of two opposing jets coming out of the central black hole of these galaxies. These jets ‘inflate’ lobes as they slam into the surrounding material and recoil back towards the centre. A powerful instrument to locate, identify and categorise such structures is the Very Long Baseline Array (VLBA), a telescope array of ten identical antennas that spans 8,000 km across the US, from Hawaii in the Pacific Ocean to the Virgin Islands at the border between the Caribbean Sea and the Atlantic Ocean. These long baselines allow researchers to precisely pinpoint – or triangulate – the location of objects. As part of a full polarisation survey of radio sources, the VLBA Imaging and Polarimetry Survey, data were also suitable to search for rare compact symmetric objects (CSOs). CSOs are smaller than 1 kilo-parsec and generally thought to be young, generally only a few hundreds of years old. They give astronomers an opportunity to observe the early evolutionary phases of these radio galaxies.



Using the VLBA data, CAASTRO postdoc Dr Steven Tremblay (ICRAR-Curtin University) and his research team have recently published their identification of 24 radio galaxies as CSOs, the smallest in their sample measuring only 1.5 parsecs across. Within their sample, the researchers were able to confirm 15 new CSOs, effectively doubling the number of these sources known to date. They also uncovered a possible new sub-class of low-powered CSOs which is similar to a distinction that also occurs in normal radio galaxies. It also allows insight into the local environments around such sources.

The multi-frequency observations (at 5, 8 and 15 GHz) presented in their study also enable understanding of the structure within the galaxies, due to the strong frequency dependence from different stages of the jets. New emission streaming out from the central engine changes slowly with frequency while the surface where the jets are pushing against the surrounding media vary greatly across the observed frequencies. These data can be combined into spectral index maps, highlighting the dynamics happening within these sources in a single snapshot. Overlaying the contour lines for one frequency (e.g. 5 GHz) with a colour scale that depicts the brightness change to another frequency (5 and 8 GHz), the researchers were able to produce 120 of such multi-frequency snapshots that were the primary basis for classification.

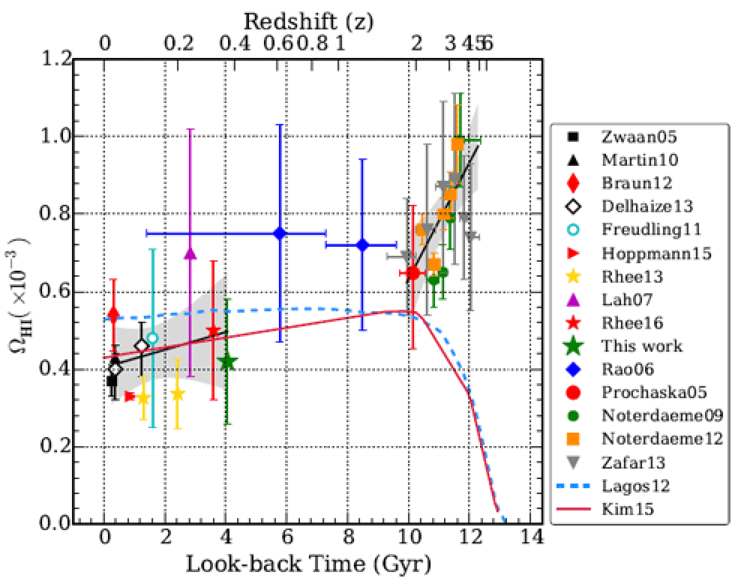
Publication details:

Steven Tremblay et al. in the Monthly Notices of the Royal Astronomical Society (2016) "*Compact Symmetric Objects and Supermassive Binary Black Holes in the VLBA Imaging and Polarimetry Survey*"

Cosmic hydrogen gas has not evolved over past four billion years

Understanding the evolution of the atomic gas (HI) content of galaxies remains one of the key challenges in the study of galaxy evolution. The sensitivity of the current generation of radio telescopes is insufficient to detect HI from individual galaxies at cosmologically significant redshifts in reasonable integration times. In fact, the detection of HI from individual galaxies at high redshifts was one of the original motivations and remains one of the key science drivers for the proposed Square Kilometre Array (SKA). It is also one of the key programs for several of the upcoming SKA pathfinder telescopes such as ASKAP and MeerKAT.

Although it is challenging to detect HI in individual galaxies at redshifts $z \geq 0.2$ with the current generation of radio telescopes, it is possible to make measurements of the average HI content of a sample of galaxies. If the positions and redshifts of all of these galaxies are known, we can stack their spectra to determine their average HI content. This is called the HI spectral stacking technique, and it is what CAASTRO researcher Dr Jonghwan Rhee and colleagues used in their recent publication.



Observing with the Giant Metrewave Radio Telescope in Pune, India, they applied the HI spectral stacking technique to data from the COSMOS field – a field for that a wealth of multi-wavelength data is available. The aim was to determine the cosmic HI mass density Ω_{HI} at a redshift $z \sim 0.37$. The researchers found $\Omega_{HI} = (0.42 \pm 0.16) \times 10\text{-}3$ at $z \sim 0.37$, which is the highest-redshift measurement of Ω_{HI} ever made using HI spectral stacking. Their result is consistent with those measured from large blind 21-cm surveys at z = 0, as well as measurements from other HI stacking experiments at lower redshifts. In conjunction with earlier measurements, their result also indicates that there has been no significant evolution of HI gas abundance over the last 4 Gyr. The Ω_{HI} measured here from HI 21-cm emission measurements at $z \leq 0.4$ is approximately half that measured from Damped Lyman-α Absorption (DLA) systems at $z \geq 2$ though. Deeper surveys with existing and upcoming instruments will be critical to understand the evolution of Ω_{HI} in the redshift range intermediate between $z \sim 0.4$ and the range probed by DLA observations.

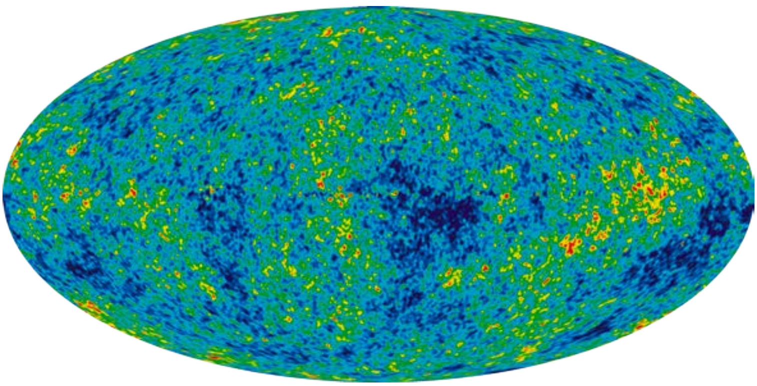
Publication details:

Jonghwan Rhee et al. in the Monthly Notices of the Royal Astronomical Society (2016) "*GMRT observation of neutral atomic hydrogen gas in the COSMOS field at z ~ 0.37*"

Local gravitational environment a proxy for expanding Universe

The large-scale structure of the Universe provides one of our most powerful tests of the cosmological model, encoding a wealth of information about the expansion history of the Universe – imprinted as a standard ruler in baryon acoustic oscillations – and its gravitational physics – inferred from the growth of structure with time. Measuring the acoustic peak allows cosmologists to probe the dynamics of the Universe and the properties of the mysterious dark energy component.

However, the late-time gravitational interactions tend to erase the acoustic peak in the matter correlation function. Hence, cosmologists seek new ways to reconstruct the initial pattern of the galaxy clustering by mapping the displacement of galaxies. By shifting the position of the galaxies according to the local surrounding gravitational potential, they can infer the initial positions of the galaxies. Measurement of the matter correlation function on the reconstructed galaxy positions can thereby restore the shape of the acoustic peak.



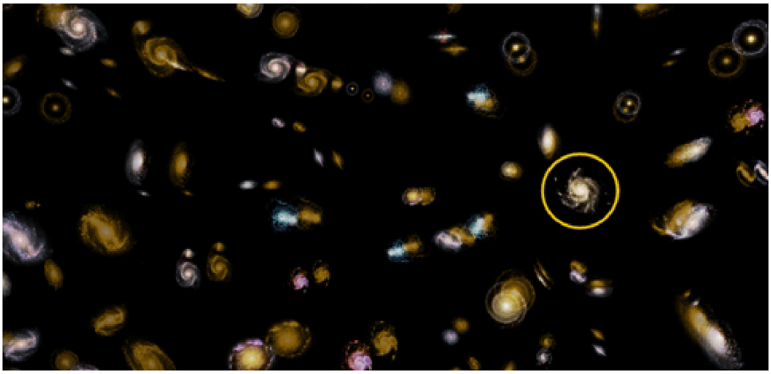
As part of the CAASTRO Dark Universe research theme, Dr Ixandra Achitouv and Prof Chris Blake at Swinburne University of Technology have now found a direct correlation between the accuracy of the reconstructed position of galaxies and the scale used to infer the local gravitational potential which is required to reconstruct the positions. The researchers have also invented a new approach to analysing the reconstructed clustering of galaxies, based on the properties of the underlying matter density field. They show evidence that under-dense regions will carry more information on the acoustic peak compared to over-dense regions. Through their simulations, they were able to provide new estimates of the correlation functions which increase the accuracy of the acoustic peak measurement by 8%. This value may even be improved through future work, using sophisticated weighting schemes. The researchers will also investigate whether their model is readily applicable to non-standard cosmologies.

Publication details:

Ixandra Achitouv & Chris Blake in Physical Review D (2015) "*Improving reconstruction of the baryon acoustic peak: the effect of local environment*"

Confirming the surprise: the many successes of dark energy

The idea that dark energy makes up 70% of the energy of the universe seems ludicrous at first sight (pun intended!). How is it that we are so confident of so much that we cannot see?



CAASTRO Chief Investigator and "The Dark Universe" theme leader Professor Tamara Davis has run through all the many-varied ways in which we have now detected the influence of dark energy. Often the observations of supernovae in the late 1990s are touted as the big breakthrough that discovered that the expansion of the universe is accelerating. And indeed they were the first really decisive observations. However, the supernova discovery fell on fertile ground. There were already many simple hints that indicated dark energy should exist. Primary among them was that the universe appeared to be younger than the oldest stars – a problem for anyone who thought that the universe should be older than the things it contained! There were too many distant galaxies, and the curvature of the universe seemed all wrong. Acceleration (dark energy) fixed all of that. It makes the universe older than we thought, changes the volume so the number of galaxies is right, and flattens out the curvature.

Since the supernova results brought dark energy to the fore, the course of cosmology has changed, and over the last 16 years an enormous amount of effort has gone into testing dark energy in every way we could conceive. We have observed light from just after the big bang (the Cosmic Microwave Background or CMB), measured the distribution of galaxies across billions of light years, detected sound waves from the big bang (yes, there was once sound in space!), measured the motion of hundreds of thousands of galaxies, detected light being bent by the gravitational field around galaxy clusters, seen galaxy clusters collide, watched time running more slowly in the distant universe (time dilation), and much, much more! Every single one of these observations confirms that dark energy exists... Our challenge, now, is to explain what the dark energy is!

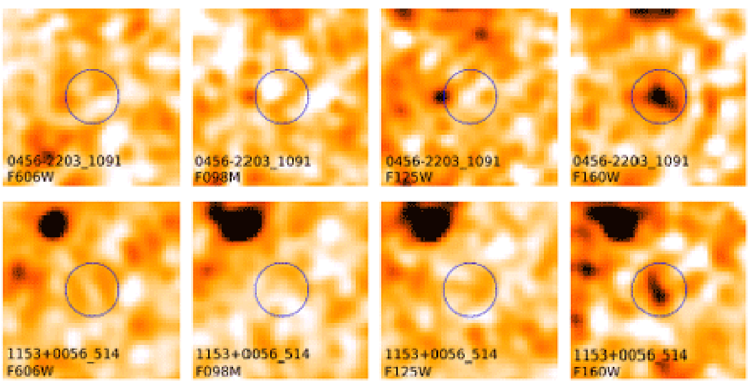
Publication details:

Tamara Davis in General Relativity & Gravitation (2014) "*Cosmological constraints on dark energy*"

The BoRG survey boosts numbers of earliest galaxies ever known

Between 100 million to one billion years after the Big Bang, the Universe went through a transition, where neutral hydrogen was ionised, transforming the intergalactic medium from opaque to transparent. This "Epoch of Reionisation" is receiving intense research focus, as there are still many open questions about this period. While future telescopes like the Square Kilometre Array (SKA) will be able to look at the neutral hydrogen, observing the stars and galaxies that were the sources of reionisation is still difficult. One possibility of investigating the formation and evolution of galaxies in the early Universe, along with the progression of reionisation, is to observe the ultraviolet light emitted by these high-redshift sources (stretched to be detected at infrared wavelengths from Earth) with space telescopes, located above the Earth's atmosphere. Deep legacy surveys with the Hubble Space Telescope (HST) have produced a growing sample of galaxies during this period.

At the highest redshifts, the number of galaxy candidates is still small, with only a handful detected in HST imaging. To increase the sample, CAASTRO PhD student Stephanie Bernard (University of Melbourne), along with international collaborators, used HST/Wide Field Camera 3 (WFC3) imaging from the Brightest of Reionising Galaxies (BoRG) survey to search for the brightest galaxies only 500 million years after the Big Bang. The team found six interesting candidates in archival data. They conclude that half of the sample are strong candidates to be some of the highest-redshift galaxies so far discovered, while the other half likely to be lower-redshift sources.



The researchers also calculated the "number density", that is, the number of high-redshift galaxies in a given volume. They then determined the "luminosity function" or the number of galaxies at a particular brightness. Interestingly, when compared to previous calculations from surveys like the Cosmic Assembly Near-infrared Deep Intergalactic Legacy Survey (CANDELS), which also used WFC3 imaging, Bernard and her collaborators found almost ten times as many bright galaxies than expected. They also noted that three candidates in their sample are located in the same WFC3 pointing, which is an indication of significant clustering, as expected for very bright galaxies at high redshift. Ongoing follow-up observations by the team will shed more light on the nature of these candidate galaxies.

Publication details:

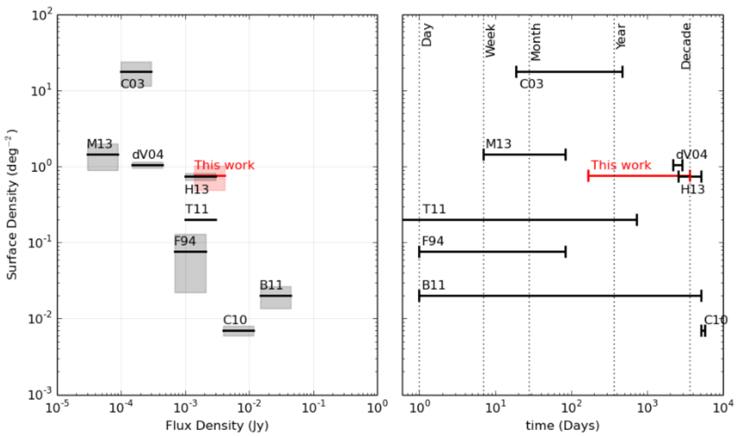
Stephanie Bernard et al. in the Astrophysical Journal (2016) "*Galaxy candidates at z ~ 10 in archival data from the Brightest of Reionizing Galaxies (BoRG[z8]) survey*"

Cadence of observations is key to variability of radio sources

Our view of the radio sky changes over time. This is partly because sources change over time: black holes devour stars and gas, stars go supernova, or clouds of fast moving electrons expand and slow. But variability is also partly due to our view through the cosmos: the gas between us and the stars and galaxies is turbulent and distorts our view of stars and galaxies, acting like a set of lenses that focus and defocus the light that we are seeing.

Much work is being done to better understand variability, in particular around a frequency of 1.4GHz. Interestingly, two surveys – both conducted with the Very Large Array (VLA) in the US – differed by a factor of ~4 in the areal density of radio variables on timescales of decades compared to timescales of less than a few years. In a new publication, CAASTRO Affiliate Dr Paul Hancock (ICRAR-Curtin University) and colleagues identified a set of archival observations from the Australia Telescope Compact Array (ATCA), suitable for a similarly sensitive survey to explain the discrepancy between the two VLA studies.

The "Phoenix Deep Survey" was conducted over 8 years during which six overlapping areas of sky were observed ("epochs") to eventually combine in a single deep map of the region. In this new study, the researchers instead looked at each of the epochs separately to identify changes in the radio brightness, or flux, of sources in the overlapping areas. Furthermore, sensitivity was similar to the two VLA studies, allowing for an independent measurement of the areal density of variable radio sources.



The team used software solutions to find and classify sources in each of the epochs, cross match sources between epochs, build up light curves for each source, and to identify sources with significant variability. In the end, they had 9 sources that were significantly variable. All but one of these sources was found to be an active galactic nucleus (accreting black hole). The key to the difference in previous areal density estimates, such as the two VLA studies, is in the cadence of the observations: one VLA study was sensitive only to variability on timescales less than a year, whilst the other was sensitive to timescales of ~7 years. Dr Hancock and his colleagues found that the largest amount of variability was seen on timescales of ~5 years.

Publication details:

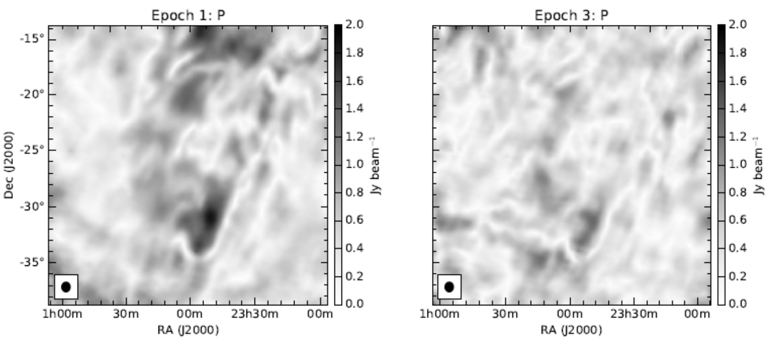
Paul Hancock et al. in the Monthly Notices of the Royal Astronomical Society (2016) "*Radio variability in the Phoenix Deep Survey at 1.4GHz*"

A CAT-scan view of our cosmic backyard with the MWA

Our understanding of the environment within our nook of the Milky Way Galaxy is surprisingly limited. Astronomers generally look how the light from nearby background sources (stars, nebulae, etc.) is effected but there are very few nearby sources against which this can be performed. A recent study, utilising the powerful capabilities of the Murchison Widefield Array (MWA), has employed a novel way to map the local environment using polarimetry.

Polarimetry is the measurement of the orientation of light waves as seen by an observer – it allows us to probe the environment through which the light has passed. Polarised sunglasses effectively turn our eyes into polarimetric instruments, ones that are only sensitive to vertically polarised light. Sunglasses work by restricting horizontally polarised light because reflected light, the kind that causes glare, is typically horizontally polarised.

When CAASTRO researcher Dr Emil Lenc (University of Sydney) and colleagues used the MWA as an electronic pair of sunglasses to measure the orientation of the cosmic radio waves it received, they revealed a whole new view of our local neighbourhood. Despite looking at the Galactic pole, where one would not expect to see much emission from the Galaxy itself – which is why this location is used to detect a signal from the "Epoch of Reionisation", the MWA revealed complex, vast and bright polarised emission.



The interstellar medium acts like a kind of cosmic fog that affects low frequency polarised signals more than higher frequency ones. Just like a radio, the MWA can tune into different frequencies, allowing it to see polarised features at different distances. Using this capability, the researchers were effectively able to perform a "CAT-scan" of the Milky Way out to approximately 160 light years in the direction of the South Galactic Pole. Mapping this structure provided a means to measure their size and also to improve our understanding of how they formed.

Interestingly, these structures were so bright that the effect of the Earth's ionosphere could also be studied. The ionosphere causes an extra rotation in orientation of the light waves measured by the MWA – the amount of rotation depends on the Solar weather at the time of the observation. By observing how the polarised emission rotates over time, the ionosphere can be mapped – an added side-effect that allowed two very different areas of science to be studied with the same observation. The findings pave the way for novel future applications in Solar and atmospheric science.

Publication details:

Emil Lenc, Bryan Gaensler et al. in the Astrophysical Journal (2016) "*Low frequency observations of linearly polarized structures in the interstellar medium near the south Galactic pole*"

Fundamental Plane relation differentiates between radio sources

The era of very large all-sky radio surveys that probe down to very faint flux limits dawns upon us. Surveys such as the Evolutionary Map of the Universe (EMU), using the Australian Square Kilometre Array Pathfinder (ASKAP) telescope, will detect emission from many radio sources that can be star-forming galaxies or accreting supermassive black holes, or Active Galactic Nuclei (AGN), that sit at the centre of most galaxies. Observations of the 1.4 GHz radio emission can be a very useful dust-free tracer of a galaxy's star formation rate because the 1.4 GHz luminosity density correlates with the far-infrared (FIR) luminosity for star-forming systems. An increased observed 1.4 GHz luminosity density is usually attributed to AGN. Hence, many studies have used this radio – FIR correlation to differentiate between radio sources whose 1.4 GHz emission is predominantly arising from star formation and/or AGN.

In a new paper, CAASTRO Affiliate Dr Ivy Wong (ICRAR-UWA) and colleagues analysed the 1.4 GHz radio properties of nearby AGN with low X-ray energies ("hard X-ray" spectrum) from the Swift Burst Alert Telescope sample at 14-195 keV. Using observations from the Faint Images in the Radio Sky at Twenty-centimeters (FIRST) survey, they found that their AGN were radio-quiet and had 1.4 GHz luminosity densities which were comparable to those originating from star-forming galaxies. The sample was consistent with the standard radio – FIR correlation that is indicative of star-forming galaxies. This was somewhat surprising because the majority of the sample were compact radio sources located at the centre of galaxies. So the question arose: are the observed 1.4 GHz luminosity densities really due to star-formation or AGN?

The researchers examined the relationship between the 1.4 GHz emission with the X-ray luminosity and estimated black hole mass via the "Fundamental Plane" relation. This relationship is known to be scale-invariant and connects the accretion of matter with the radio outflow in

Galactic stellar-mass black holes, as well as central supermassive black holes. They found that their hard X-ray selected sample was consistent with the black hole "Fundamental Plane", with the exception of one source where the extended 1.4 GHz emission seemed to include emission from the star-forming disk. Their results suggest that the observed 1.4 GHz emission originates from the low-luminosity radio AGN after all, not the star formation process. The team suggest that the observed consistency between the 1.4 GHz emission and the FIR emission might be due to a component of the 1.4 GHz emission that originates from the accretion disk corona. The radio emission from the disk corona is likely to correlate with the dust temperatures, and hence the FIR emission.

Publication details:

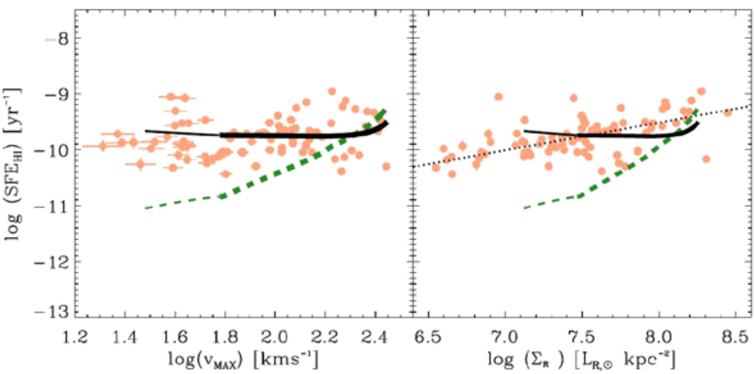
Ivy Wong et al. in the Monthly Notices of the Royal Astronomical Society (2016) "*Determining the radio active galactic nuclei contribution to the radio–FIR correlation using the black hole Fundamental Plane relation*"

Constant disk stability key to galactic star forming efficiency

Star formation in galaxies is a local process whereby stars form out of molecular Hydrogen (H_2). Detailed multiwavelength studies of the gas and stellar components of nearby galaxies have found the H_2 star formation efficiency (SFE_{H2}) – the ratio of star formation rate to the H_2 mass – to be approximately constant. Similarly, the atomic Hydrogen (HI) star formation efficiency (SFE_{HI}) has also been observed to be uniform across 5 orders of magnitude in galaxy stellar masses. Since the fraction of HI and H_2 is known to vary within a galaxy, as well as between galaxies, it is unclear what is driving the observed uniformity in SFE_{HI}.

A new model, by CAASTRO Affiliate Dr Ivy Wong (ICRAR-UWA) and colleagues, is the first to link the uniform SFE_{HI} observed in low-redshift galaxies to star-forming disks with constant marginal stability. In their simple model, disk stability is derived from a two-fluid approach: one fluid representing the gas component and the other the stellar component. The researchers tested two versions of their model with differing prescriptions for determining the molecular gas fraction, based on either the hydrostatic pressure or the stellar surface density of the modelled disk. For high-mass galaxies such as the Milky Way, they found that both prescriptions were able to reproduce the observed SFE_{HI}.

However, the hydrostatic prescription was the only prescription that was able to reproduce the observed SFE_{HI} for both low- and high-mass galaxies. The primary driver of the disk structure in the model is the amplitude of the rotational velocity, V_{max}, while the specific angular momentum of the galaxy may play a role in explaining the weak correlation between SFE_{HI} and the effective surface brightness of the disk. The team was also able to reproduce the observed star formation properties of a proto-Milky Way at higher redshifts when the Universe was at its peak star formation period.



The success of their model at reproducing the observed star formation properties in galaxies at low and high redshifts suggests that star formation in galaxies is largely governed by the formation and stabilisation of their disks.

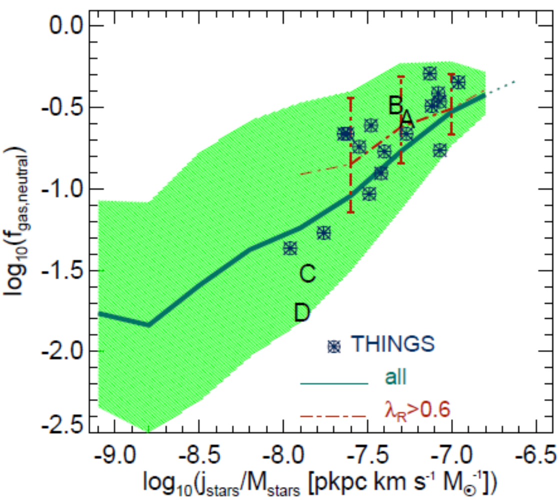
Publication details:

Ivy Wong et al. in the Monthly Notices of the Royal Astronomical Society (2016) "*Characterising uniform star formation efficiencies with marginally-stable galactic disks*"

EAGLE simulation shows gain and loss of galaxies' angular momentum

Angular momentum is a fundamental property of galaxies, together with mass and energy. It is crucial to many scaling relations, for example the relation between a galaxy's luminosity and its rotational velocity and size. Galaxy formation theory postulates that the amount of angular momentum in spiral galaxies can be obtained by assuming that they formed in dark matter halos through conservation of angular momentum. Elliptical galaxies though, which have much lower spins, need to lose more than 90% of the angular momentum they were formed with. Galaxy mergers are the main scenario invoked to explain such a major loss.

In a new publication, CAASTRO member Dr Claudia Lagos (ICRAR-UWA) and colleagues analysed the evolution of the angular momentum of galaxies in the EAGLE hydrodynamical simulations. EAGLE is a state-of-the-art simulation that has a unique compromise between the resolution required to study the structural properties of galaxies (spatial resolution of 700 pc) and the simulated cosmological volume (100 Mpc box side length). This allows for the study of about 13,000 galaxies in the simulation-equivalent of the local Universe. EAGLE is unique in its accurate reconstruction of galaxy properties across multiple research studies, predicting galaxies of roughly the right sizes, morphologies, colours, gas contents and star formation throughout cosmic time.



This new study has found a correlation between the galaxies' specific angular momentum (i.e. angular momentum as function of mass) and their stellar mass – in excellent agreement with observations and with the positions of galaxies as they correlate with gas content.

Analysing galaxy evolution in EAGLE paints a picture that is more complex than what theory predicted: galaxies that have high specific angular momentum now formed most of their stars during the second half of the age of the Universe, from gas that was falling into their halos with high specific angular momentum. In contrast, galaxies that have low specific angular momentum now formed most of their stars during the first half of the age of the Universe, from material that had much lower specific angular momentum compared to the infalling gas later. The researchers conclude that the simple picture of two alternative scenarios – conservation of specific angular momentum or mergers that spin-down galaxies – does not capture what EAGLE has revealed to happen. How quickly a galaxy spins appears to depend on the individual star formation history with a contribution from the merger history.

Publication details:

Claudia Lagos et al. in the Monthly Notices of the Royal Astronomical Society (2016) "*Angular momentum evolution of galaxies in EAGLE*"