Astrometric surveys

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Astrometric surveys

1. Astrometric surveys: a major tool for astrophysics

Astrometric surveys: why astrometric data?

- **Parallaxes** = only distance determination without assumption about the observed object
- **Proper motion** = 2 components of the space velocity

Relative astrometry: in small fields (not developed here):

- perturbations in the stellar motion: detection of companions (stellar, sub-stellar, planets), motion of stars around a black hole, etc.
- distance indicator when no parallaxe: reduced PM, statistical parallaxes…)

Global astrometry: all sky, linked to a reference system (ICRS)

- Optical/IR materialisation of IRCS: reference for
  - Small field observations with large to extremely large telescopes
  - Photometric and spectroscopic surveys
- Unbiased sampling of (by increasing level of accuracy)
  - The solar neighbourhood
  - All galactic components
  - Nearby Local Group galaxies

Astrometric surveys: why astrometric data?

"Astrometry is the metrological basis of astronomy"

J. Kovalevsky

Modern Astrometry, p.8

Astrometric surveys: why surveys?

Large number of stars ---> statistical analysis

- Exhaustive stellar types sampling and characterisation (all galactic populations, all types, all evolutionary phases)
- Exhaustive kinematic and dynamic investigation of the MW
- Systematic membership determination for clusters, streams, spiral arms, warp, bar, …
- Systematic detection of duplicity and of exoplanets

Homogeneous data sets

- better control of selection effects
- better identification of the sources of errors
  - better control of systematic errors
  - better determination of internal errors

2. Ground-based astrometric surveys

1. Astrometric surveys: a major tool for astrophysics
   - 1.1. Why astrometric data?
   - 1.2. Why surveys?

2. Ground-based astrometric surveys
   - **2.1. Past and present surveys**
   - **2.2. Future surveys**

3. Space surveys
   - 2.1. Past and present surveys
   - 2.2. Future surveys

Distance limited parallax surveys

RECONS: discover and characterise all stars **< 10 pc**

Results: 17% increase of known stars within 10 pc

Example: 63 images, 18 nights from 1976 to 1990, **± 5.2 mas**

http://www.chara.gsu.edu/RECONS/

CTIOPI (Cerro Tololo Interamerican Observatory Parallax Investigation) **from 1999**

Investigate **< 25 pc** with trigonometric parallaxes: **± 3 mas**

Telescope 90 cm, 6.8' field , 401 mas /pixel, mag 9-19

Phase I: 167 targets, phase II: 209 new targets

Results: 46 parallaxes ± 2.3 mas

Red dwarfs, red subdwarfs, white dwarfs

http://www.chara.gsu.edu/%7Ethenry/CTIOPI/index.htm, Henry et al. 2005

USNO, Flagstaff station

Optical (±1 mas) and IR (± 4mas) programmes: late M, L an T dwarfs

http://www.nofs.navy.mil/, Dahn et al, 2002, Vrba et al. 2004

USNO CCD Astrographic Catalog: UCAC

Astrometric all sky survey. New observations with the USNO 20 cm aperture Twin Astrograph (1998-2004)

Final catalogue, **UCAC3**, expected by **mid-2007**:

60 million stars, R mag 10 to 16

Position accuracy: 15 mas at R 10 70 mas at R = 16

systematic error < 10 mas

Proper motions: 1 to 3 mas/yr for stars to R ~ 12

4 to 7 mas/yr for the fainter stars

new observations and 143 catalogues

UCAC2 (2004): 48 million stars, -90° < δ < +40° , up to +52° in some areas

R magnitudes: ~ 7.5 to 16.

Completeness: ~ 48 million of the 58 million observed stars

- No stars brighter than R ~ 8
  (Bright Star Suppl. built from Hipparcos and Tycho-2: 430 000 stars)
- Multiple systems with separations up to 6 arcsec mostly excluded
- No problem stars, no stars with no or poor proper motion

Will be improved for **UCAC3**

http://ad.usno.navy.mil/ucac, Zacharias et al., 2004, Zacharias JD16

USNO-B1

General all-sky catalogue derived from scans of 7435 Schmidt plates taken for the various sky surveys during the last 50 years

More than **10^9 objects** derived from 3.6×10^9 separate observations

i.e. all entries which were detected in the digitized images of several photographic sky surveys).

Magnitude range: 12-21 **Completeness down to V = 21**

Products: positions, relative proper motions, magnitudes in three colours (up to five in some fields), and star/galaxy estimators

Accuracy

- 0.2″ position accuracy at J2000
- ? mas/yr proper motion accuracy
- 0.3 mag photometric accuracy in up to 5 colours
- 85% accuracy for distinguishing stars from non-stellar objects

Caveats

- Objects with proper motions larger than 1 arcsec/yr unreliable
- Dense fields unreliable
- Bright stars unreliable

http://www.nofs.navy.mil, Monet et al., 2003

Other catalogues

NOMAD: "best" astrometric data for 1.1×10^9 stars

- Bright stars: Hipparcos, Tycho-2, UCAC-2
- Fainter stars: Hipparcos, UCAC-2, Tycho-2, USNO-B1, YB6, 2MASS

http://www.nofs.navy.mil/nomad/

Starnet 2.0: 4.3×10^6 stars

- Proper motions from Starnet + Tycho-2, UCAC2 and, for fainter stars, 2MASS

being compiled at ARI, Heidelberg

SuperCosmos Sky Surveys (SSS): photographic plate digitised sky survey of the whole Southern sky

- Typical proper motion error: ±10 mas/yr at J ~ 19, ±50 mas/yr at J ~ 22

http://www-wfau.roe.ac.uk/sss/

YB6: Yellow-Blue catalog version 6, from scans of NPM and SPM plates

- Limiting mag ~ 18

Monet 2004

CMC14: 10^8 stars, -30° to 50° (2005) http://www.ast.cam.ac.uk/~dwe/SRF/cmc14.html

PM2000: 3×10^8 stars, 11° to 18° (2006), excellent pm Ducourant et al. 2006

2 Micron All Sky Survey: 2MASS

Infrared photometric all sky survey

1.3-m telescopes: Mt. Hopkins, AZ, USA and CTIO, Chili

3 bands in the near IR: J (1.25 μm), H (1.65 μm) et K (2.16 μm)

Stellar products **471 million stars**

- **Completeness**: J < 15.8, H < 15.1, <14.3
- Photometric accuracy: 5% for bright stars σ_{mag} < **0,03 mag**
- Photometric uniformity: 4% over the sky
- Positional accuracy: < **100 mas** relative to Hipparcos
- no proper motion

Science drivers for stellar objects

- large-scale structure of the Milky Way, free of obscuring effects
- search for rare objects, cool or heavily obscured at optical wavelengths

Astrometric use, in combination with UCAC2, Tycho-2, etc.

- Open cluster membership and study down to brown dwarfs
- Galactic warp, halo streams, tidal debris, etc.
- Detection and kinematics of cool stars and brown dwarfs

http://www.ipac.caltech.edu/2mass, Skrustkie et al. 2006

Sloan Digital Sky Survey: SDSS

Photometric and spectroscopic survey of 8000 square degrees

Main science driver

- Milky Way structure and supernovæ 0,1 < z < 0,3

Telescope 2.5 m New Mexico **215 million objects**
Five photometric bands: u, g r, I z + spectra at R = 1800
Completeness: u < 22.0, g < 22.2, r < 22.2, I < 21.3, z < 20.5
Photometric accuracy ≈ **0.02-0.03 mag**
Positional accuracy **< 100 mas**

Proper motion catalogue combining USNO-B + SDSS
Catalogue **90 % complete to g > 19.7**
Proper motions statistical errors **3-3.5 mas/yr**

http://www.sdss.org/, Abazajian et al. 2006, Munn et al. AJ 127 3034 2004, **Ivezic JD13**

USNO Robotic Astrometric Telescope: URAT

All sky astrometric survey. New observations with a dedicated astrometric new USNO instrument: 85 cm, FOV 4.5°, 660-750 nm

Prototype camera expected end 2006

Observations: systematic observations (no bias vs high proper motions)
10^9 stars and galaxies,
one hemisphere 6 times per year
Magnitude range: **14 to 20** (+ extended survey: 7-15)

Products:

- positions, absolute proper motions and parallaxes on the **5-10 mas** level for stars in the 14 to 18 mag range

Main science drivers

- Densification of the stellar reference frame
- Galactic dynamics in the pre-Gaia era
- Unbiased observations of parallaxes in the Solar neighbourhood

Zacharias 2004, Zacharias 2005, Zacharias et al. 2006

Panoramic Survey Telescope and Rapid Response System PAN-STARRS

Primary goal: to survey potentially dangerous asteroids **2010**

First light of prototype telescope: **30/06/2006**

- optical/near IR survey: 400 to 1000 nm, 5 passbands
- 30 000 square degree survey with four dedicated 1.8m telescopes
- 7 square degree field of view (3 for each mirror)
- 30 second exposures: entire visible sky scanned in less than a week
- magnitude range : 15 - 24

Relative astrometry: to a few mas (?)

Systematic errors: less than 0.1" over a 10' field.

Fundamental limitations:

- knowledge of the atmospheric profile as a function of exposure time and angular separation
- Telescope axes encoders and mount model

http://pan-starrs.ifa.hawaii.edu, Chambers 2005, **Kaiser JD13**

Large Synoptic Survey Telescope: LSST

Key science drivers: dark energy
solar system survey
optical transients
mapping the stellar populations in the Galaxy

Expected **first light October 2012**, lifetime 10 years

8.4 m telescope, 6.5 m effective clear aperture

Sky coverage: 20 000 deg^2, observed in ~ 3 nights, 15 sec exposures

Field of View: 9.6 deg^2

Six band survey: u, g, r, i, z, y, from 320nm to 1060nm

Parallaxes and proper motions in mag range: ~ 17-24

Specification on relative astrometry: **1 mas on parallaxes**
0.2 mas /yr on proper motions

Many uncertainties to be addressed to assess astrometric accuracy

http://www.lsst.org/, Wolff 2005

3. Space astrometric surveys

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Hipparcos

ESA satellite, **in operation 1989 - 1993, catalogue 1997**

First and only astrometric satellite: two fields of view, continuous scanning (110 observations per star), modulation grid in the focal plane

Results: **118 000 preselected stars** over the sky

- Reference system: coincidence with ICRS ± 0.6 mas, deviation from inertial ± 0.25 mas /yr
- Median σ for positions (Hp < 9): 0.7 mas
- Median σ for absolute parallaxes (Hp < 9): **1 mas**
- Median σ for proper motions (Hp < 9): **0.8 mas / yr**

Smallest error with a 30 cm telescope and a photometer: **0.27-0.38 mas**

- Magnitude Hp for all stars: ± 0.001 at mag 7, ± 0.005 at mag 11
- Magnitudes B_T, V_T: ± 0.01 at mag 8, ± 0.12 at mag 11

Complete to V = 7.3 to 9 f(galactic latitude, spectral type)

Main science drivers: galactic structure and evolution, stellar structure and evolution, Solar neighbourhood

http://www.rssd.esa.int/Hipparcos/, Perryman at al. 1997, ESA-SP 1200, 1997

Tycho-2

Tycho: uses the star mapper of the Hipparcos satellite

- 10^6 stars $V_T < 11.5$, survey 99% complete down to $V_T \approx 10$
- Position ± 25 mas at $V_T = 10.5$ at epoch 1991.25
- B_T-V_T ± 0.1 mag

Tycho-2: re-reduction of Tycho observations

Results: absolute astrometry and 2-coulour photometry for **2.5 10^6 stars**, optical materialisation of ICRS

- Survey **99% complete to V=11.0**
  90% complete to V=11.5
- Position ± 7 mas for $V_T < 9$ syst. errors < 1 mas
  ± 60 mas for all stars
- Proper motions: ± **2.5 mas/yr** syst. errors < 0.5 mas /yr
- B_T, V_T ± 0.013 mag for $V_T < 9$
  ± 0.10 mag for all stars

Tycho Double Star Catalogue: 66 000 components

Høg et al. 1997, 2000a, 2000b, Fabricius et al. 2002

Gaia

ESA mission, fully funded **end 2011**, lifetime 5-6 years

All sky scanning satellite:

- **astrometric, photometric and spectroscopic survey**
- multi-epoch observations of **10^9 stars to V=20**

Main science drivers

- Stereoscopic and kinematic census of the Galaxy
- Structure, formation and evolution of the Galaxy, dark matter distribution
- Stellar structure and evolution
- Cosmic distance scale
- Astrometric and photometric detection of exoplanets

Expected products

- **Absolute astrometry** to 5 μas at V < 10
  8 - 20 μas at V < 15
  110 - 250 μas at V < 20

-->> **150 x 10^6 stars with 10 % accuracy on parallaxes**

Gaia (cont.)

Expected products (cont.)

- **Spectra for V < 16-17**, R ≈ 11000

---> radial velocity: from ± 1 km/s to ± 15 km/s
+ rotational velocity and abundances for the brighter stars

- **Spectrophotometry in the red and blue domain**

--> Teff, Av, log g, [M/H], [α/H]

- Variability (80 observations per star)
- Duplicity (with the 3 instruments)

http://www.rssd.esa.int/Gaia, Lindegren & Perryman 1994
Bailer-Jones JD13, Lindegren JD16

Space Interferometer Mission SIM PlanetQuest

NASA-JPL project, preliminary Design Review in 2007**2015**, lifetime 5 years
Long baseline Michelson interferometer, 0.4 - 0.9 μm

Main scientific drivers

- Search for planets down to a few Earth masses around the nearest stars
- Stellar luminosities and masses to 1%
- Calibration of cosmic distance scale
- Galactic mass distribution, streams and formation of of the halo

Pointed mission with ~ 10 000 pre-selected targets

Products (goals)

- Wide-angle astrometry (15°) : 4 μas mission accuracy down to 19 mag with measurements referred to a grid of 1300 reference stars
- Narrow Angle Astrometry (1°): 1 μas single measurement accuracy
- Limiting Magnitude: 20 mag

http://planetquest.jpl.nasa.gov, Unwin 2005, Unwin JD16

Japan Astrometry Satellite Mission for Infrared Exploration: JASMINE

Astrometric IR survey of the central part of the Galaxy

1 FOV telescope, primary 75 cm. Target launch date: **2015**

Main science drivers

- Map the bulge of the Galaxy
- Investigate stars in star forming regions

10 million stars, 200 degree^2 in the bulge, observed over 5 years

z-band (0.9 μm), z < 14 mag

Parallaxes and positions to 10 μas, proper motions to 4 μas/yr

Nano-Jasmine Target launch date: **2008**

Precursor scanning microsatellite with 2 FOV, similar to Hipparcos (< 10 kg, telescope 5 cm)

Science products: positions and proper motions, ±1 mas at mag 7

http://www.jasmine-galaxy.org, Gouda et al. 2005, **Gouda JD13, Kobayashi JD13, Yano JD13**

The Milli-Arcsecond Pathfinder Survey: MAPS

Micro-satellite studied at USNO **2010**

All-sky astrometric and photometric survey, mag 3 to 15

Main science drivers:

- Astrometric detection of planets in nearby systems
- Search for Galactic mergers
- Kinematics of the solar neighbourhood

Step and stare mission with a single aperture (15 cm), FOV 1.5°

Expected products: 1 mas positions, parallaxes
1 mas/yr proper motions
0.1 mas/yr proper motions for the Hipparcos stars

To be supplemented by a ground-based program to reach 18th mag on the 5 mas level

Pathfinder for OBSS

Dorland et al. 2005, Zacharias & Dorland 2006, Gaume et al. JD16

Origins Billion Star Survey: OBSS

USNO-JPL proposal to NASA (Origins roadmap AO 2004) **2014**

Science drivers

- Census of giant extrasolar planets within 200 pc from the Sun
- Characterisation of stars in half of the Galaxy, dynamics of the Galaxy
- Reference frame

Step-stare astrometric mission with a single aperture (1.5m), FOV 1.3°

Two observing modes

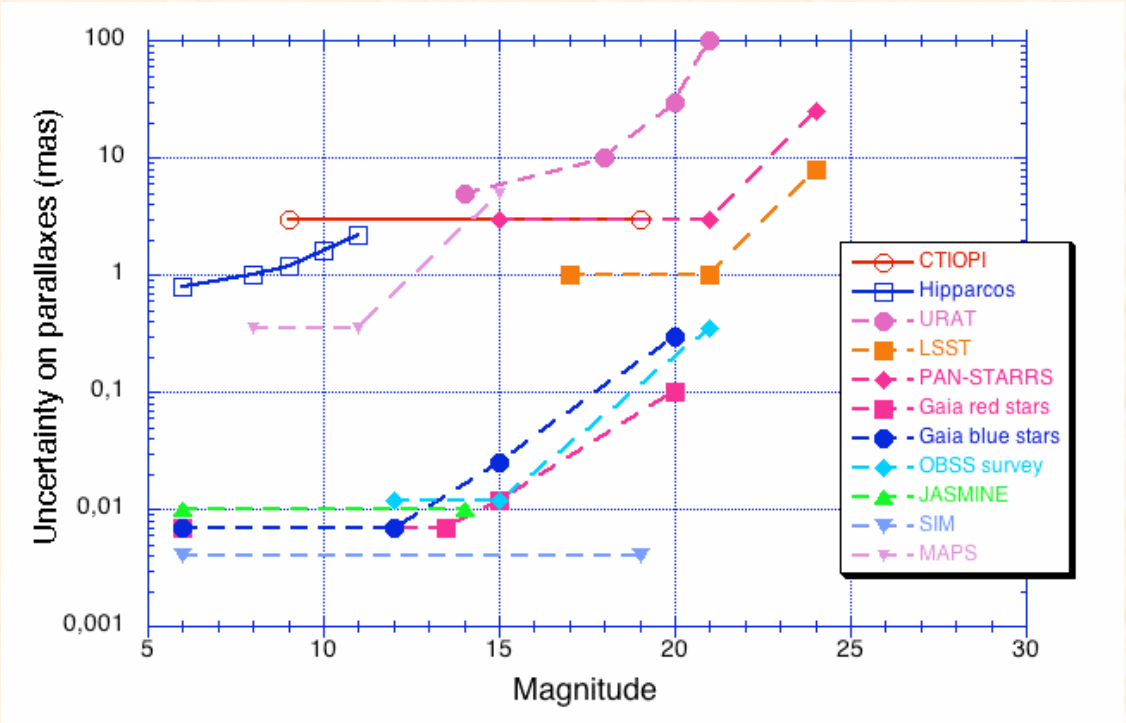
- All sky **survey** with 36.5 s cycles: all sky observed twice a month **to V = 21**
- Targeted observations: could go as deep as V = 24 in selected areas

Products

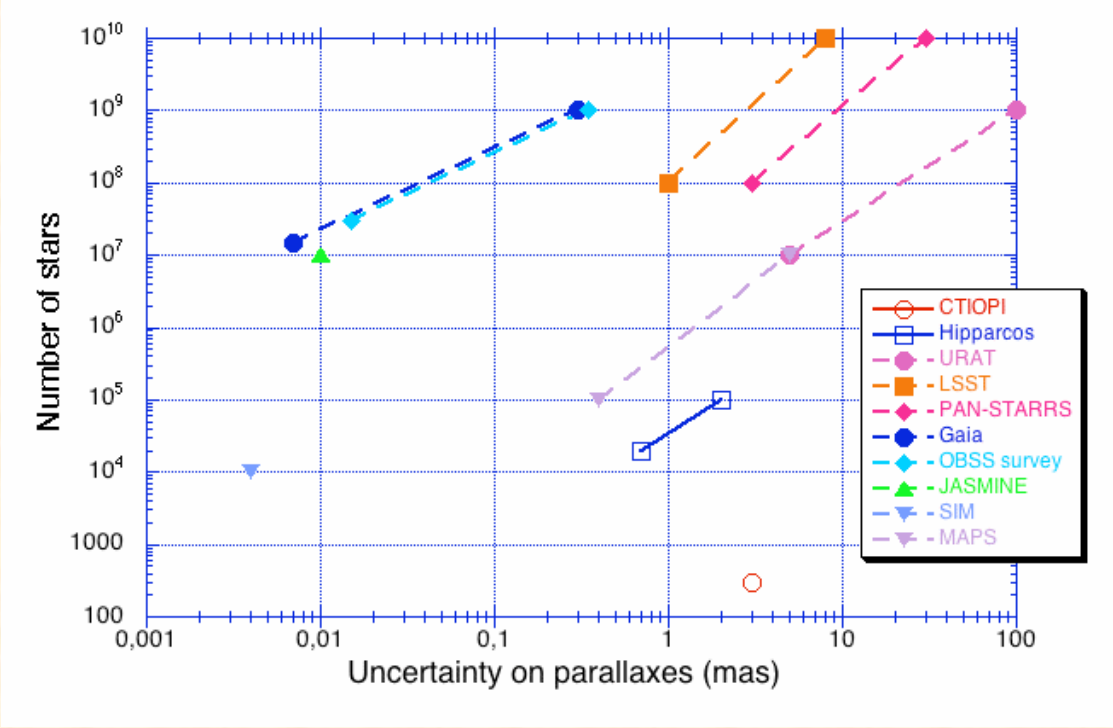
- absolute positions, parallaxes and proper motions for **1 billion stars**
- mission accuracy: **~ 15 μas (survey), 10 μas (targeted) at V=15**
- stellar colours in 16 bands up to V ≈ 18 (low resolution spectrograph)

http://ad.usno.navy.mil/OBSS/, Johnston et al. 2005, Zacharias & Dorland 2006

Parallaxes and magnitudes of stars



Parallaxes and number of stars



References

- Web sites of each project + references
- “Astrometry in the Age of the Next Generation of Large Telescopes”, ASP Conference Series, 2005, Vol. 338, Lowell Observatory, October 2004
- Michelson Summer Workshop, Caltech, July 2005, in particular presentations of N. Zacharias and Henry
- Presentation of A.G.A. Brown at ESF Exploratory Workshop Modelling the Galaxy, Oxford, Sept 2005

Merci pour votre attention