PRIMAL: A particle-by-particle M2M Algorithm

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Hunt, Kawata & Martel (2013), MNRAS, 432, 3062
Hunt & Kawata (2014), MNRAS, 433, 2112
The Goals

- Milky Way Structure & Dynamics unknown;
  - \( R_0 = 8.35 \pm 0.35 \) kpc
  - \( M_d = 6.43 \pm 0.63 \times 10^{10} M_\odot \)
  - \( R_{d,\text{thin}} = 2.6 \pm 0.52 \) kpc
  - \( R_{d,\text{thick}} = 3.6 \pm 0.72 \) kpc
  - \( V_{\text{rot},\odot} = 239 \pm 5 \) kms\(^{-1}\)

- Hard to know global picture due to position and extinction.

Thus we need good surveys and good models!
Gaia (Launched 19th December 2013)
ESA corner-stone mission
Mapping a billion stars in the Milky Way

• Also ground based surveys, e.g. Gaia-ESO (VLT)

Credit: X. Luri & DPAC-CU2
We are developing a new Made-to-Measure dynamical model of the Milky Way.

The vast majority of observed stars will be from the Disc, so we focus on the disc.
The Basic M2M Concept

Observation

Compare

N-Body Model or test particle

Use

Alter

Before

After
The Basic M2M Formula

For example, with density:

- If $\Delta \rho > 0$ then $m_p$ decreases
- If $\Delta \rho < 0$ then $m_p$ increases

\[
\Delta_j = \frac{y_j(t) - Y_j}{Y_j}
\]

Our adaptation: PRIMAL

- Compares target and model observables at target particle positions.
- Uses SPH Kernel to calculate contribution to observable.
- Use of self-gravity leads to structure and dynamics.
Our adaptation: PRIMAL

• \( \mu_{\alpha,\delta} \) & \( \nu_r \) use likelihood equation with SPH Kernel.

• Allows individual errors.

\[
\hat{L}_j = \frac{1}{\sqrt{2\pi}} \sum_i W_{ij} m_i e^{-\frac{(v_j - v_i)^2}{2\sigma_j^2}}
\]

• Resample model particles when their mass is too large or too small.
Making target Gaia data

- Gaia astrometry data release expected 2016.
- Need mock Gaia catalogues to test.
- Can ‘observe’ an $N$-body model to get mock data.
The Target Galaxy

- N-body simulation with GCD+ (Kawata & Gibson (2003), $10^6$ particles, 2 Gyr old.
- $R_d=3.0$ kpc, $z_0=0.3$ kpc, $M_d=5.0 \times 10^{10}$ $M_\odot$.
- Fixed dark matter halo, $M_h=1.75 \times 10^{12}$ $M_\odot$. 

![Image of galaxy simulation]
Adding Extinction

- Assume (for now) particles are M0III tracers, with one star = one particle.
- Use 3D extinction maps from Galaxia (Sharma et al. 2011).
- Calculate extinction values for each tracer.

Schlegel, Finkbeiner & Davis (1998)

http://irsa.ipac.caltech.edu/applications/DUST/docs/background.html
Adding Error

- Use Gaia performance estimates (pre launch).
  (www.cosmos.esa.int/web/gaia/science-performance)
- Calculate errors for each tracer (M0IIV).
Selecting Observed Range

- Observed data limited to selected range of 10 kpc and 16.5 mag (for M0III).
- For M0III, 173,821 of 1,000,000 selected.
Initial Model Conditions

- Same properties as target except lower scale length ($R_{d,m} = 2.0 \text{ kpc}$, $R_{d,t} = 3.0 \text{ kpc}$).
- Smooth, $10^6$ particle, $m_p = 5.0 \times 10^4 \text{ M}_\odot$
- Assumed known dark matter halo.
Applying PRIMAL to data

- Morphology recovered well, but missing arm and thinner box.
- Pattern speed recovered excellently.

\[ \Omega_p = 28.9 \text{ kms}^{-1}\text{kpc}^{-1} \]
\[ \Omega_p = 29.7 \text{ kms}^{-1}\text{kpc}^{-1} \]
Radial profiles reproduced

- Not directly constrained.
- Density and velocity radial profiles recovered well.
Surface Density

- Fractional difference in surface density
- Excellent bar recovery.
- Missing arm.
- Over-dense patches.
The next step

- Fit multiple populations with PRIMAL. (In Progress)

- Use SNAPDRAGONS mock data (our Gaia based population synthesis code)

- Construct multi-component models (e.g. thin & thick disc).
Summary

• New self-gravity M2M tailored to Gaia data.

• Testing using mock Gaia data from N-body model.

• Results promising despite extinction & error, especially pattern speed.
SNAPDRAGONS

- Resampling $N$-body particles into stars (Hunt et al. In prep)
- Adds extinction (from Galaxia maps) and Gaia error.
- No smoothing: clear particle <-> star relation.
- Can make mock Gaia stellar data.
Previous M2M example

- Bissantz et al. (2004), looks at the bulge.
- Mass model -> Dynamical model.
- No kinematic constraints.
- Matches kinematics in many bulge fields.

Gerhard (2009)