Exchange Visit Grant : Scientific Report

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1 Purpose of the Visit

The Gaia mission will soon provide an unparalleled view of the Milky Way in exquisite detail. The addition, over the coming years, of spectroscopic followups will provide abundance information etc. and will further enhance our knowledge of the *current* distribution of stars in the Galaxy. However, as our observations become ever more accurate and wide ranging, we still need to understand the processes which give rise to the features we observe at the present time, in order to interpret observations.

The Gaia mission, and its followups, will provide us with kinematic, metallicity and abundance information from which further quantities such as stellar ages can be derived. In order to make full use of these data we need to gain a good theoretical understanding of the various processes which galaxies *in general* experience during their lifetimes, in order to understand how to identify the *specific* events experienced by the Milky Way in particular.

Alternatively, we can view the Gaia mission as an in depth study of a single galaxy with which to test our models of Galaxy Formation. The Milky Way is an ideal testbed for our theories because we can can observe it to a precision and accuracy impossible in external galaxies. Thus, models and observations of the Milky Way and cosmological simulations of disc galaxies complement one another.

There are a number of tools available which can be used to explore galaxy formation. It will take a wide range of approaches in order to understand the results from the current, and next, generation of, surveys.

We sought to bring together our experience of a wide range of methods, combining the results of observations, Galactic Chemical Evolution models, cosmological simulations and idealised simulations, in order to better understand how galaxies in general, and the Galaxy in particular form and evolve.

Although many cosmological simulations model a disc galaxy rather than the Milky Way specifically it must be remembered that the Milky Way is one galaxy among many and, as we grow in understanding, the properties of the formation and evolution of galaxies provides us with more information about the formation of our own.

During my post-doctural fellowship at the Observatoire de Paris in Meudon (GEPI) I developed a closed box chemical evolution model. This model was applied to recent data from Adibekyan et al. (2013) and Haywood et al. (2013). These data have highly precise chemical abundance information, ages and kinematic information. By fitting our model to the data we recovered a star formation history for the Milky Way (Snaith et al. 2014). This star formation history implies a thick disc of comparable mass to the thin disc. This result matches well with the masses of the thin and thick discs inferred from the radically different radial scale lengths of the thick and thin discs derived by Bovy et al. (2012).

During my visit to Paris we sought to explore the ramifications of a massive thick disc using models, simulations and observations.

We expanded on our previous work by developing a set of simulations incorporating a massive thick disc. Dr Paola Di Matteo has developed an initial conditions code with this in mind. Our group will use N-Body and SPH simulations including chemistry, to explore how the thick disc affects idealized galaxies.

We also sought to develop links between my current group at University of Alabama, and in the research group of which I was part while in Paris. We discussed the possibility of future collaborations.

Although the group in Paris has extensive knowledge of observations (M. Haywood) and idealised SPH simulations (P. Di Matteo) and the Gaia mission, the group in Alabama has expertise in cosmological simulations. By developing multipath approach to the study of galaxy formation, each with its own strengths and limitations, we sought to discuss how all the different methodologies can be used.

2 Description of Work Carried Out

2.1 Week 1

I discussed with my hosts our recent work. This was important so that we all knew the research directions which we had pursued since I started in Alabama. We outlined the ongoing work on the chemical evolution of the Milky Way and the inclusion of thick discs in idealized simulations which is being developed at GEPI. These projects seek to expand on the model of the Milky Way developed in Haywood et al. (2013) and explored in Snaith et al. (2014). This model of the galaxy interprets the Milky Way as consisting of an inner thin and thick disc and a outer thin disc with a separate formation history. This model of the Milky Way is different to traditional models, which treat the thick and thin discs as separate.

We also discussed my own work on cosmological SPH simulations of galaxies using the MUGS (Stinson et al. 2010) and MAGICC (Stinson et al. 2013) simulations. We explored how these simulations can be used to explore the evolution of the Milky Way in a self-consistent way. Although the MUGS and MAGICC galaxies are not intended to replicate the Galaxy, the same processes can be expected to take place in these galaxies as in our own. A limitation of this approach is that a full cosmological simulation requires more computer time than an idealized simulation and can only, therefore, be run at lower resolution. This makes it difficult to distinguish scale heights required for studying the thick and thin discs equivalently to the Milky Way.

I also discussed on-going work with collaborators at the Observatoire and the IAP in which the results presented in Snaith et al. (2014) is interpreted in the context of high redshift galaxies.

In order to distribute my previous work in Paris to a wide audience the Observatoire de Paris paid for my attendance at the SF2D meeting for French Astronomers where I presented my work. This will lead to the publications of Proceedings by the end of October. This in turn will further distribute the ideal of the inner and outer discs model discussed in Haywood et al. (2013) and Snaith et al. (2014), and thus provide an alternative model to which to compare Gaia data.

2.2 Week 2

We explored future research directions for adding massive thick discs to idealized simulations, with and without hydrodynamics. Massive thick discs have previously been neglected because it was considered to be a negligible component.

In order to further expand on our concept of using cosmological simulations to enhance the work on the structure of disc galaxy I proceeded to examine the MUGS (Stinson et al. 2010) simulations for the signatures of a thick disc component. This is not easy, because the MUGS gravitational softening length is similar to, or larger than, the expected scale length of the thin disc. This avenue of interest developed because I noticed similar features in the age-[α/Fe] distribution in the MUGS data (Snaith et al. IN PREP) for a cosmological disc galaxy and the Haywood et al. (2013) data for local Milky Way stars. In Paris I was able to discuss this with Dr Haywood et al and thus gain deeper insight.

Further research is required to see if this exploration of the simulation is a useful research path to pursue. The research carried out in Paris was preliminary and was set aside in the interests of time. I expect that this research requires further development due time constraints during my exchange visit.

2.3 Week 3

I modified the galactic chemical evolution code presented in Snaith et al. (2014) to include infall. The code replicated the star formation history presented in Chiappini et al. (1997) based on the two-phase infall method described in that paper. This modified code can then be used to compare the results of a 'traditional' infall based GCE code to our closed box model.

A preliminary exploration of this infall model, using the best fit routine presented in Snaith et al. (2014) shows it to be a worse fit than the 'closed box' model. However, this was only an initial exploration of the new model and the data.

2.4 Week 4

In my fourth week I began work on completing the enrichment of the SPH code (Semilin & Combes 2002) with chemistry and gas release. We followed the 'probablistic' approach of Jungwiert et al. (2001), Torrey et al. (2011). This method allows gas particles to change into stars according to a Schmidt law (Schmidt et al.

1959), as with other simulation codes, but also allows star particles to transform back into gas.

In a traditional approach the total number of baryonic particles in the simulation is allowed to change. In the method we have chosen the total number of baryonic particles is preserved. However, instead of thinking in terms of particles as the smallest unit of the simulation, we must now consider that baryons are modelled using ensembles of particles. In other words if a thousand gas particles are transformed into stars at the same time, with the same metallicity, 300 of them will be transformed back into gas over cosmic time if we assume a Kroupa (2001) IMF.

Particles transform back into gas using a simple probability that depends only on the age and metallicity of the star. Figure 1 shows that the method is surprisingly robust for large numbers of particles. The difference of the recovered mean gas release fraction for 100 samples of 10 particles is only of order 10% to 15%. The model is most robust for high resolution simulations, and therefore best for idealized simulations where the lower computational compared to cosmological simulations allows them to be run with more particles and higher resolution.

I revised my previous work and performed a few numerical tests to compare the recovered 'gas release' with the theoretical expectation from the model developed in Snaith et al. (2014) based on a single stellar population of solar metallicity.

With the gas and metal release from the stars which turn back into gas after a given time calculated I distributed the gas to the surrounding gas particles using the SPH kernel and tested the approach using a simple model to make sure that it was accurate. This ensures that the metals are not locked onto the particle which produced them, but can enrich neighboring particles. I also began testing of this code to ensure that the gas release method is implemented correctly using a full galaxy simulation with hydrodynamics with a variety of resolutions. This is important to ensure that the implementation is robust.

I experimented with adding diffusion into the code, so that the metals and energy can be 'smoothed' across particles over time. This was only an initial experiment and awaits further development and testing.

The method had been implemented previously, but was not completed. This exchange visit gave be the chance to add return to this project and move it closer to completion.

I attended a meeting in Nice, France, at the Observatoire de Côte d'Azure. This meeting was the final meeting of the funding which sponsored my post-doc in France and was co-incidentally arranged to take place during my visit. We discussed the possibility of future collaborations and gave me another chance to discuss my past and future work with the French astronomical community. The research group is involved with the Gaia mission and we had an interesting discussion of my work.

3 Main Results

In order to enrich the results of the Gaia survey we must develop theoretical methods in order to understand what we see. There is no one approach which offers

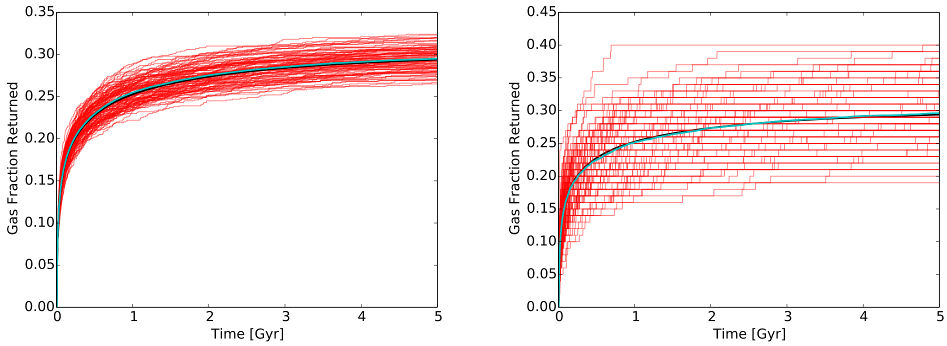

Figure 1: Gas released from a simple stellar population over time. The black line gives the theoretical expectation based on the model presented in Snaith et al. (2014). The red lines gives different gas fractions based on the probabilistic approach implemented in the SPH code. There are 100 different realizations of the gas release. The blue line gives the mean of the red lines.The left hand panel used 1000 particles, the right hand uses 100 particles and 10000 time steps.

a route to understanding all galactic evolution. We must, therefore, develop a multidisciplinary approach. Between the groups in Paris and Alabama we have experience with observations, idealised simulations, cosmological simulations and galactic chemical evolution. This visit allowed us to strengthen ties and develop future research directions.

- I was able to further develop the implementation of chemistry in the SPH code which I began before I finished my Postdoc in Paris. This will be the foundation of considerable future research, particularly in Paris. Various problems were corrected and I was able to add a procedure to distribute metals onto neighboring particles, previously missing from the code. This will allow us to perform SPH simulations with chemistry and perform numerical experiments of galaxy evolution.

- The possibility of further collaborations between the groups at Paris and Alabama was discussed. We had an interesting meeting between the group in Paris, myself, and Dr Bailin in Alabama via Skype.

- Infall was implemented in the Galactic Chemical Evolution code presented in Snaith et al. (2014). This can be further developed to explore the data in the same way as for the closed box model in Snaith et al. (2014) and the differences in the predicted formation histories explored.

- Numerous future research directions were discussed, potentially leading to a number of papers. We expect to develop these ideas in future as our work progresses.

4 Further Collaboration

We have developed a variety of future directions and have plans to continue our collaboration in a series of papers over the coming months. This exchange visit was an unparalleled chance to maintain my links with the group at GEPI, and continue to further develop the projects I have discussed in this report.

5 Projected Publications

We have discussed several future papers which will explore the effect of a large thick disc on idealised simulations of galaxies using both N-body and SPH simulations with chemistry included.

Another paper, with myself as first author, is expected in the coming months, discussing my changes to the SPH code of Semilin & Combes (2002). I will describe the implementation of probabilistic gas release (e.g. Torrey et al. 2012) where a star particle can transform back into gas and apply it to idealised simulations of disc galaxies like the Milky Way.

Additional work, discussing the results of the galactic chemical evolution codes are also expected, which we discussed during my visit.

6 Other

While visiting Paris I received funding from the Observatoire de Paris to present my work in the Gaia session at the SF2A (French Astronomical Society Meeting). This was an ideal opportunity to present my research on reconstructing the Milky Way star formation history to a segment of the astronomical community which is focused on the Gaia mission. A conference proceeding will be forthcoming.

Subsequently, after the completion of my 4 weeks in Paris, I was able to visit the University of Central Lancashire in Preston, UK and give a talk on my research to astronomers there.

7 Bibilography

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