Action-based Dynamical Modeling of the Milky Way Disk with Gaia & RAVE

Wilma Trick (MPIA, Heidelberg)

Hans-Walter Rix (MPIA)

Jo Bovy (Uni Toronto)
Open Questions of Galaxy Formation
Can we answer them with Gaia in our Milky Way (MW)?

- Core/cusp problem & shape of the dark matter halo?
- Is there a dark disk?
- Mass contrast of spiral arms?
- Formation of the disk: Relation between stellar orbits, their abundances and ages?
- Characterizing infall/sub-structure? Need smooth model...

Approach
Solving simultaneously for $\Phi$ and DF by rigorous fitting to discrete Gaia data

Gravitational Potential $\Phi$

Stellar orbit distribution function (DF)
Recovery of the Orbit Action Distribution of Mono-Abundance Populations & Potential INference for our Galaxy

Trick, Bovy, D’Onghia & Rix (2017)
Trick, Bovy & Rix (2016)
Bovy & Rix (2013)
Binney (2012)
Binney & McMillan (2011)
The gravitational potential $\Phi$ relates a star’s obs. 6D $(x,v)$ to its orbit within the Galaxy.

The actions $J = (J_R, J_\varphi = L_z, J_z)$ are integrals of motions:
- label orbits in a given $\Phi$
- hard to calculate, except for axisymmetry $\Phi$ (e.g. Sanders & Binney 2016)
Galactic disk is superposition of stellar orbits in $\Phi$.
- action-based distribution function $DF(J, [X/H], t_{age}, ...)$

RoadMapping Modeling

- Recovery of the Orbit Action Distribution of Mono-Abundance Populations & Potential INference for our Galaxy

see, e.g., talks by Rosemary Wyse, Carlos Allende Prieto, James Binney, ...
 Recovery of the Orbit Action Distribution of Mono-Abundance Populations

Stellar Mono-Abundance Sub-Populations (MAPs)
- disk stars with same [Fe/H] & [α/Fe]
- simple phase-space structure

DF model: "quasi-isothermal DF": qDF(J) (Binney & McMillan 2012)

kinematically hot MAP:
kinematically cool MAP:

exponential disk
quasi-isothermal velocity distribution

Wilma Trick (MPIA)
RoadMapping Modeling

DF model: “quasi-isothermal DF“: qDF(J) (Binney & McMillan 2012)

Φ model: axisymmetric, analytic disk+halo+bulge

(x,v) data fitting to observed

Selection Function of the survey shaped by

Parame-trized by

Recovery of the Orbit Action Distribution of Mono-Abundance Populations & Potential INference for our Galaxy

Advantage of using MAPs:
- implicit treatment of chemical abundances in the modeling
- the MAPs are independent tracers for the same Φ
Breakdown of several modeling assumptions:

Data:
- affected by strong non-axisymmetric spiral arms

Model in general:
- axisymmetric!!

DF model:
- most simple: single qDF

Potential model:
- halo, bulge & "wrong" disk
RoadMapping in a Spiral Galaxy Simulation

Trick, Bovy, D’Onghia, & Rix (2017)

Result

Where most of the stars are located, RoadMapping recovers the local gravitational forces.
Application To Data from Gaia & RAVE

- **Gaia** (DR1, Lindegren et al. 2016)
- **RAVE** (DR5, Kunder et al. 2016)
- **Tycho-Gaia Astrometric Solution** (Michalik et al. 2015)
- **NIR spectroscopy** (Majewski et al. 2015)
- **NIR photometry** (Skrutskie et al. 2006)

**TGAS**

- R.A., Dec., $\mu_{\text{R.A.}}, \mu_{\text{Dec.}}$
- for $\sim 2 \cdot 10^6$ stars

**RAVE-on**

- $V_{\text{los}}$
- for $\sim 200,000$ stars on southern sky / in TGAS

**APOGEE-Red Clump**

- $T_{\text{eff}}, \log g, [\text{Fe/H}], [\text{Mg/Fe}]$
- for $\sim 80,000$ giant stars in RAVE / TGAS; labels on APOGEE scale

- $d_{\text{phot}}$
- for $\sim 20,000$ red clump stars in RAVE / TGAS

Additional:

- Red clump star identification & precise photometric distances (Bovy et al. 2014)
- NIR photometry
- NIR spectroscopy
- Tycho-Gaia Astrometric Solution
- Gaia

Special note by Johanna Coronado on the calibration of photometric distances.
INGREDIENTS FOR THE TGAS/RAVE ROADMAPPING ANALYSIS

Potential model:

- Exponential disk (Smith et al. 2015)
- NFW halo (Navarro, Frenk, & White 1997)
- Hernquist bulge (Hernquist 1990)

Further ingredients:

- outlier model for halo stars
- prior information on flat slope of rotation curve (Bovy et al. 2012a)
- convolution with corell. measurement uncertainties

Selection Function:

\[
\frac{N_{RAVE}(l, b, I)}{N_{2MASS}(l, b, I)} \quad \text{completeness} \quad \frac{N_{TGAS}(l, b, G)}{N_{Gaia\ DR1}(l, b, G)}
\]

Effective survey volume for RC stars in (R,z)
Red Clump Stars from 13 Maps in TGAS/RAVE

Trick et al. (in prep.)

effective survey volume

Wilma Trick (MPIA)

1) Intro RoadMapping 2) Spiral Galaxy Modeling 3) MW potential from Gaia

IAUS 330, Nice, 27.04.17
The DF Model describes the galactocentric Data Well

Trick et al. (in prep.)

Wilma Trick (MPIA)

1) Intro RoadMapping
2) Spiral Galaxy Modeling
3) MW potential from Gaia

IAUS 330, Nice, 27.04.17
A Smooth Model in Orbit Space Will Help to Find Disk Sub-Structure

Trick et al. (in prep.)

Sub-structure? Not yet significant. Wait for DR2…

radial action
angular momentum
vertical action
Our Estimate for the Milky Way Potential

**Result**

Joint constraint from all MAPs:

- Circular velocity @Sun: $v_{\text{circ}}(R_\odot) = (232.5 \pm 0.8) \text{ km s}^{-1}$
- Disk scale length: $R_{S,\text{disk}} = (2.98 \pm 0.06) \text{ kpc}$
- Disk scale height: $z_{S,\text{disk}} = (460 \pm 50) \text{ pc}$
- Halo fraction @Sun: $f_{\text{halo}}(R_\odot) = \left(\frac{v_{\text{circ,halo}}}{v_{\text{circ,tot}}}\right)^2|_{R=R_\odot} = 0.23 \pm 0.02$

Current best estimates from literature:
review by Bland-Hawthorn & Gerhard (2016)

$f_{\text{halo}}(R_\odot)$ from Bovy & Rix (2013)
Our Estimate for the Milky Way Potential

- Circular velocity curve
- Surface density profile

\[ v_{\text{circ}}(R) [\text{km s}^{-1}] \]

\[ \Sigma_{1.1 \text{kpc}} [\text{M}_\odot \text{ pc}^{-2}] \]

- Model from RoadMapping
- Radial extent of the TGAS/RAVE data
- Measurements from literature:
  - \( v_{\text{circ}}(R_\odot) \):
    - See review by Bland-Hawthorn & Gerhard 2016
  - \( \Sigma_{1.1 \text{kpc}} \):
    - E.g., Kuijken & Gilmore 1989; Catena & Ullio 2010; McMillan 2011; Bovy & Rix 2013; Piffl et al. 2014a

Trick et al. (in prep.)
Our Estimate for the Milky Way Potential

- Circular velocity curve
- Surface density profile

Result:
- Rotational support of disk: ~75%
- Disk is maximal!

(Sackett 1997; Gerhard 1999; Bovy & Rix 2013; Piffl et al. 2014)

Trick et al. (in prep.)
Constraining the Milky Way with Gaia

RoadMapping action-based dynamical modeling:

...robust & well-tested machinery
...using discrete 6D stellar \((\mathbf{x}, \mathbf{v})\)
...recovering the MW grav. potential

RoadMapping application to TGAS/RAVE:

...new & very precise measurements of the MW potential parameters
...survey selection function is crucial

RoadMapping promises:

...constraints on Galaxy formation from future Gaia DRs.

Trick, Bovy & Rix (2016),
Trick, Bovy, D’Onghia & Rix (2017),
Bovy & Rix (2013), Ting et al. (2013),
Binney (2012), Bovy et al. (2012a,b,c),
Binney & McMillan (2011)

Thanks also to Jennifer Wojno (AIP Potsdam) and Georges Kordopatis (OCA Nice) for help with the RAVE data.