The Gaia Challenge

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acknowledgements: ESA, the Gaia scientific community and industrial partners
Gaia in a nutshell

- high accuracy astrometry: parallaxes, proper motions
- radial velocities, photometry
- Entire sky to V=20, 100 times over 5 years
- 6D phase space survey + physical parameters
- ESA mission for 2011 launch
Science objectives

Main science driver: Galactic composition and formation
- sets parallax/proper motion precision and magnitude limit
- *dark matter, merger history, chemical evolution* ...

- Stellar astrophysics (*HRD, abundances, binaries*)
- Star formation (*OB assoc., clusters*)
- Exoplanets (*orbits, masses, transits*)
- Solar system (*new discoveries, orbits, taxonomy, NEOs*)
- Extragalactic (*local group galaxies, SNe*)
- Cosmic distance scale (*geometric to 10 kpc, Cepheids, RR Lyr*)
- Reference frame (*quasars*)
- Fundamental physics (*light bending, $\gamma$ to $5\times10^{-7}$*)
What is astrometry?

- Mean 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
Distances

- important in every area of astronomy
  - angular scales → length scales  proper motions → velocities
  - 3D spatial structure
  - intrinsic stellar luminosities (HRD, ages)
- all other measures calibrated with parallaxes
- strength of Gaia is accuracy *and* statistics
  - 1% distance accuracy at 1kpc for V=15
  - 500,000 stars with distance accuracy better than 0.1%
  - 20 million stars  1%
  - 200 million stars  10%
- only from space, and only Gaia
Global astrometry from space

- **Ground-based astrometry**
  - narrow (single) 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
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
## Hipparcos vs. Gaia

<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>7 μas at V&lt;10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12-25 μas at V=15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100-300 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>
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 (Jordi et al. 2006)
- vital for exploiting astrometric data!
Gaia spectroscopy

- Slitless spectrograph
- $R = 11\,500$
- around CaII 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. $[\alpha/\text{Fe}]$
Launch and orbit

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

\( \Rightarrow \) 25 \( \mu \)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 (Madrid)
Stellar structure and evolution

- structure models
  - luminosities (also need $A_V$ and $T_{\text{eff}}$)
  - helium abundances (not available in spectrum; need accurate luminosities)

- open clusters and SFRs
  - 70 within 500pc, providing *individual* distances to 0.5-1% (<5pc) at $V=15$
  - accurate ages from position in HRD of MS turn off
  - Gaia will discover thousands more (from clustering in 6D space, HRD)

- binaries
  - directly calibrate Mass-Luminosity relationship
Galaxy formation

- $\Lambda$CDM models
  - galaxies built up by many small units
- look for evidence of mergers/accretion
  - in external galaxies
  - but in more detail in our Galaxy
Spatial overdensities in the halo

Brown et al. 2005

- spatial overdensities/streams found
  - Sagittarius dSph
  - Canis Major

- but limited discovery space
  - low contrast
  - projection effects
  - streams well-mixed spatially

- can improve with
  - radial velocities
  - better identification of tracers

- ultimately need astrometry
Substructure fossils in phase space

Helmi & de Zeeuw 2000

Initial distribution

Final distribution after 12 Gyr convolved with Gaia errors
Galactic thin and thick disks

- mass of the disk
  - determine gravitational potential from stellar motions
  - from stellar LF determine dark matter distribution

- formation of disk
  - monolithic collapse or via accretion of satellites?
  - is there a smooth age-metallicity-kinematic relation?
  - phase space measurements to look for substructure
  - age from WD luminosity function (200,000, precise to <0.5 Gyr)
Exosolar planetary systems

- astrometric binaries (AB1)
  - $\alpha = (M_p/M_s)(a_p/d)$
- extensive, unbiased survey
  - monitor $10^5$ stars to 200 pc (V<13)
  - all stellar types to P ~ 10 years
  - ~ 5000 new planets expected
  - orbital solutions for 1000 – 2000 systems
- need additional spectroscopy to determine mass (ratio)
  - masses to few $10 \ M_{\text{Earth}}$ to 10pc
  - no sin i ambiguity

47 Ursa Majoris astrometric displacement = 360 $\mu$as
(Sozzetti et al. 2001)
Solar system

• Gaia capabilities
  – all sky complete survey to G=20, to within 40° 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 \(J_2\))
Our challenge: the 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, solar system objects...
- \( \sim 10^{21} \text{ FLOPS} \) (\( 10^{17} \) 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
  - prime contractor selected in January 2006
  - optimization and implementation phase starts mid 2006
  - launch December 2011
  - nominal mission in 2012 – 2016
  - data processing complete ca. 2018

- Scientific community is responsible for the data processing
  - funding by national agencies
  - currently setting up the Data Processing and Analysis Consortium
  - major partners already identified (following “Letters of Intent”)
  - significant commitment, investment and expertise required
  - but rewards will be extensive
CU8: Astrophysical Parameters

- **stellar parameters**
  - $T_{\text{eff}}$, $\log g$, [Fe/H], $A_V$, [$\alpha$/Fe]
  - include parallax to derive luminosity; evolutionary model to derive age

- **Gaia observes entire sky to V=20**
  - no prior information; very wide parameter space
  - need an initial classification (esp. QSO identification)

- **many complications**
  - optimal combination of photometry, spectroscopy and astrometry
  - differing spatial resolutions and flux limits; source variability
  - parameter degeneracy; problem of “weak” parameters

- **solutions**
  - supervised machine learning methods (extensive development required!)
Summary

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

All sky survey to $V=20$ ($10^9$ stars)
5D phase space (6D to $V \sim 17$)

Physical stellar properties
(multiband photometry)

Accuracy = 15 $\mu$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