Final Reporting: Project 4421

Signatures of Formation of Disk Galaxies: Simulations and Observations of the Milky Way

Purpose of the Visit

The purpose of this visit was to compare observational data from the Abundances and Radial Velocities Galactic Origins (ARGOS) survey (Freeman et al., 2013) with a set of new state-of-the-art N-body models of disk galaxies by Lia Athanassoula which were run for this project.

We broke up this project into 3 exchange visits under this GREAT grant, as initially proposed. Melissa Ness visited the OAMP during two visits of 11 days and 9 days respectively and Lia Athanassoula visited the MPIA for a period of 7 days.

Description of work carried out during the visit & main results

Our work comprised two avenues of investigations during the exchange visits:

1. We examined a series of new simulations with two initial disks: a thin and a thick disk, to compare the stellar density distribution and kinematics of these models to the ARGOS observational data. Our aim was to understand the origin of the kinematics of the different populations described in Ness et al., (2013b).

2. We investigated new chemodynamical models to understand the origin of the metallicity dependence of the split red clump seen in stars observed at $|b| > 5^\circ$ at the minor axis for only the metal-rich stars.

Results from models with two initial disks

We examined models with a thin and a thick disk to see if the metallicity dependence of the kinematics in the bulge measured by ARGOS could be explained by a two-disk evolution. We aimed to test if the secondary, thicker disk structure could explain the kinematics seen in the metal-poor stars of the Galactic bulge, the so called component C in the ARGOS survey, comprising stars with a metallicity $-1.0 >$ [Fe/H] > -0.5 (see Figure 1) and if the kinematics of the metal-rich stars observed by ARGOS (A and B, [Fe/H] > -0.5) was better matched by the stars initially in the thin disk.

The observational data in Figure 1 shows this dependence of kinematics on [Fe/H] from ARGOS and that the stars more metal-rich than [Fe/H] > -0.5 show cylindrical rotation and a dispersion profile that is characteristic of the single disk N-body models where a boxy/bulge forms via a dynamical instability (see Ness et al., (2013b)). The stars in component C show a cylindrical rotation profile but a hotter dispersion profile than the more metal-rich stars and also a much lesser dependence of the dispersion on latitude, across longitude, which is dissimilar from single-disk N-body models.

We examined 14 different thick+thin disk simulations with different initial scalings of the thin and thick disk lengths and heights as well as different dark matter distributions and tested these simulations at three different time steps in evolution (t=1000, t=1500, t=2000). We identified two best matching

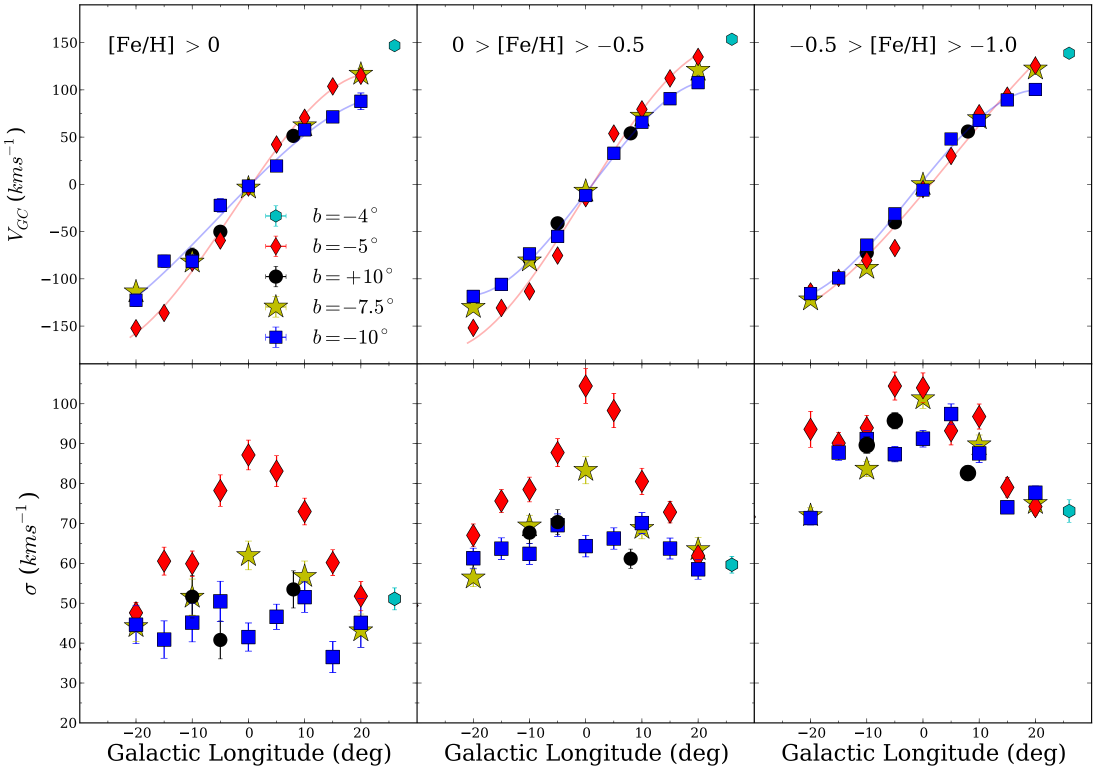
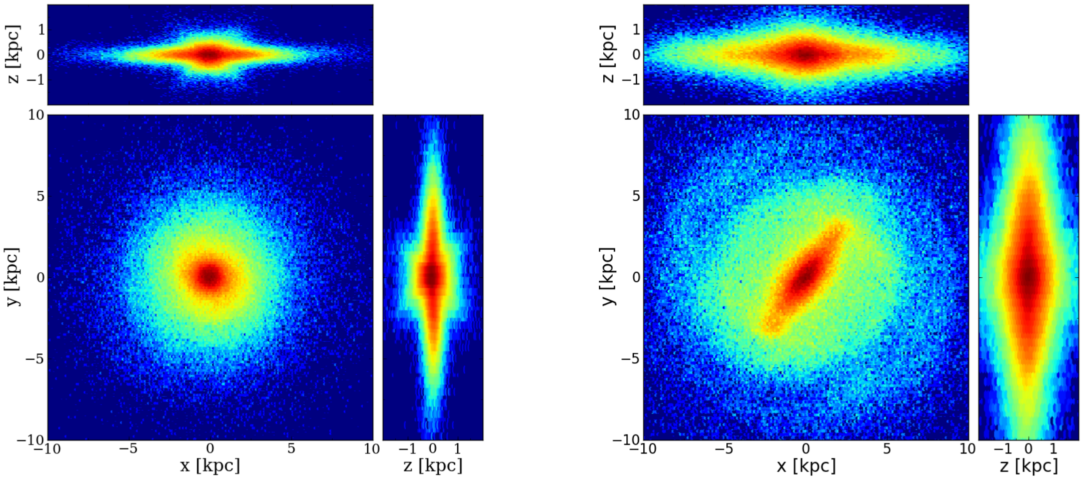


Figure 1: ARGOS kinematics of components A,B,C

simulations to the ARGOS data, both at the final time step of evolution t = 2000. We found that the stars initially in the thin disk structure evolve differently to stars in the initial thick disk structure. Stars in the thin disk evolve into a small central bulge/bar with a strong X-shape bulge and have a slower rotation profile than the stars in the thick disk. The stars initially in the thick disk produce a longer and thicker-bar and a dispersion profile that is similar to stars in the observations of metal poor stars, with a flatter dispersion at high latitude and a centrally peaked dispersion at low latitude. The final timestep of evolution of one of the simulations is shown in Figure 2. This Figure shows the face on, side on and end on profiles of the thin and thick disk in the simulation. The stars of the initial thin disk at left in Figure 2 (a) is clearly a more X-shaped structure than the stars of the initial thick disk in Figure 3 (b).



(a) (b)

Figure 2: (A) This is the thin disk at t = 2000 and shows that it is a small central structure that is boxy but not with a long bar and (B) This is the thick disk at t = 2000 and shows that it is a strong bar with a strong boxy structure

Examining the kinematics for the simulations comprised of a thin + thick disk, the stars initially in the thick disk did quite well reproduce the kinematics of component C in the ARGOS survey, which was proposed to be the thick disk. A better agreement was found for the stars initially in the thick disk in the model compared with component C, than for the stars initially in the thin disk in the model compared with components A and B. The rotation profile of stars initially in the thin disk is far slower than observed for the metal-rich stars in the ARGOS survey, proposed in Ness et al., (2013a) to have originated form the thin disk (components A and B). However, the overall dispersion profile at low latitudes for the stars initially in the thin disk very well matches the observed dispersion profile of metal-rich stars ([Fe/H] > –0.5). The dispersion profile for metal rich stars at higher latitudes is not similarly well reproduced by the simulation for stars initially in the thin disk.

These comparisons of the simulation for stars initially in the thin and thick disk, with the corresponding data from ARGOS for stars [Fe/H] > –0.5 and < –0.5, respectively, is shown in Figure 3. *That the stars initially in the thick disk shows a good agreement with the component C in the ARGOS survey is an important and new finding and this result will comprise paper 1.* Furthermore that the metal-rich stars at low latitudes show a steep dispersion profile observationally which is matched by the stars initially in the thin disk argues for a thin disk origin for the metal-rich stars in the bulge of the

Milky Way for the low latitude stars observed.

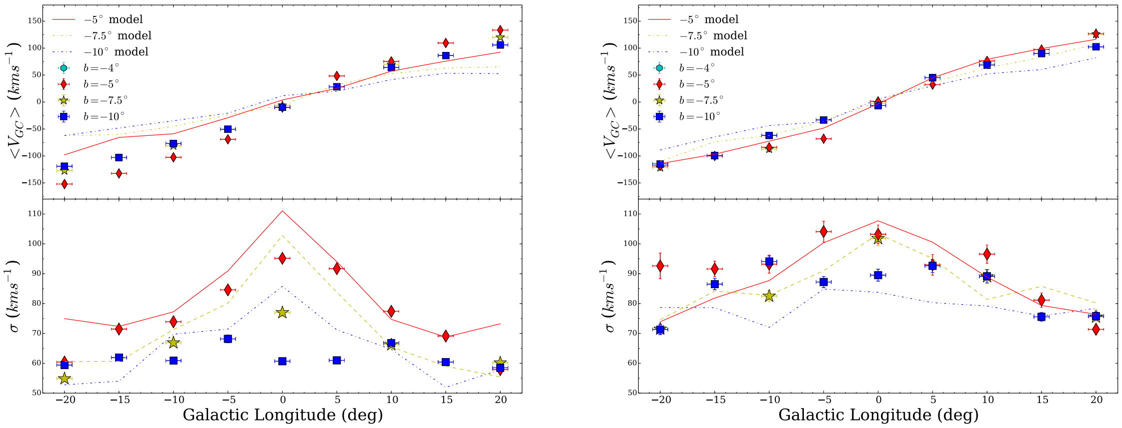


Figure 3: (A) Kinematics of stars initially in the thin disk compared with ARGOS observations for stars [Fe/H] $>$ –0.5 and (B) Kinematics of stars initially in the thick disk compared with ARGOS observations for stars [Fe/H] $<$ –0.5, both at simulation time step t = 2000

Results from chemodynamical models

We investigated a series of models of a single disk, with gas, with star formation. One of these evolved simulations is shown below in Figure 4

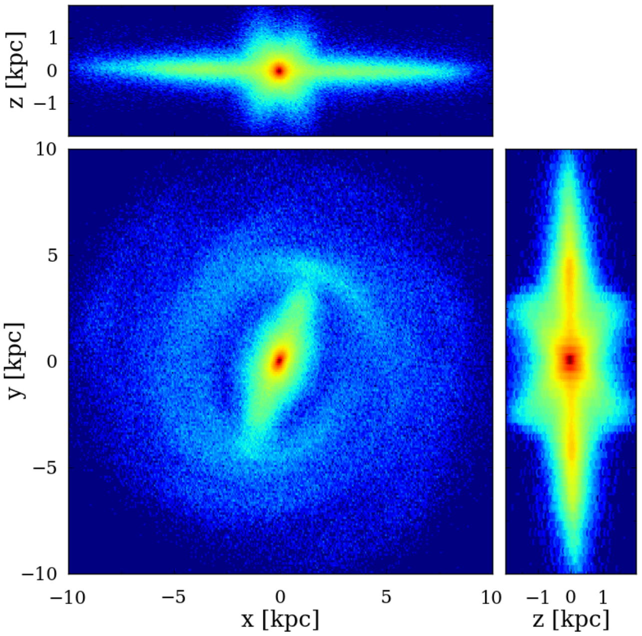
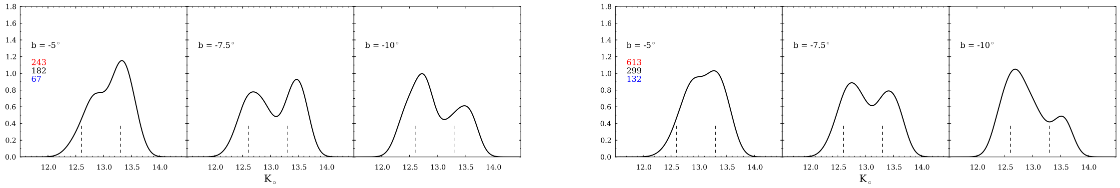


Figure 4: Chemical simulation showing the stars at t = 2000

We wanted to see if we could use these simulations to understand the origin of the split in the red clump seen at the minor axis in the Milky Way, which is seen only for the more metal-rich stars ([Fe/H]

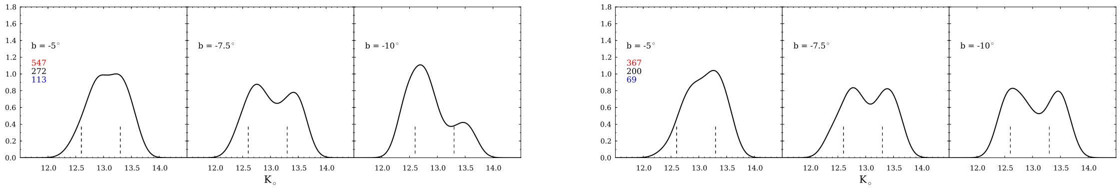
> –0.5) and is stronger for the most metal-rich stars (Ness et al., 2012). We examined our chemodynamical simulations and broke up the simulations as a function of [Fe/H] as shown in Figure 5. These figures show a weak dependence of the split on [Fe/H], shown at three latitudes at the minor axis, of $-5°$, $-7.5°$ and $-10°$ for bins of 0.5 dex in [Fe/H]. The simulation is dissimilar to the observations in that the split is seen across all metallicities. However, the split is still weakest at the lowest metallicities (comparing Figures 5(a) and 5(f)).

We are continuing this investigation by running the chemodynamical models with both a thin and a thick disk component, as it was clear from the investigation of the thin + thick disk N-body models, that the stars of the thin disk are redistributed into an X-shape and the stars of the thick disk are redistributed into a barred distribution (for which a split in the clump would not be present).



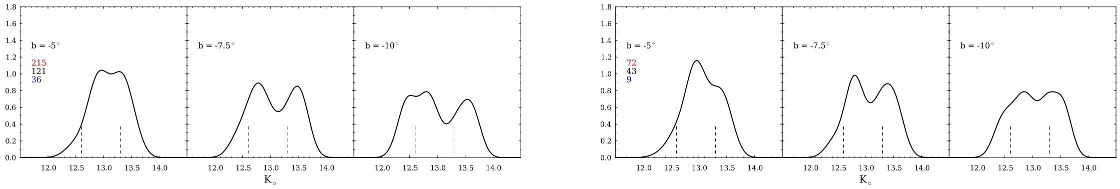
(a) [Fe/H] > 0

(b) 0 > [Fe/H] > -0.5



(c) -0.5 > [Fe/H] > –1.0

(d) -1.0 > [Fe/H] > –1.5



(e) [Fe/H] < –2.0

(f) [Fe/H] < –3.0

Figure 5: Split in the density distribution of the red clump stars in the chemodynamical simulation as a function of [Fe/H] from most metal-rich stars (a) to most metal-poor stars (f)

We aim to have a second paper examining the origin of the split clump in the Milky Way using our chemodynamical models with a thin + thick disk. The thin and thick disk models have been instructive in demonstrating how the evolution seen in the simulations may explain why in the Milky Way we see the most metal-rich stars in the bulge to be in the split clump, with the largest separation in the split, arguing for the strongest X-shape where as the more metal-poor stars are more weakly in the split (and not at all for the most metal-poor stars). The hotter stars in the initial disk from which the bulge formed in the Milky Way were likely not redistributed into orbits which are the backbone of the X-shape, but were distributed into barred orbits, as seen in the simulation. On the other hand, the colder stars are those more affected by the instability and redistributed into the X-shaped orbits. This would argue that the stars in the X are somewhat younger than the stars in the bar. Photometric analyses is not sensitive enough to be able to measure any difference in ages for stars integrated along the line of sight in the bulge. However, spectroscopic analyses similar to, but on a lager scale than the microlensed dwarf age analysis of Bensby et al., (2014), would allow such age differences to be seen. An ongoing target of opportunity program to examine microlensed dwarfs at higher latitudes including at the locations of the split clump may reveal information here. Therefore this analysis allows us to make predictions for observations.

Future Collaboration & Projected Publications

Our collaboration to complete these investigations and these papers is ongoing and we also will compare our results to the kinematics from the APOGEE survey (Majewski et al., 2014), which show good agreement with ARGOS but also probe fields nearer to the plane than ARGOS. We aim to complete *paper 1* from this work by September 2015.

We also plan to run a thin + thick disk series of simulations with gas, as ongoing star formation is an important additional description which we are currently missing from our thin + thick disk model. Our investigation thus far has indicated that this is important for understanding the origin of the split clump in the Milky Way, the focus for our planned *paper 2*.

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