Mapping the universe in six dimensions with Gaia

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acknowledgements: ESA, the Gaia scientific community and industrial partners
What is astrometry?

- **Positions**
  - Right Ascension, Declination
- **Distances**
  - parallaxes
- **Kinematics**
  - 2D (angular) proper motions
  - combined with parallaxes
    => 2D transverse velocities

Astrometry gives five components of $r,v$ phase space
What do we learn from astrometry?

• Distances
  – fundamental problem in astronomy (sky is 2D)
  – puts angular measurements on a spatial scale → 3D structure
  – converts apparent luminosities to absolute luminosities
  – all other distance measures depend on astrometric parallaxes

• Kinematics (3D motions)
  – identify common motions of widely separated stars (e.g. streams)
  – determine orbits (star, planets, asteroids etc.)
  – measure gravitational potential (mass distribution)
<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>125 B.C.</td>
<td>Precession of the equinoxes (Hipparchus)</td>
</tr>
<tr>
<td>1717</td>
<td>First proper motions measured (Halley)</td>
</tr>
<tr>
<td>1725</td>
<td>Stellar aberration (Bradley), confirming</td>
</tr>
<tr>
<td></td>
<td>- Earth's motion through space</td>
</tr>
<tr>
<td></td>
<td>- finite velocity of light</td>
</tr>
<tr>
<td>1761/1769</td>
<td>Transits of Venus across the Sun (various)</td>
</tr>
<tr>
<td></td>
<td>- solar parallax</td>
</tr>
<tr>
<td>1838/9</td>
<td>First stellar parallaxes (Bessel, Henderson, Struve)</td>
</tr>
<tr>
<td>1989-1993</td>
<td>Hipparcos satellite (ESA)</td>
</tr>
</tbody>
</table>
arcseconds and parsecs

\[ \frac{d}{\text{parsec}} = \frac{1}{\theta/\text{arcseconds}} \]

1 pc $= 31 \times 10^{12}$ km $= 3.26$ light years

1 microarcsecond is the angular size of
- a grain of rice seen on the Moon
- a human hair seen in Kabul
Global astrometry from space

- **Ground-based astrometry**
  - narrow field
  - reference stars share common parallax effect
  - therefore only *relative* astrometry
  - limited to a few milliarcseconds precision

- **Space-based astrometry**
  - observe simultaneously in two widely separated fields separated by a fixed *basic angle*
  - measure relative positions along great circle
  - repeat for many orientations over whole sky
Entire sky to $V=20$

high accuracy astrometry: $10 \mu$as @ $V=15$

radial velocities and photometry

ESA mission launch 2011

Key objective: composition, formation and evolution of the Galaxy
<table>
<thead>
<tr>
<th></th>
<th>Hipparcos</th>
<th>Gaia</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Magnitude Limit</strong></td>
<td>12.4</td>
<td>20</td>
</tr>
<tr>
<td><strong>No. sources</strong></td>
<td>120,000</td>
<td>1,000,000,000</td>
</tr>
<tr>
<td><strong>No. quasars</strong></td>
<td>none</td>
<td>0.5-1 million</td>
</tr>
<tr>
<td><strong>No. galaxies</strong></td>
<td>none</td>
<td>1-10 million</td>
</tr>
<tr>
<td><strong>Astrometric accuracy</strong></td>
<td>~1000 µas</td>
<td>2-3 µas at V&lt;10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5-15 µas at V=15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40-200 µas at V=20</td>
</tr>
<tr>
<td><strong>Photometry</strong></td>
<td>2 bands</td>
<td>19 bands</td>
</tr>
<tr>
<td><strong>Radial velocities</strong></td>
<td>none</td>
<td>1-10 km/s to V=17-18</td>
</tr>
</tbody>
</table>
10 μas = 10% distances at 10 kpc

10 μas/yr = 1 km/s at 20 kpc
Sky scanning principle

Continuous three-axis motion:
- axis rotation ($P = 6$ days)
- fixed sun angle precession ($P = 70$ days)
- orbit around sun ($P = 1$ year)

Traces quasi great circles on sky

5 year mission
The satellite

Sunshield diameter = 11m  Total mass = 1700kg (800kg telescope/instruments)
Payload overview

Astrometric instrument: 1.4m x 0.5m primary mirrors

Astrometric focal plane

SiC optical bench

Spectroscopic instrument: 0.56m x 0.45m primary mirror
Astrometric focal plane

- The two fields-of-view are superimposed on a single CCD focal plane.
- 180 CCDs (2000 x 5600 pixels)
- CCDs clocked in "TDI mode"
- Real-time detection of objects
- Transmission only of "windows" around objects

Direction of motion across focal plane
Gaia photometry

- Broad Band Photometric system (BBP)
  - 5 broad bands
  - primarily for chromatic correction

- Medium Band Photometric system (MBP)
  - 14 medium bands
  - object classification
  - determination of stellar parameters and interstellar extinction

- systems optimized specifically for Gaia
- vital for exploiting astrometric data!
Gaia spectroscopy

- Slitless spectrograph
- \( R = 11 \, 500 \)
- around Call triplet (848–874 nm)
- radial velocities (Doppler effect)
- \( V_{\text{rad}} \) to 1–10 km/s for \( V < 17.5 \)
- high SNR spectra for millions of stars with \( V < 14 \)
  - physical stellar parameters, e.g. \([\alpha/Fe]\)
Launch and orbit

basic angle must be stable to $\sim 1 \mu\text{as}$ over 6 hours

$\Rightarrow$ 25 $\mu\text{K}$ thermal stability
$\Rightarrow$ high mechanical stability (no moving parts!)

Lissajous' orbit about Earth-Sun L2 point
5 year mission

Phased antenna array:
- 3 Mb/s for 8 hours per day
- single ground station (Perth or Madrid)
Distance and velocity accuracy

Astrometric accuracy $= 10 \mu\text{as} @ V=15$

Astrometric error:

$$\delta \pi \propto \frac{1}{\sqrt{N_{\text{photons}}}}$$

**Distances**

- 1% accuracy at 1 kpc at $V=15$
- 20% accuracy at 1 kpc at $V=20$
- $<0.1\%$ for 700 000 stars
- $<1\%$ for 21 million stars
- $<10\%$ for 220 million stars

**Transverse motions**

- 1 km/s accuracy at 20 kpc at $V=15$
- 1 km/s accuracy at 1 kpc at $V=20$
- $<0.5\text{ km/s}$ for 44 million stars
- $<1\text{ km/s}$ for 85 million stars
- $<5\text{ km/s}$ for 300 million stars
Distance accuracy to nearby stars

Ground

Hipparcos

Gaia
Galactic structure

- galaxy formation
  - how and when did the galaxy form?
  - structure/origin of bulge, halo, disk, spiral arms
  - substructure in the halo (merger history)

- evolution of stellar populations
  - star formation history and chemical evolution
  - abundance distributions in 6D phase space

- mass and dark matter
  - gravitational potential from 3D stellar motions
Stellar clusters

- ~70 clusters within 500 pc
  - *individual* distances to 0.5%, <2.5pc at V=15
  - transverse velocities to <1 km/s for all stars down to M dwarfs out to 200pc
- stellar structure and evolution
  - calibration of luminosity–mass relation
  - ages from Main-Sequence turn off
- kinematics
  - mass segregation (dynamic vs. primordial)
  - evaporation of low mass members, dispersion into interstellar medium
- Gaia will discover thousands more open clusters
Exosolar planets

- **astrometric companion search**
  - \( \alpha = \left( \frac{M_p}{M_s} \right) \left( \frac{a_p}{d} \right) \)
  - 47 UMa: astrom. displacement 360 \( \mu \)as
  - no \( \sin i \) ambiguity in mass

- **extensive, unbiased survey**
  - monitor \( 10^5 \) stars to 200 pc (V<13)
  - all stellar types to \( P \sim 10 \) years
  - \( \sim 5000 \) new planets expected
  - orbital solutions for 1000-2000 systems
  - masses to \( 10 \, M_E \) to 10pc

- **transits**
  - Jupiter across Sun \( \Rightarrow 0.01 \) mag photometric ampltiude
  - expect 6000 detections for 0-2 AU orbit around F-K stars
Solar system

• Gaia capabilities
  - all sky complete survey to G=20, to within 35° of Sun (“daytime”)
  - discovery of $10^5$-$10^6$ new objects (cf. 65000 now)
  - very accurate orbital elements (~30 times better)
  - multi-band photometry (taxonomy, chemistry)
• main belt asteroids
  - solar system formation
  - sizes, albedos, masses (~ 100, cf. 10 now)
• Near-Earth Objects
  - expect 1600 Earth-crossing (vs. 100 now)
• General Relativity
  - light bending (Sun: 4 mas at 90°), $\gamma$ to $5 \times 10^{-7}$
  - perihelion precession (and solar $J_2$)
Data reduction principle

Sky scans (highest accuracy along scan)

Scan width: 0.7°
Data processing

- 1 Mb/s for 5 years (~ 100 TB raw)
- complex data treatment
  - objects mixed up in time and space
  - astrometry, photometry and spectroscopy
  - iterative adjustment of parameters for ~100 million stars
- many tasks, e.g.
  - object matching, attitude modelling, global astrometric processing, binary star analysis, radial velocity determination, photometry, variability analysis, CCD calibration, object classification, determination of stellar physical parameters
- \( \sim 10^{21} \) FLOPS (\( 10^{17} \) FLOPS from 1 PC in 1 year)
  - 1s per star for all operations would require 30 years
- basic data processing prototype (GDAAS)
Timeline and the scientific community

- Fully approved and funded ESA mission
  - phase A study 2001-2005
  - implementation phase starts early 2006
  - launch 2011
  - end of nominal mission in 2016 – 2017
  - data processing complete ca. 2019

- Scientific community is responsible for the data processing
  - funding by national agencies
  - DACC currently responding to “Letters of Intent” to set up an trans-European data processing consortium
  - significant commitment, investment and expertise required
  - but rewards will be extensive
Summary

Formation and evolution of the Galaxy
Stellar structure and formation
Exoplanets
Solar system
Fundamental physics

All sky survey to V=20 \((10^9 \text{ stars})\)
5D phase space \((6D \text{ to } V\sim17)\)

Physical stellar properties
(multiband photometry)

Accuracy = 10 \(\mu\text{as} @ V=15\):
\(\Rightarrow\) distances to <1% for 20 million stars
\(\Rightarrow\) transverse velocities to 1km/s at 20 kpc

Launch 2011; 5 year mission
http://www.rssd.esa.int/Gaia