PhD Research Proposal

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Contents

PhD Research Project:
A study of feedback processes and their impact on the kinematic properties of dwarf galaxies

Abstract

The aim of my PhD is to improve the treatment of various feedback mechanisms within simulations of dwarf galaxies, particularly the way that energy is injected into the interstellar gas via different types of supernovae explosion. The hope is that this research will shed light on how these feedback processes fit into our picture of the hierarchical formation and evolution of galaxies in our Universe. With such improvements to the prescriptions of supernovae feedback, my simulations will become a valuable and reliable tool that observers can use to interpret the kinematic behaviours of galaxies. The reasons that this work is necessary are outlined below.

Background

Why are we interested in feedback processes?

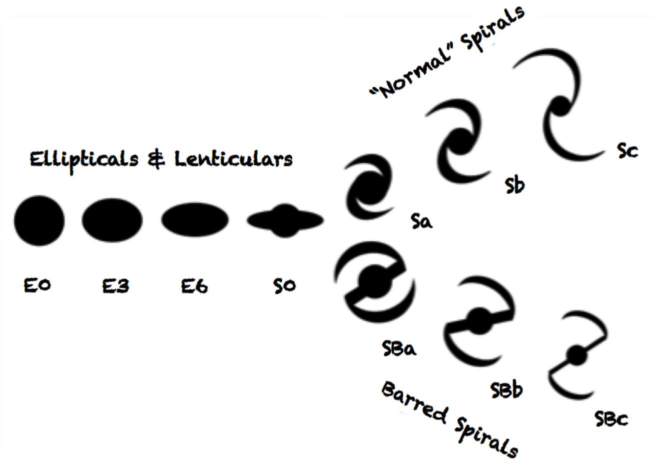


Figure 1: *Hubble's 1926 tuning fork used to classify galaxy morphologies. Ellipticals and lenticular galaxies are known as the "early types" and vary from circular (E0) to highly elongated (E7). Lenticular galaxies are considered a transition between the two types (S0). Spiral galaxies are classed as "late types" and subdivide into two branches based on whether or not they contain a bar-like arm feature in their central region. They range from tightly bound with large bulges (Sa/SBa) to loose spiral arms with small bulges (Sc/SBc).*

In 1926, Hubble designed the classification scheme still commonly used today to categorise the range of galaxy morphologies observed across the sky; figure 1 demonstrates his "tuning fork" cataloguing system. Of course, it is not enough to just sort observations into groups. All astronomers want to answer the fundamental questions: Why? When? How? While observations of morphology and kinematics give us the categories, we want to understand the physics that led to the construction of these shapes and how they change over time.

Feedback has a key role to play in this complicated story of galaxy formation and evolution. The umbrella term, "*feedback*" is used to describe any process that affects the distribution of gas in a galaxy. These could be environmental effects, such as interactions with the intracluster medium in which the galaxy lives or galaxy-galaxy collisions and mergers. Alternatively, they could be secular effects that come from within the galaxy itself, such as energy injection from stars exploding as supernovae or from active galactic nuclei (AGN or black holes) accreting material at their centre.

All of these processes cause the morphology of a galaxy to change. We are interested in learning the extent to which secular feedback, specifically, can impact the formation and evolution of dwarf galaxies.

Why feedback in dwarf galaxies?

When considering isolated galaxies (such that environmental processes like galaxy mergers do not affect the system), the types of secular feedback processes that occur are strongly dependent on the luminosity - and by extension, the mass - of the system (Silk and Mamon, 2012). This dependence is outlined in figure 2.

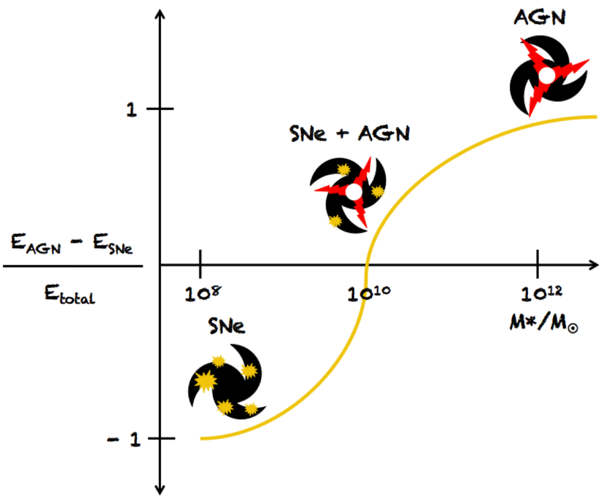


Figure 2: *A cartoon demonstrating the mass dependence of different secular feedback processes. We are interested in low mass galaxies as they are a clean probe of supernova (SNe) feedback. At higher masses, active galactic nuclei (AGN) dominate the secular feedback processes; the intermediate masses contain a messy mix of the two.*

Dwarf galaxies are defined as those galaxies with a magnitude, $M_B \gtrsim -18$ corresponding to masses of $\sim 10^7 - 10^9 M_\odot$ (solar masses) (Sandage and Binggeli, 1984). Because supernovae feedback is the dominant process at this mass range, isolated versions of these dim, low mass galaxies are an important and clean probe of secular feedback.

It has been known for over 30 years that dwarf galaxies are particularly sensitive to supernova feedback (Dekel and Silk, 1986). The energy injected following the explosion of a star will have significant catastrophic effects on the shallow potential well of a low mass dwarf; however, the specific details of this energy transfer between the explosion and galaxy components is still poorly understood (Mo et al., 2010). As we are interested in understanding the role that supernovae feedback has on the history of galaxy formation and evolution, isolated dwarf galaxies are the perfect objects to consider.

Why use simulations?

No matter how far our observational techniques progress, we will always be disadvantaged by the fact that observations are a 2D projection of a 3D system - a large proportion of information will always be inherently missing. Observers often want to invert their data to gain greater insight into the physics; however, mathematically, such an inversion is usually impossible. Hence, we require a suitable generative model that represents the physics that has occurred. We then evolve that model forward to see if we can recreate the observed "posterior" data. The role of computational astrophysicists is to create these suitable generative models by which to explain observed data.

Over the last 40 years, simulations have proved to be a valuable modelling tool for both predicting and explaining observations. In 1972, Toomre & Toomre utilized "restricted three-body computations performed with massless particles" to show that bridge and tail features observed between galaxies were remnants of mergers. Navarro, Frenk & White (1996) used N-body simulations tuned to the observed rotation curves of disk galaxies to determine a universal density profile of the underlying invisible dark matter. The presence of bars in spirals was investigated by Athanassoula & Misiriotis (2002) who used three N-body simulations to find a link between central dark matter concentration and the shape of the bar that is formed.

But where have simulations failed?

Of course, while simulations have had many successes, there is a whole discipline of research focused on making simulations as accurate as possible – which is not a trivial task.

Galaxy simulations are difficult because we are trying to model a very large number of processes simultaneously. Typically we divide these into three categories: N-body processes dictate the particle motions caused only by gravitational interactions; hydro-dynamical techniques are added to describe the behaviour of the diffuse baryonic matter component; various prescriptions of feedback and radiative cooling are then required to describe all the other physical processes that occur in the gas (Dolag et al., 2008).

Ideally, we would compute the motions of all particles in a galactic system to create a realistic model; however, this is of order 10^{68} particles and, as such, the computational cost of such a simulation is far too high (Mo et al., 2010). Hence, instead of particles reflecting individual proton masses, we group particles into dimensionless *mass elements* of infinite mass density allowing the computational cost to be greatly reduced.

This causes other serious problems, however, when calculating the gravitational forces between the mass elements in the simulation. When mass elements approach one another, the distance between them can go to zero because they are dimensionless particles without finite size. In equation 1, we can clearly see that this would cause the denominator of our equation to approach zero and the gravitational potential to unrealistically shoot off towards infinity as a result,

$$\Phi(r_\alpha) = \sum_{\alpha \neq \beta} \frac{-GM_\beta}{|r_\beta - r_\alpha|}, \tag{1}$$

where Φ is the gravitational potential, G is the gravitational constant, M is the particle mass and r is the radial position each considered at points α and β.

To avoid this, we introduce an additional artificial parameter called the gravitational softening, ϵ, as shown in equation 2. This artifice removes the troublesome short-range singularity occurring at close encounters by effectively giving each particle size. On large ranges the effects of gravity are left largely unchanged as this softening factor is very small, i.e. $\epsilon << |r_\alpha - r_\beta|$.

$$\Phi(r_\alpha) = \sum_{\alpha\neq\beta} \frac{-GM_\beta}{\sqrt{|r_\beta - r_\alpha|^2 + \epsilon^2}}. \tag{2}$$

While softening may succeed at making our simulations more realistic in some respects, the overall performance of the model is sensitive to the size ϵ that is chosen. Along with the number of particles and size of time-step, the softening is one of the major parameters that describe the resolution of the simulation. It is this resolution that dictates how useful our simulation can be. This choice is very important for this study of feedback processes, as we will require very high resolutions to disentangle the energy injection of supernovae explosions into the interstellar gas. However, this is not necessarily simple. Much work has gone into understanding how the choice of resolution parameters effects the stability of the dark matter halo particles (Power et al., 2003) and the dynamical properties of disc galaxies (Romeo, 1997, 1998a,b).

Why are feedback prescriptions important in simulations?

Resolution difficulties are the predominant cause of uncertainty in our models. While current simulations are very successful at recovering the large-scale structure of the Universe, the same cannot be said on smaller scales (Binney and Tremaine, 2008). Commonly these issues are described in the context of three major problems originating in the early 1990's: the cusp-core problem, the missing satellites problem and the "too big to fail" problem.

The cusp-core problem refers to the difference in simulated and indirectly observed dark matter density profiles at the centres of galaxies. We know that there must be a large proportion of mass missing within galaxies as the rotation speeds of stars at the outer radii are moving too quickly to be explained by the gravitational force of the stellar component alone. At the inner regions of disk galaxies, the rotational velocity is found to rise almost linearly with radius indicating that a central core of dark matter must be present. However, N-body cold dark matter (CDM) simulations suggest that the central dark matter density would be better described by a steep power-law distribution – a "cusp" (de Blok, 2010).

This may simply be a problem caused by resolution. Most cosmological simulations cannot be reliably resolved down to 100 parsec scales and so the slope of the mass-density distribution at the galaxy centre will be reliant on an assumed analytic fitting function. Alternatively, work by Pontzen & Governato (2012) suggests that the lack of the dark matter cores we expect in our simulations may be due to the lack of supernova feedback prescriptions in our models.

Theoretical models also predict an over abundance of small halos (the missing satellite problem) and that the majority of the larger halos produced are too dense resulting in maximum rotational velocities that are much too high (the "too big to fail" problem); specifically, around Milky-Way-type galaxies in cosmological simulations there exist over 500 theoretical satellites, in competition with the observed 11 (Kauffmann et al., 1993; Moore et al., 1999). According to the Aquarius simulation project run by Springel et al. in 2008, these satellites should have infall circular velocities of $30 - 70$ km s^{-1}, but this is far higher than observed $20 - 30$ km s^{-1}(Boylan-Kolchin et al., 2011).

Observers are investigating the idea that there may be a population of very dim, low mass dwarf galaxies that simply fall below current detectable limits of our telescopes (Lin et al., 2017). However, it is also likely that we have not fully described the complex baryonic physics, feedback and cooling that can occur in a galaxy. Such processes may reduce the central densities of massive dark matter subhalos, alleviating the "too big to fail" problem (Boylan-Kolchin et al., 2011); similarly, including supernovae feedback and tidal stripping can lower the central masses of bright satellites and help to lessen the missing satellites problem (Zolotov et al., 2012).

Overall, the motivation for this research stems from an interest in galaxy formation and evolution, but the outcomes may also impact a wide variety of simulation research.

Progress to date

One way to investigate feedback is by studying the effects that the processes have on the kinematics of a galaxy. Throughout the last decade, we have seen significant advances in observing techniques that allow us to measure the spatially resolved spectra of a galaxy using integral field units (IFUs). These instruments give us both spatial and kinematic information about the source. Experiments such as the **S**ydney-**A**AO **M**ulti-object **I**ntegral field spectrometer (SAMI) (Croom et al., 2011) and the **Ma**pping **N**earby **G**alaxies at **A**pache point observatory (MaNGA) (Bundy et al., 2015) have allowed the movement of gas in low mass galaxies to be mapped with impressive resolution.

However, as discussed above, observations are always limited by the fact that they are a 2D projection of a 3D system. This poses the question: how well can we be sure that the observed quantities map to the kinematic properties we wish to measure? As I wish to investigate the effects that feedback has on the galaxy kinematics, this is an important question to address.

Extracting useful kinematics

A very useful kinematic diagnostic to measure is the angular momentum of a galaxy. In 2007, Emsellem et al. began measuring the observable angular momentum per unit mass (or the spin parameter) of galaxies in an early IFU survey called SAURON. The aim of this was to distinguish better galaxy categorisations that were not simply based on visible morphologies, as Hubble had suggested. Using IFU data, Emsellem et al. defined an observational measure of the specific angular momentum, the λ_R-parameter, given by equation 3,

$$\lambda_R = \frac{\sum_{i=1}^{N} F_i R_i |V_i|}{\sum_{i=1}^{N} F_i R_i \sqrt{V_i^2 + \sigma_i^2}}, \tag{3}$$

where r is the radial position, F the flux, V the line of sight velocity and σ the velocity dispersion measured in each bin, i (Emsellem et al., 2007). This value has some serious limitations, however; it is not directly comparable across galaxies at different inclinations, between galaxies with certain morphological features and when telescope limits are taken in to account.

I began by studying how the observed value of λ_R changes for the same galaxy model when it is inclined from 0^o (face-on) to 90^o (edge-on). Following the methods of Jessiet et al. (2009) and Emsellem et al. (2011), I found that, while the parameter is fairly consistent for galaxies inclined between 40-90^o, the value falls rapidly below an inclination of 40^o. It also does not give a true measure of the total angular momentum per unit mass. The results of this investigation can be seen in figure 3.

Aside from inclination, the λ_R parameter is also sensitive to morphological features such as strong bars at the centres of spiral galaxies; this can cause the kinematic and photometric major axes of the galaxy to appear misaligned which is indicative of a slow rotator - even though most spiral galaxies are classed as fast rotators (Emsellem et al., 2011). Similarly, beam smearing, that occurs due to telescope limitations in IFUs, can cause inconsistencies with measured velocities and hence the measured λ_R (Cecil et al., 2016).

With this in mind, it seems sensible to use my simulations to investigate how all of these limitations combine to affect the value of λ_R that is measured and how it relates to the true angular momentum of the galaxy observed.

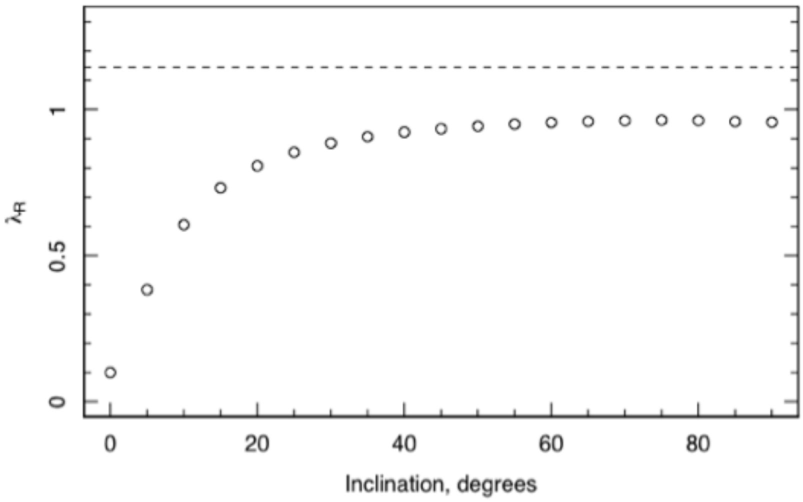


Figure 3: *Considering the measured λ_R parameter at a range of galaxy inclinations. The dashed lines show a scaled version of the true angular momentum per unit mass. Clearly, we do not recover the true value at any inclination, but the parameter is roughly constant at inclinations above 40^o.*

Creating a mock galaxy catalogue

I have been constructing a mock catalogue of galaxies from Hubble type S0-Sd. Using this catalogue, I will study how λ_R measurements are affected by observational limitations. The end goal of this work will be to produce an empirical formula from my data that maps the measured λ_R value to the true angular momentum per unit mass of a galaxy.

To begin, galaxy models are constructed using two codes. Particle positions and velocities in each model are calculated to construct a stable, isolated galaxy using Denis Yurin's code, `GalIC` (Yurin and Springel, 2014). These initial conditions are then evolved over time using Volker Springel's `Gadget2` (Springel, 2005). The galaxies that are produced can then be "observed" as they would be by SAMI. One example of this can be seen in figure 4.

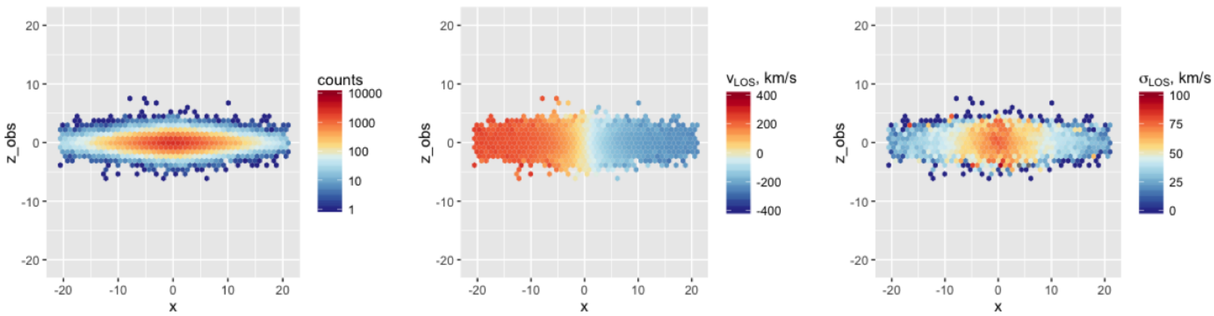


Figure 4: LEFT - *Demonstrating the particle counts in each hexagonal bin.* CENTRE - *The line of sight velocities in each hexagonal bin.* RIGHT - *The line of sight velocity dispersion in each bin. The hexagonal binning method has been chosen to match the observational view that would be seen by IFU surveys such as SAMI.*

Each galaxy will be observed across a range of inclinations and different degrees of beam smearing; λ_R will be measured in each case and compared to the true spin parameter measured directly from the simulation. Using this information, I will attempt to define an empirical formula that relates the measured λ_R to the true specific angular momentum of a galaxy.

This is important as it will allow us to understand the observable impacts of feedback processes, such as the winds and outflows caused by supernovae, on the kinematics of galaxies.

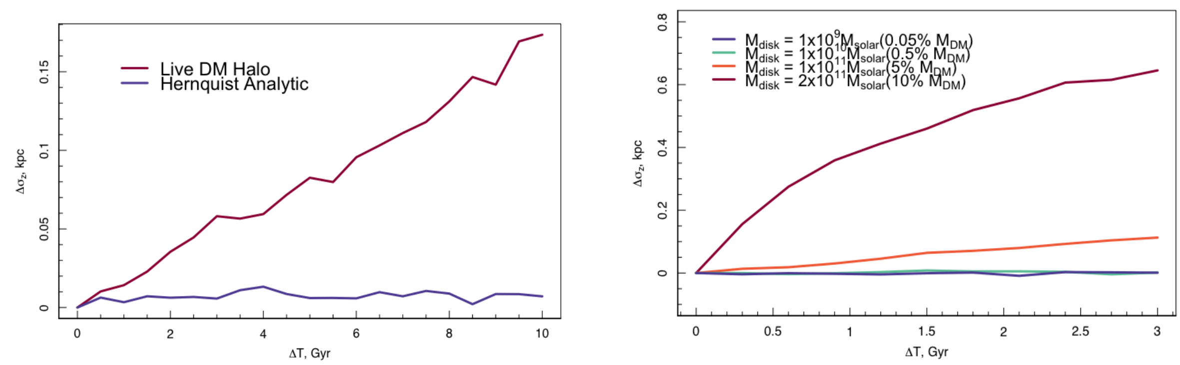
Project aims

At the recent *Mock Perth 2017* workshop, it was discussed that the computational astrophysics community required work that focused on providing astronomers with realistic models that are compatible with their observational techniques. It is my aim to fulfil this requirement; to connect the two disciplines of theoretical and observational astronomy and provide useful tools for both parties.

Below, I outline the main aims of this work. My thesis will be in the form of a series of academic papers, the general descriptions of which can be found here.

Understanding λ_R and the true angular momentum

My first paper will describe the relationship between the observed and true specific angular momentum of a galaxy. The aim of this paper will be to prove that the effects of feedback on galaxy kinematics could be accurately measured observationally. To do so, I will be constructing a mock galaxy catalogue as described above.



(a) *Demonstrating the disk scale height stability when using different versions of* ***`Gadget2`****; the red line shows the standard live dark matter halo implementation while the blue shows the affect of adding an analytic halo potential to the code.*

(b) *Demonstrating the stability of the disk scale height when the mass of the disk is increased within its dark matter halo when using the analytic potential version of* ***`Gadget2`****. Clearly, as long as the disk mass is $< 5\%$ of the halo mass, our system is stable.*

Figure 5: *Considering the gravitational stabilities of the galaxies in my mock catalogue.*

This requires stable, isolated galaxy models at an appropriate resolution for testing the kinematics of dwarf galaxies. Some of my stability tests can be seen in figure 5. Initially, these models will be simple N-body simulations in which particles are only subject to the force of gravity; the purpose of this is to construct an empirical formula using the simplest models available.

Understanding how realistic feedback prescriptions improve the consistency of simulations with observations

As I progress, I will begin to add gas and feedback into my simulations to understand the affects these processes have on the kinematics of the galaxies.

Creating stable disks of gas and stellar material is quite difficult (Mayer et al., 2008) and so another series of stability and resolution tests will be required. The addition of gas in my models will cause the gravitational potential at the centre of the system to change significantly; this will cause the greatest impact on the construction of the galaxy disk. Supernovae feedback processes that inject large amounts of energy into the system, especially at the low mass scales of dwarf galaxies, will cause the system to move away from an equilibrium state. I will be studying the kinematic features that these processes induce in the simulation, and the observational signatures that they would present in SAMI data.

As such, my second paper will focus on the construction of realistic hydrodynamic disks with a variety of supernova feedback mechanisms built in.

Understanding how feedback affects small scale structure in cosmological simulations

Finally, I will be considering how my improved prescriptions of feedback could be implemented in larger cosmological runs; the purpose of my final paper and thesis will be to study how important these processes are for dwarf galaxies in our simulations and what these reveal about our understanding of dark matter in the Universe.

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Research Project Details

Confidential information and intellectual property

While this project does not involve collection of confidential or sensitive information, I will be creating my own software and developing existing code. This will not hold any commercial significance and will be released to the public domain onto GitHub under a GPL-3+ license.

I confirm that I have read and understood the terms and conditions of the Project agreement, in particular the parts related to confidentiality and publication, intellectual property, conflicts of interest, student involvement and reporting. I understand that I own the copyright of my own thesis.

Field work

While the majority of my research will take place at the University of Western Australia, I am aware that I will be travelling around Australia and to Europe to collaborate on projects throughout my PhD. This involves both conferences and longer visits, as outlined in the *Research project communication* section.

I declare that I have read and understand the University field work and insurance policies.

Facilities

The majority of my work will be conducted at ICRAR/UWA.

I will require access to supercomputers in order to run my simulations. While I have access to the in house machine, Pleiades, I have also been given a portion of 300,000 hours on the supercomputer housed at the Pawsey Supercomputing Centre, Magnus. This is sufficient to complete the first part of my research plan. While this time was awarded to my supervisor, I will be assisting with applications for computing time in the future.

Statistics

Having completed a Master's degree and several internships at the University of Nottingham in Physics and Astronomy, I have been trained sufficiently to analyse my data using appropriate statistical tools.

However, to better improve my list of skills, I will also be taking a module (STAT4066) in Bayesian Statistics and Computing to prepare for the data analysis that will be undertaken throughout my research. This is further explained in the skills audit shown in table 1.

Required skills

The skills audit table is displayed in table 1.

Approvals

There is no need for specific approvals for this project.

Professional & Research Skills	Personal Rating *None*	*Basic*	*Competent*	*Proficient*	Evidence
Understanding and application of relevant data collection and analysis methods			x		I have completed a Master's degree in Physics and Astronomy at the University of Nottingham.
Identifying and accessing appropriate bibliographic resources				x	Throughout my degree, I have been trained to critically analyse scientific data using Matlab and Python and a variety of analysis tools and mathematics.
Use of information technology relevant for the research			x		While this degree has taught me to a competent level how to present and write about my own scientific research and how to use academic journals and articles effectively, there is always more to learn; for example how to run simulations and work with supercomputers.
Familiar with the principles and conventions of academic writing			x		As part of my PhD with ICRAR, I will be assessed on my presentation skills at 6 months and then at the end of every year. I will also travel to conferences and present my work externally around the world. I am expected to produce an academic paper per year of my research.
Ability to constructively defend research outcomes at seminars and conferences			x		I will also be taking a master's level course in Bayesian Statistics and computing in order to better prepare for the statistical analysis required throughout this project. Throughout my PhD, I will also be learning to work with C, C++ and R assisted by my supervisors and online teaching tools.

Table 1: *An audit presenting the necessary skills for my research project and evidence of my proficiency in these areas. Where only rated "competent", I give examples of ways in which I intend to improve to reach a proficient level by the completion of my PhD.*

Data management

Work on this project will be conducted using my own computer and external supercomputers such as Pleiades, the in-house ICRAR HPC Cluster, and Magnus, the Cray supercomputer at the Pawsey Supercomputing Centre.

In addition to these external systems, I will be backing up all data on an external hard-drive every week and to an online cloud database every month.

Research project communication

It is my intention for my thesis to consist of a series of papers. These will fall into the three themes outlined in the *Project Aims* section.

Aside from this, I have already taken part and contributed at several academic conferences:

- A short presentation at the CAASTRO 2016 Retreat in Busselton giving brief introduction to my project (28-30th Nov 2016).
- A 10 min talk at the SAMI Group Meeting held at ICRAR/UWA discussing how my work could assist observers working with IFU data (6-7th Feb 2017).

- A 10 min talk at the ASA ANITA Conference in Hobart describing my plans to create a suite of simulations to assist observers (8-10th Feb 2017).
- A 15 min talk at the Mock Perth 2017 Workshop in Perth discussing the progress made with my mock catalogue for the interpretation of λ_R (20-22nd Mar 2017).

In the future, I plan to continue to attend conferences and discuss my work with potential collaborators. In the near future, I will be travelling to the University of Nottingham to discuss my work so far and collaborate with members of the MaNGA IFU survey. I will also be attending a conference on "The Role of Gas in Galaxy Dynamics" in Malta in October 2017.

Working hours

I confirm that I intend to be studying for the normal required hours, at least 30 hours Monday to Friday, 9am-5pm.

Budget

Description		Source	Estimated Cost ($AUD)
Materials	*Laptop & Software*	ICRAR School of Physics and FEMS	$2000
Travel & Communication	*Conference Poster Printing*	ICRAR	$100
	Conference Fees	ICRAR School of Physics and FEMS	$900
	Conference Travel & Workshops	ICRAR School of Physics and FEMS Graduate Research School	$3500
		ASA CAASTRO3D	$1000
		UWA Research Collaboration Award 2017	$5000
		Total	$12,500

Table 2: *A table to demonstrate the budget allocated for my research project in throughout my PhD. As I am a member of the Astronomical Society of Australia (ASA) and the ARC Centre of Excellence for All-sky Astrophysics 3D (CAASTRO3D), I will receive additional travel bursaries for conferences. My supervisor also has a UWA RCA budget awarded for me to travel and collaborate abroad.*

Supervison

Principal Supervisor: A/Prof. Chris Power (60%)

A/Prof Power and I will meet once a week to discuss my progress during the first six months of my candidature. As an expert in simulations, he will be helping me to implement new prescriptions into existing galaxy evolution codes.

As I progress, it is likely that the frequency of our meetings will change; however, I will consistently keep track of my progress by sending him weekly emails.

Co-supervisor: Dr Aaron Robotham (40%)

Dr Robotham will join the weekly progress meetings during my candidature to advise on the observational and statistical analysis details of my project.

Project plan

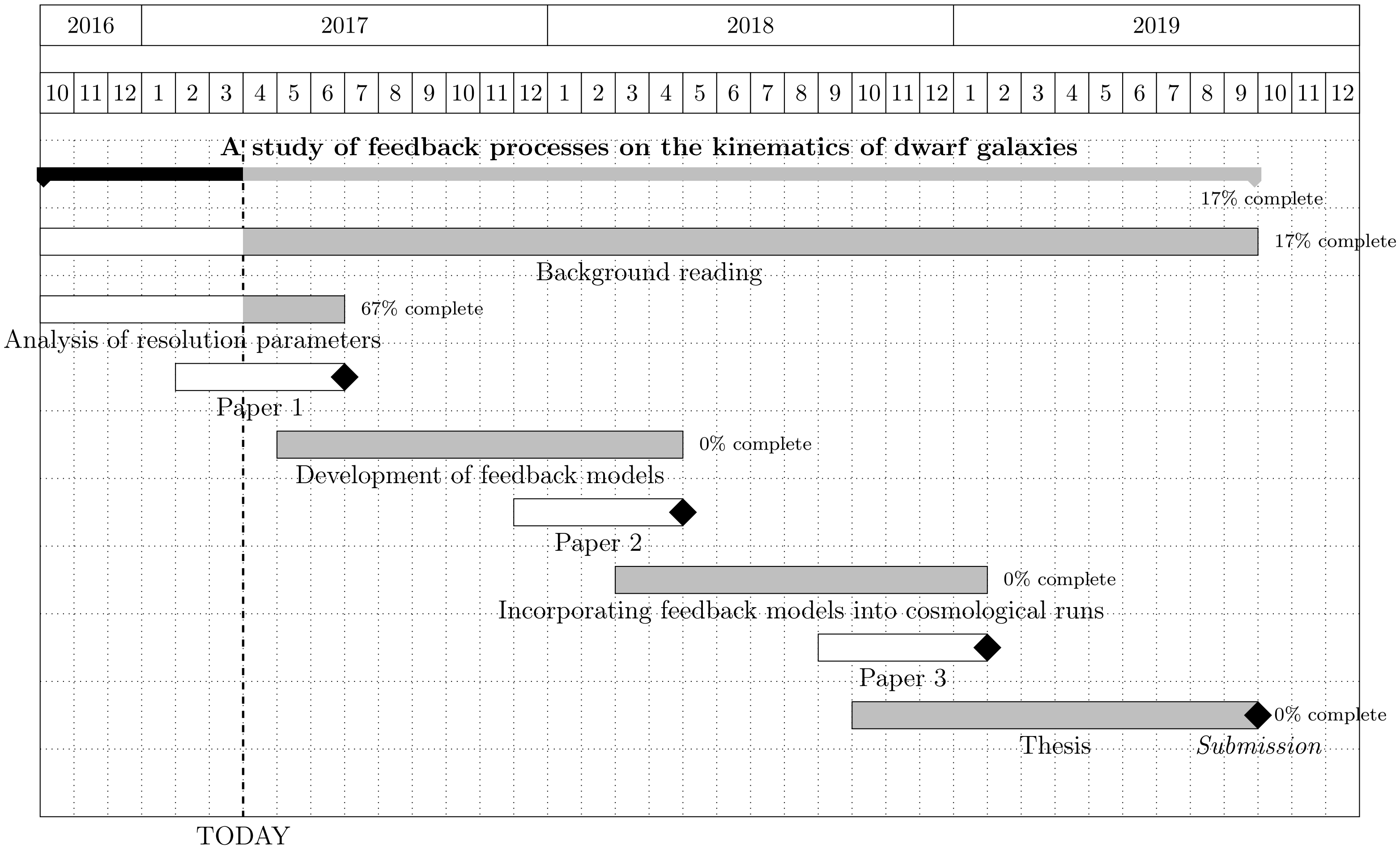

Figure 6: *Demonstrating the plan for project progression from enrolment (04/10/16) to completion (04/10/2019)*

Research training plan

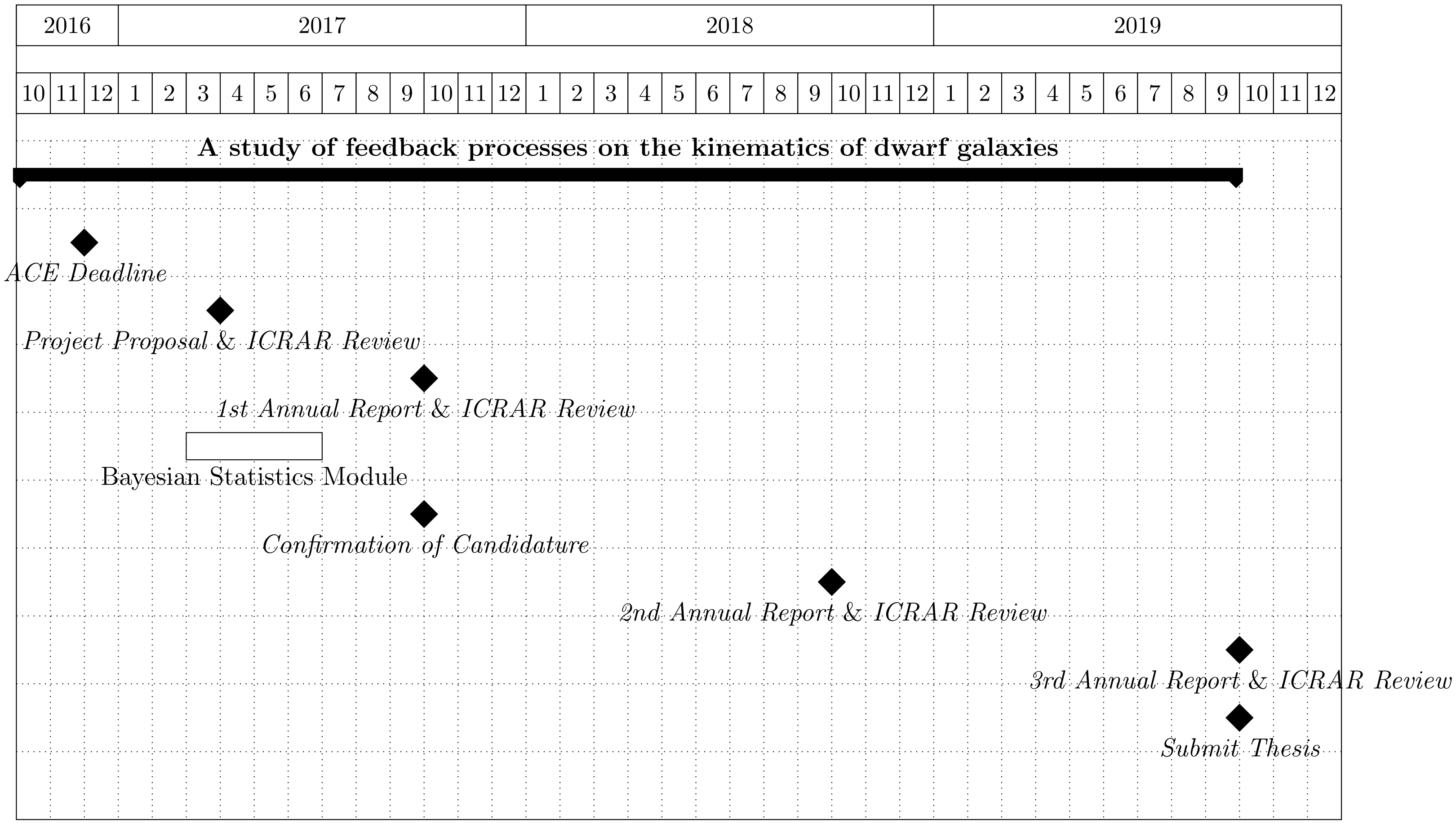

Figure 7: *Demonstrating the plan of research training from enrolment to completion, including the UWA and ICRAR milestones required for my project.*

Date	Activity	Details
28/11/2016	CAASTRO retreat presentation	I gave a short “sparkler” presentation at the CAASTRO annual retreat in Busselton outlining the plan for my PhD research.
14/01/2017	Academic Conduct Essentials (ACE) Module	This module contains information required for students and researchers to perform ethical and credible research. I completed this module within the deadline and achieved an ungraded pass (UP).
06/02/2017	SAMI Group Meeting	I gave a short 10min presentation about the plan for my first paper and how my research would tie into the SAMI survey.
08/02/2017	ASA ANITA Conference	I gave a similar 10min presentation about the plan for my first paper, but with more emphasis on the simulations and coding.
20/03/2017	CAASTRO Mock Perth Workshop	I gave a 15min presentation explaining the purpose and current results of my first paper, specifically focusing on the modifications made to code to reduce the computational cost and make the process more efficient.
02/04/2017	Six-month PhD Proposal	This report is due to the GRS for review of my PhD research plan.
05/04/2017	ICRAR six-month PhD Proposal Presentation	A 30min presentation detailing the background and research plan for my project is required after six months. This is given in front of all members of ICRAR so that they can provide feedback and suggest any changes that may improve my research.
08/05/2017	Paper 1 draft	I will have completed several sections of paper 1 concerning the derivation of an empirical formula relating the observed and true spin parameters (introduction outline, method, appendix regarding simulation tests).
22/05/2017	Paper 1 results completed	Completing the exploration of my simulations and producing the relevant data required to derive the physical empirical formula. Adding this to complete the results section of paper 1.
05/06/2017	Paper 1 draft complete	Including conclusion, introduction and abstract to be read and given feedback by my supervision team and requests for collaboration.
26/06/2017	Paper 1 submission	Following submission to the SAMI team and ICRAR for feedback, the aim is to have paper 1 submitted to MNRAS by the end of June 2017.
26/06/2017	Bayesian Computing and Statistics (STAT4066)	For confirmation of candidature, ICRAR requires that I complete one 6 credit module. This is a valuable course to take as it ties into the statistical analysis necessary for my project.
01/07/2017-30/09/2017	Adding gas disks to the analysis	Following the submission of Paper 1, I will begin looking at gas disks and the inclusion of supernovae feedback mechanisms within my models.
02/10/2017	Gas in Galaxies Conference in Malta	I am planning to attend the “Gas in Galaxies” conference in Malta in early October 2017 as my project will consider how the gas in a galaxy is impacted by supernovae explosions.
04/10/2017	Confirmation of Candidature (Year 1 Report)	This report is due to the GRS for review of my PhD research plan and to confirm my candidature as a PhD student at ICRAR/UWA.
11/10/2017	ICRAR year 1 PhD Seminar Presentation	A 30min seminar style presentation detailing the research plan and progress for my project is required after the first year. This is given in front of all members of ICRAR so that they can provide feedback that may improve my research.

Table 3: *A table detailing the plan of how my research will progress over the first 12 months.*