GALACTIC STRUCTURE, EVOLUTION AND MERGER REMNANTS

The Role that Astrometry Plays in Understanding the Kinematical Structure of the Galaxy

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Perturbed Spiral Galaxies

SDSS
The Milky Way as a Growing System

G. Gilmore and R. Sword
Majewski et al. 2003 – 2MASS
The Sagittarius Dwarf Galaxy: Tidal Streams Mapped from 2MASS
(Majewski et al. 2003)
The Science Goals

1) Better describe and understand the accretion process in our Galaxy, and its contribution to the formation of the halo, bulge, and disk.

2) Kinematically characterize the main components of the Milky Way in order to describe the Galactic potential: i.e., measure mean velocities and velocity dispersions over the relevant size of the Galaxy.

Requirements

Absolute proper motions of:

1) Globular clusters, MW satellites, stars in known streams, and anonymous stars in deep, survey-type programs.

2) Tracers of the main Galactic components: stars, open and globular clusters.
Absolute Proper Motions

By means of an inertial reference frame defined by:

1) galaxies, QSOs (many pencil beam surveys, clusters and MW satellites programs, NPM, SPM, USNO_B-SDSS, etc.)

2) Stars with already determined absolute proper motions: Hipparcos, Tycho2, UCAC2, NPM, SPM

3) Stars with modeled or assumed known kinematics, e.g., disk stars in the case of Sgr, (Ibata et al. 1997), SMC stars for 47 Tuc (Anderson & King 2003), bulge stars for NGC 6522, 6528, 6553 (Terndrup et al. 1998, Feltzing & Johnson 2002, Zoccali et al. 2001), kinematic Galactic model for 14 globular clusters (Cudworth & Hanson 1993).

Millisecound pulsars in globular clusters:

From timing data, very accurate absolute positions are obtained. These can be used to determine absolute proper motions over a relatively short time baseline (e.g., Freire et al. 2003).
Required proper-motion uncertainty

$$\varepsilon_v = 4.74 \times \varepsilon_\mu \times d$$

- **Fornax dSph**
  - $d = 138 \text{ kpc}$
  - $1 \text{ mas/yr} = 650 \text{ km/s}$

- **LMC**
  - $d = 50 \text{ kpc}$
  - $1 \text{ mas/yr} = 240 \text{ km/s}$

- **M3**
  - $d = 10 \text{ kpc}$
  - $1 \text{ mas/yr} = 47 \text{ km/s}$

Milky Way
Most notable systematics found in proper-motion determinations

1) Magnitude-dependent: practically all photographic plates have guiding-induced positional biases of image centroids that occur due to long exposures combined with the non-linear response of the photographic plate.

Fig. 2. Plate pair #Y43–#Y36 positional differences illustrating the presence of magnitude and color equatorials. The bold dots are for red stars with 0.9<(B–V)<1.3.

Fig. 4. Plate pair #Y43–#Y36 residuals after correction for magnitude and color equatorials as described in Sec. 3.4. Symbols are the same as in Fig. 2.

Kohzurina-Platais et al. 1995 – NGC 3680
SPM – Girard et al. 1998; grating images were used to correct magnitude equation in positions: proper-motion differences between blue and visual plate pairs.

SPM – cluster program, Dinescu et al. 1999; field of M4 after magnitude equation correction based on grating images.
2) Color-dependent: due to color dependence of atmospheric refraction. Observations taken at different hour angles, and with different filter-plate combinations and telescopes are affected by color terms. This is why QSOs and galaxies may give different answers when determining absolute proper motions.

Dinescu et al. 2004; Fornax field: galaxies and QSOs
3) Position-dependent: mainly due to optical distortion. Most notable for wide field, short f/ratio telescopes (e.g., Schmidt telescopes that were used for deep, all-sky surveys). Other: field rotation, coma. Distortion can be modeled (e.g. Chiu 1976, Cudworth & Rees 1991, Zacharias et al. 2004 –UCAC1, UCAC2, Anderson & King 2003). However, position-dependent systematics may remain in the proper motions. These can be overcome by defining local “plate” solutions around objects of interest-clusters, extragalactic objects- through reference stars of the same kinematical population.

Dinescu et al. 2001, NGC 7006
Proper-motion Results: Globular Clusters

M 4
-12.26 (0.54) -18.95 (0.54) Kalirai et al. 2004 – HST, ~12 galaxies
-13.21 (0.35) -19.28 (0.35) Bedin et al. 2003 – HST, 1 QSO
-12.50 (0.36) -19.92 (0.49) Dinescu et al. 1999 - SPM, ~100 Hipparcos stars
Sagittarius Dwarf
- Ibata et al. 1997 and Dinescu et al. 2005, proper-motion measurements agree and produce an orbit that agrees with the location of tidal debris.

LMC

SMC
- Kroupa & Bastian 1997 (Hipparcos), Irwin 1999 (galaxies)

More distant dwarf spheroidals (Sculptor, Ursa Minor, Draco, Carina and Fornax)
Scientific Results

1) Characterizing the Globular-Cluster System: Age, Metallicity, Orbit Shape

Mackey & Gilmore 2004 with orbits from Dinescu et al. 1999, 2000, 2001, ages from De Angeli et al. 2005
2) Detecting/Characterizing Accretion Signatures

Sagittarius and its tidal debris

Pal 12 proper motion - Dinescu et al. 2000

Table 1. Integrals of Motion

<table>
<thead>
<tr>
<th>Object</th>
<th>$\mathcal{E}_{\text{ej}}$ ($10^4$ km$^2$ s$^{-2}$)</th>
<th>$L_1$ (kpc km s$^{-1}$)</th>
<th>$L_2$ (kpc km s$^{-1}$)</th>
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Cohen 2004  Majewski et al. 2004  Martinez-Delgado et al. 2002
Sagittarius and its tidal debris (cont.)

SA 71 - Dinescu et al. 2002

Putman et al. 2004
$\omega$ Centauri

Collection of CMDs from WFPC2 and ACS data of $\omega$ Cen. For each CMD, the label indicates the distances of the field from the cluster center. Panel $\omega$ shows the subsample of the stars plotted in panel $\beta$, located at radial distances $r > 4'$ and with photometric rms lower than 0.025 mag.

Bedin et al. 2004

Lee et al. 2001

Self-enriched system with a complex chemical pattern
$\omega$ Cen’s Orbit

Retrograde; $R_p = 1.6$ kpc, $R_a = 6.0$ kpc, $z = 2.0$ kpc, $ecc = 0.57$, $P_r = 80$ mill. years, plane crossing $\sim 22$ mill. years (Dinescu et al. 1999)

On the current orbit, $\omega$ Cen couldn’t have chemically enriched itself (Gnedin et al. 2002)
N-body modeling of the disruption of ω Cen’s parent galaxy

ω Cen’s parent system: a massive system of 8 $10^9 M_\odot$ and half-mass radius of 1.4 kpc. It has a radial, low-inclination orbit that starts at ~ 60 kpc from the Galactic center and decays in ~ 2 Gyr to the current orbit of ω Cen (Tsuchiya et al. 2004, 2003). The debris form a disklike structure within 6 kpc from the Galactic center. Kinematical and chemical surveys within 1-2 kpc of the Sun should be able to detect such a structure (Dinescu 2002, Meza et al. 2005). The thin disk of the Galaxy is potentially strongly affected by such a massive satellite. Very likely, other globular clusters may originate from this satellite (Dinescu 2002).
Searching for debris from ω Cen's parent galaxy Dinescu 2002, use Beers et al. 2000 cat., and highlight RR Lyrae Meza et al. 2005
The Monoceros tidal stream

Pennarubia et al. 2005; proper motions from Munn et al. 2004 (USNOB-SDSS) of 3-4 mas/yr precision per star. These allow the distinction between pro and retrograde orbits of the parent satellite.
3) Milky Way Satellites: Interactions, Orbit Alignments

Fornax crossed the Magellanic plate ~200 Myr ago, a time that coincides with the termination of the SF process in Fornax. The excess, anomalous clouds within the SGP region of the Magellanic stream (Putman et al. 2003), whose origin has long been debated in the literature as constituents of either the MS or of the extragalactic Sculptor group, are found to lie along the orbit of Fornax. Cloud orientations differ from those in the MS, and their radial velocities are well below those of galaxies in the Sculptor group. These clouds may be stripped material from Fornax as the dwarf crosses the orbit of the Magellanic clouds.
3) Galactic Structure: Characterizing the Main Components

Thin disk

Solar neighborhood samples with proper motions from e.g. Hipparcos, Tycho2, UCAC2, NPM/SPM aim to describe the disk in terms of:

- Galactic potential via surface density as a function of z (e.g. Korchagin et al 2003, Galactic rotation (Oort coefficients, e.g., Ollig & Dehnen 2003), bar’s signature in local velocity groups (Dehnen 2000, Fux 2001).

- Disk’s heating mechanism via velocity dispersion as a function of age (e.g., Nordstrom et al 2004).

More distant tracers (OB stars, possibly open clusters) can be used to describe/understand the disk on a larger scale:

- The spiral pattern and the warp: (Fernandez et al. 2001, Drimmel et al. 2000)
3) Galactic Structure: Characterizing the Main Components (cont.)

**Thick disk**

There are numerous studies that use particular tracers to measure the thick disk's mean velocity and dispersion. It was found that the mean velocity $\langle V_\phi \rangle$ decreases with increasing distance from the Galactic plane $|Z|$. The following relations were derived from the observed data:

\[-0.8 \leq [\text{Fe/H}] \leq -0.6\]
\[-2.4 \leq [\text{Fe/H}] \leq -1.9\]

These relations were obtained by Chiba & Beers (2000) using homogeneous datasets.

Chiba & Beers 2000
Thick disk (cont.)

Girard et al. (2004 and work in progress); SPM + 2MASS toward SGP

\[ V_\phi^2 = \sigma_U^2 \left\{ \frac{R}{\rho \sigma_U^2} \frac{\partial (\rho \sigma_U^2)}{\partial R} + 1 - \frac{\sigma_V^2}{\sigma_U^2} \right\} + \frac{R}{\sigma_U^2} \frac{\partial (\Phi_{disk} + \Phi_{halo})}{\partial R} \]
3) Galactic Structure: Characterizing the Main Components (cont.)

The Bulge/Bar

A very complex system where a LOT is happening. Current studies (HST and ground based, e.g. Kuijken 2002, 2004, Zoccali et al 2004, Feltzing & Johnson 2002, Terndrup et al. 1998, Spaenhauer et al. 2002) have focused on determining proper-motion dispersions that are to be matched with dynamical models of the bulge. Currently, there are too few directions sampled in the bulge to allow robust constraints on the models, and there are very few absolute proper-motion studies. Two ongoing programs that can probe a large area of the bulge are: the OGLE proper motion catalog (Sumi et al. 2004, has a 4-yr time baseline!), and absolute proper motions of globular clusters in the bulge (Dinescu et al. 2003).
3) Galactic Structure: Characterizing the Main Components (cont.)

**Halo**

See above discussion for the accreted component.

For the “traditional” stellar halo – as in the case of the thick disk – there are many “localized” studies that have provided mean velocities in the Galactic poles. In the globular-cluster data and field-star data towards the Galactic poles, hints that the halo has an inner, dissipational-collapse component are already found in the globular-cluster data and field-star data (Chiba & Beers 2000). However, we lack a satisfactory global kinematical description of the halo, i.e., mean velocities and velocity dispersions as a function of galactocentric distance.

Chiba & Beers 2000
CONCLUDING REMARKS

- In light of the complex picture of the Galaxy that has emerged from all-sky photometric surveys, velocities are key quantities to understand the present structure and the active, dynamical history of the Galaxy. Velocities combined with chemical abundances are the most powerful tool to map out the formation process of the Galaxy. This kind of study is possible only in our Galaxy and perhaps the Local Group, and astrometry has a crucial part to play.

- When using proper-motion catalogs/data, it is imperative that the limitations are understood. Search through the descriptions for various tests for systematics!