Bringing Milky Way and Large Magellanic Cloud potentials to life to explain the Milky Way halo disequilibrium

The disequilibrium detected in the Milky Way stellar halo -- induced by the Large Magellanic Cloud -- requires new methodologies to model. We discuss a new technique that allows one to bring a broad range of potential families to life, enabling exploration of dynamical mechanisms inherent to nonlinear dynamics. We present one new finding from the new models for the Milky Way and Large Magellanic Cloud interaction: the disequilibrium distortion of the outer Milky Way halo, as reflected in the kinematics of distant tracers. We review what this means for modeling the time-evolving dark matter distribution in the Milky Way, what we can infer from such models, and where the current and future observable effects may lie.

SLIDE 1
I'm Mike Petersen, from the University of Edinburgh. I'll talk about some of my recent work with Jorge Peñarrubia bringing disequilibrium potentials to life. That is, when a potential is changing on relatively short timescales, how can we model the key effects? I'll be talking about the influence of the Large Magellanic cloud (the LMC) on the Milky Way halo, but many of the techniques could be generalised to a variety of dynamical scenarios, both on galactic scales and down to much smaller scales.

In the case of the Milky Way and LMC, the reason that we need disequilibrium potential models is depicted here in this cartoon. The key result is that the infall of the LMC (shown here in red) displaces the Milky Way (shown in blue) from its original centre. This displacement happened over only the last Gyr or so, and the interaction is still ongoing, so the dynamical repercussions are still being felt.

At its heart, the dynamical effect is the displacement of the disc. In the impulse approximation limiting case, we can think of the inner halo as tied to the Milky Way disc center, and the outer halo still tied to the pre-LMC infall barycentre. Those two points are no longer concident.

If one wants to study anything in the outer halo, from substructure to satellite galaxies to the Milky Way history, we need to use potential models that take this displacement into account.

SLIDE 2
The dynamical reason is straightforward. The LMC crossed the virial radius of the Milky Way within the last Gyr. But, the dynamical times of orbits in the outer halo can be longer than this!

Because of the mismatch in timescales, the orbits in the outer halo haven't yet fully begun to react to the presence of the LMC. The mismatch in timescales is connected to the mass ratio of the Milky Way and LMC, as well as the mass distribution within each, but the simple picture remains.

SLIDE 3
Recalling that physical picture of the disc displaced from the barycentre of the halo, we can look for signatures of the displacement. One place to find unambiguous signals is in the kinematics of the stellar halo, as we predicted in a letter from early last year. In such a model, the line of sight velocity and observed proper motions have an all-sky coherent signal that can't be mimicked by rotation or substructure.

The downside is that this requires assembly a six-dimensional data set, which is still a challenge. However, we were able to build up a large enough sample and a statistical model to investigate the possible displacement of the stellar disc from the centre of the MW.

SLIDE 4
Even for a relatively simple model for the dynamical effect the LMC is inducing on the Milky Way, we needed nine parameters. The parameters broadly describe three things: the reflex motion, the bulk motions in the halo, and hyperparameters. We're going to focus on just the reflex motion, but I think there is science in all of the other parameters as well – good fodder for discussion!

Luckily you can pause this recording and look for yourself, or you can refer back to our paper, where we explain the parameters in detail.

SLIDE 5
For now, let's focus on the reflex motion.

The reflex motion, or the apparent motion of the outer halo relative to the disc. This is what you want to 'invert' to learn about the motion of the disc: that is, the reflex that you observe in the outer tracers of the halo owes to the motion of the stellar disk.

We find a strongly non-zero signal that we estimate around 30 km/s. With this velocity signal, we can also localise where the peak is on the sky, which tells us the direction that the disc is traveling in. We're showing the localisation here in galactic coordinates, but it's easier to visualise on the sky.

SLIDE 6
So here's the localisation of the apex, or peak signal, which tells us the direction the Milky Way disc is traveling.

The direction of the Milky Way disc travel is actually a little surprising at first glance, in that it's 100 degrees away from the LMC. But, it's coincident with the former trajectory of the LMC. This is effectively telling us that the Milky Way disc is traveling towards an earlier point on the LMC orbit. The current speed of the LMC makes it a moving target, and the stellar disc of the Milky Way hasn't yet started reacting to the pull of the LMC just past its pericentre.

Note that on both this slide and the previous two, we find the signal in three different tracers with six-dimensional data: Blue Horizontal branch stars, K Giant stars, and the collection of Milky Way satellites, each of which trace the outer halo.

SLIDE 7
To go back for just a moment, I'd like to emphasise the need for velocities when trying to determine structure in the outer halo, as well as informing the structure so that we can model orbits in the outer halo.

If all one has is density on the sky, the signal can be ambiguous. On the right, I'm now showing what you observe in terms of stellar halo density structure on the sky, much like we might if we had all-sky coverage of the stars we used to fit the reflex motion. What's causing the observed overdensities?

SLIDE 8
One option that we already know must be taken into account is the displacement of the stellar disc from the old barycentre of the halo. If we create a very simple displacement model where the stellar disc is offset from the outer halo, we can create the dipole signature (that is, one overdensity) on the sky. So presumably that displacement is a part of the observed mock signal, which is difficult to measure without velocities. To what extent is the observed overdensity driven by the displacement of the stellar disc from the barycentre?

The rest of the signal in the observed mock might come from global modes stirred up in the outer halo – and modeled velocities will help to disentangle the effects.

SLIDE 9
One other option that bears investigation only densities are observed is the possibility of a triaxial halo in the outer parts of the MW. Cosmological simulations regularly predict triaxial halos, which could create overdensities on the sky.

Again, models that include velocities will help to understand what is going on in the outer halo of the MW – but we also need more line-of-sight velocities! Luckily, some future surveys are poised to provide velocities, so it now behooves dynamicists to investigate the signatures inherent to different model scenarios.

SLIDE 10
Hopefully between the showing the reflex motion results and the open questions regarding the cause of overdensities on the sky, I've convinced you that we need to design models to explain the interaction of the Milky Way and LMC. One last tidbit to persuade you that these potential models also need to be evolving.

In preliminary fits where we split the halo tracers up into annuli, we find that the reflex motion signal varies with distance. This is to be expected given the range of dynamical times in the halo, but just illustrates the challenges with accurately modeling the Milky Way potential.

SLIDE 11
Okay, so how do we do this? I'm going to give a very short rundown of the technique, which we're looking forward to using more in the near future.

In an equilibrium world, you write down the ideally analytic potential functions that describe the structure. Then you can integrate orbits efficiently and test simple effects. However, these simple parameterisations fall short of recovering the necessary dynamics to fully describe the interaction of the Milky Way and the LMC.

In a paper from a couple of years ago, Denis Erkal used a model Milky Way-LMC system to reproduce the orbit of a stellar stream in the halo that exhibited perturbations from the LMC. The models in that work were equilibrium, but we can bring them to life using a basis function expansion.

SLIDE 12
The basis function expansion technology isn't new, but further recent developments have made them more tractable for use in modeling the Milky Way-LMC system.

To accomplish flexible potential descriptions, we use basis function expansions as the N-body solver – this was the model MW that you saw earlier – and then 're-play' the forces from the simulation. With basis function expansions, the potential of the fully-live and reactive simulation can be reconstructed at any point.

This is true nonlinear or disequilibrium dynamics: capturing the full evolution of the potential as it evolves on shorter timescales than the dynamical time in the outer halo.

SLIDE 13
The effect from the LMC is on the order of a few percent at any instant in recent time, but that effect can be enough to cause significant differences in the evolution of orbits in the outer halo. So things like stellar streams, globular clusters, and satellites can be investigated for differences in their behaviour.

SLIDE 14
We're at a frontier for modeling nonlinear and disequilibrium dynamics in the outer Milky Way halo, with good reason to investigate the time-evolving potential, and new methods to do so.

We found that the kinematics of the outer halo indicate significant displacement of the Milky Way disc from the barycentre of the halo. The kinematics are critical to understanding the dynamics of the outer halo, but data is currently lagging behind the predictions.

However, the current data is good enough to detect radial variations in the reaction of the halo, something that we're looking at in detail now.

We were able to make progress modeling the potential of the Milky Way with time-dependent basis function expansions, which can be used to play back the entire evolution of the Milky Way-LMC system and reveal new dynamics.

Thank you, and I look forward to questions at the meeting.