# Dancing with the stars

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# English Summary

What we know is a drop, and what we don't know, an ocean. Some claim that the only things we can know are those which are seen with the naked eye. To take in light, and produce knowledge. That is the way information, raw and without interpretation, makes its way to places like Wikipedia, books, schools, and into the minds of the next generation. The next time you experience a blackout at night in your city go outside and look up. If luck favours you, you won't find clouds but rather the cosmos staring down at you. You'll note that most of those lights twinkle, like a distant candle in the wind. An odd few you'll note do not twinkle, and, as you may already know, those are the planets of our solar system. Mars, Venus, Jupiter... these characters of myth conjure up scenes of the gods' wars, loves, and vengeance, and it doesn't take long before your mind starts to wander. When was it, the last time you looked up in the night sky?

If you could see in the radio spectrum, that is if your eyes could sense wavelengths greater than 1 cm, you would see a night sky that looks vastly different from the star-strewn scene you're used to in the visible spectrum. The radio sky contains large diffuse structures, compact pulsating sources, filamentary structures, ring like structures, and more. These shapes correspond to a diversity of physical processes at play throughout the Universe.

One such physical process that we discuss in this thesis is synchrotron emission resulting from the merging of galaxy clusters. Synchrotron emission is radio frequency light that results from fast moving electric charges in the presence of an ambient magnetic field. Galaxy clusters, on a scale some 100 millions times larger than our solar system, are the largest gravitational wells of the Universe with masses on the order of $10^{14}$ $M_{\odot}$. Galaxy clusters form the vertices of the cosmic web, with elongated filaments and sheets connecting them. Since the scales are so large, they present an interesting laboratory for testing physics.

Occasionally, galaxy clusters merge with matter in-falling from the cosmic web with relative speeds exceeding 1000 $\mathrm{km\,s^{-1}}$. Such merger events can be thought of as the analogue of particle accelerators here on Earth, where we test theories of physics on the smallest scales. A merger event produces large outward travelling shocks in the intra-cluster medium (ICM), releasing gigantic amounts of kinetic energy ($10^{56}$ J) in the form of turbulence and acceleration of cosmic ray electrons (CRe) to ultra-relativistic speeds. These CRe emit synchrotron emission that traces the dynamics of the mergers, and with advanced computational methods allow us to test theories of physics on the largest scales.

In Chapter 1 we investigate one particular galaxy cluster (called PLCK G004.5-19.5) that has the interesting property of being at large cosmological time (with a redshift of $z = 0.52$). We analyse the cluster at 150 MHz, 325 MHz, and 610 MHz with the Giant Metrewave Radio Telescope [GMRT; Gupta et al., 2017] and find emission that suggests the cluster has undergone a merger in the past, however the arrangement of emission is too complicated to say much more. An interesting finding is that the central region of the cluster appears to have a diffuse component that resembles what is called a radio halo. Radio halos are thought to be driven by turbulence, however their existence at high redshift is rare. Their rarity comes from the fact that radiant energy is lost through a process called inverse Compton scattering, and this energy loss goes as $\propto (1+z)^4$. Therefore, it's not that they don't exist at high redshift, they are merely too dim. In fact, this cut-off in cosmological redshift acts a a valuable means of testing cosmology. The prevelence of faint complicated emission in high-redshift galaxy clusters, and the hidden treasure trove of information, prompts the need for high-resolution, low-frequency, wide-bandwidth, high-sensitivity radio telescopes.

Radio astronomy has changed a lot since it began. Early pioneers of radio interferometry [Ryle and Vonberg, 1946] acquired so-called 'visibilities' with analog-driven pens on paper. They could touch their data with their hands. Today, a radio astronomer ironically rarely sees the visibilities, and the trend is increasing in that direction. Radio telescopes are some of the biggest data experiments of humankind. One such telescope that occupies a large portion of this thesis is the Low-Frequency Array [LOFAR; van Haarlem et al., 2013].

Since there is a clear need for deeper and better radio images, a large part of radio astronomy is technical in nature and known as calibration and imaging. In short, the visibilities characterise how light from two very distant, but neighbouring, sources in the sky interferes with each other. Much like how the interference pattern in Thomas Young's double-slit experiment told him how far apart the slits were, the visibilities tell us how far apart radio sources are on the sky. Calibration and imaging is the process of using computers to invert large sets of visibilties.

Chapters 2 to 4 deal with the aspect of calibration. Calibration has to do with the fact that the telescope and medium between the telescope and sources are constantly changing. Physical properties like temperature and humidity can change how a radio antenna receives light, and something known as the ionosphere alters how radio waves propagate to the telescope. In this thesis we are concerned with calibration of the ionosphere.

One of the challenges of ionospheric calibration is that you can't directly see the ionosphere. There is a long history of trying to solving this challenging problem. There are two main types of methods for ionospheric calibration, field-based calibration [Cotton et al., 2004] which models image domain apparent source shifts, and facet-based calibration [Intema et al., 2009, van Weeren et al., 2016, Tasse et al., 2018] which performs calibration on disjoint patches of the sky called facets. In this thesis we focus entirely on the facet-based approach.

Facet-based calibration has several orders of complexity, however we will just sketch the basic idea here. The idea is that when radio frequency light traverses a medium with a low density of electric charges – as in the case of the ionosphere – the light wave takes on a small time delay. This time delay is proportional to how many electrons the wave passes, and so one can imagine counting all the electrons between the radio antenna and the source and using this quantity to calibrate the effect of the ionosphere. In a way that is what facet-based calibration does, except once for each bright source in the field of view.

How does this work though, since one cannot see the ionosphere? Indeed, the challenge all lies in inferring a physical quantity based only on the light that the antennas receive. In this thesis we borrow a concept from an entirely different field called seismic imaging. In seismic imaging the goal is to see inside the Earth by bouncing acoustic waves off of structures inside and recording them on the surface again. This method is built on the principle of tomography.

Tomography and probability theory is used in Chapter 2 to derive a method that can infer the ionosphere's effect, and we show using simulations that it is superior to an array of other methods that aim to do the same thing. The superiority follows because we have used physics to place strong constraints on the result. In general, using physics to constrain the possible outcomes of a process is very powerful.

With this powerful new method proven to work on simulated data, in Chapter 3 we apply it to real data for the first time. In this case we apply it to an 8-hour LOFAR observation that previously showed large calibration errors in the image. We pleasantly find that our method is able to remove these image errors and we have a much clearer view of that small piece of the sky.

We naturally want to know if that success was just luck, and if the method is robust. Therefore, in Chapter 4 we apply the same method to twelve 8 hour LOFAR observations all pointed at the Ursa Major (The Big Dipper) constellation. This area is known as the Lockman Hole, for it shows very little HI emission in the galactic foreground. In this case we observe that there is a general improvement in ten out of twelve cases, however it also brings to our attention a low-level systematic in the data that we were not aware of. This systematic proves to be very difficult to quantify.

Our method has shown great initial success and there are clear directions in which to improve it in order to account for this systematic. This process is typical in science. As methods get better, uncertainty decreases and, in the process, reveals lower-level phenomenon. Often this is the threshold where discoveries and advances are made.