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Memorie della

Astrometric surveys

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Abstract. Astrometric surveys are a basic tool for galactic astronomy: they provide the only distance determination without assumption about the observed object as well as two components of the space velocity. A large number of stars, observed in a systematic way, yield to an unbiased sampling of the Galaxy and, for the most accurate surveys, of the brightest parts of Local Group galaxies, at larger and larger distances as the accuracy increases. The major astrometric surveys obtained or planned from ground-based observations or from space missions will be described, along with their main science drivers.

Key words. Stars: distances – Stars: kinematics – Stars: fundamental parameters – Stars: statistics – Galaxy: kinematics and dynamics – Galaxy: fundamental parameters – Galaxy: formation – Galaxy: evolution

1. Introduction

Astrometric surveys became a major tool for stellar and galactic astronomy with the publication of the Hipparcos Catalogue (Perryman et al. 1997; ESA 1997). For the first time trigonometric parallaxes and proper motions were accurate (to the mas) and numerous enough (more than 100 000 stars) to provide a new insight into the three-dimensional structure of our Galaxy. As a result, luminosity calibrations for stars all over the HR diagram could be revised, the kinematics of the Solar neighbourhood scrutinised in detail, the age of the Universe and of the oldest objects in our Galaxy made compatible, streams in the halo discovered, etc. Increasing the accuracy of trigonometric parallaxes allow an unbiased sampling of increasingly large parts of the Galaxy and even of the Local Group: Hipparcos and the (few) modern ground-based measurements of trigonometric parallaxes are sampling the Solar neighbourhood, a mission such as Gaia will sample the whole observable Galaxy and the brighter stars in the neighbour galaxies, SIM would even allow to go further.

Astrometric surveys provide trigonometric parallaxes, the only distance determination without any assumption about the observed object, and proper motions. Jointly with radial velocity observations, this gives the full phase space information. By astrometric survey, it is meant global astrometric observations, i.e. linked to a reference system, and observations all over the sky, or over very large parts of it. The first application of this type of observation is the optical realisation of the International Reference System (ICRS), which then is the reference frame to small field observations with large telescopes and to photometric and spectroscopic surveys.

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The quality of the statistical analysis which can be obtained from a survey is directly linked to the large number of stars observed, but also, and mainly, to the clear definition of the limits adopted to include or not a star in the survey. Homogeneous data sets with clearly defined limits are mandatory to control selection effects and to better identify the sources of errors (both systematic and internal errors). A good astrometric survey will provide an exhaustive sampling and characterisation of all stellar types (all along the HR diagram, all galactic populations, all evolutionary phases), an exhaustive investigation of the kinematics and dynamics of the Milky Way, with a systematic determination of the membership for clusters, streams, spiral arms, warp, bar, etc. and also a systematic detection of the duplicity of target stars, including the detection of exoplanets.

2. Ground-based surveys

Astrometric surveys accurate to the mas level have been developed from the ground with the use of automatic instruments (astrographs, plate measuring machines and, to a lesser extent, meridian circles). However, the astrometric accuracy is intrinsically limited by the motions of the atmosphere, by the gravity deforming the telescope, and by the small fields within reach of ground-based telescopes. The major surveys are described below.

2.1. Past and present surveys

2.1.1. Distance limited parallax surveys

The attempt to obtain a complete census of the close Solar neighbourhood is a long-standing quest (Gliese 1969; Woolley 1970). These pioneer studies were using photometric and spectroscopic data in addition to astrometric data, and part of their findings have been questioned by the accurate trigonometric parallaxes obtained with the Hipparcos satellite (see, for example, Turon (1999)). Besides long-term programmes of trigonometric parallaxes measurements dedicated to classes of stars of special interest (for example the USNO programme, Harris et al. (2005)), specific ground-based parallax programmes are being developed aiming at a complete census of the Solar immediate neighbourhood and at the discovery and characterisation of yet unidentified nearby red, white, and brown dwarfs within 10 parsecs (Research Consortium on Nearby Stars: RECONS, www.chara.gsu.edu/RECONS/) or 25 parsecs (Cerro Tololo Inter-American Observatory Parallax Investigation: CTIOPI, www.chara.gsu.edu/~thenry/CTIOPI/). The accuracy of these ground-based programmes is in the range 3 (CTIOPI) to 5 mas (RECONS). The results so far are an increase of 17 % of the number of stars known within 10 parsecs (253 systems, 31 new) and more than 100 additional systems revealed between 10 and 25 parsecs (Costa et al. 2005; Henry et al. 2005). The Nearby Stars Database (http://nstars.nau.edu/) provides an up-to-date source of scientific data about all stellar objects within 25 parsecs.

2.1.2. UCAC

The USNO CCD Astrographic Catalog, UCAC, is an astrometric all sky catalogue relying on new systematic observations made with the USNO 20 cm aperture Twin Astrograph between 1998 and 2004. The final catalogue, UCAC3, is expected by mid-2007. It will include 60 million stars with a position accuracy, at mid-epoch, of 15 mas at $R = 10$, up to 70 mas at $R = 16$, and systematic errors smaller than 10 mas. Proper motions are being computed using the new observations and 143 old position catalogues. The resulting accuracy is in the range 1 to 3 mas/yr for stars up to $R \sim 12$, 4 to 7 mas/yr for the fainter stars. A preliminary version, UCAC2, is available since 2004 (Zacharias et al. 2004) and it is the most accurate catalogue available for positions and proper motions within this range of magnitude, for stars not included in the Hipparcos Catalogue. UCAC2 contains about 48 million stars in the declination zone $-90°$ to $+40°$ (up to $+52°$ in some areas), and is not complete (ad.usno.navy.mil/ucac): there are no star brighter than $R \sim 8$, most multiple

Table 1. Summary of some characteristics of parallax surveys

Project	status	years of operation	magnitude range	total number of stars	range of σ_π [mas]
CTIOPI	in progress	1999-	[9 - 19]	300	3
URAT	partly funded	2009-2014	[14 - 21]	10^9	[5 - 100]
Pan-STARRS (PS4)	prototype (PS1)	2010-2020	[15 - 24]	10^{10}	[3 - 25] (?)
LSST	partly funded	2012-2022	[17 - 24]	10^{10}	[1 - 10] (?)
Hipparcos	complete	1989-1993	[2 - 12.4]	118000	[0.8 - 4]
Gaia	fully funded	2011-2017	[6 - 20]	10^9	[0.007 - 0.3]
SIM	phase B	2015-2020	[6? - 19]	10000	0.004
JASMINE	in project	2015-2020	[6? - 14]	10^7	[0.01 - ?]
MAPS	in project	2010-2015	[3 - 15]	10^7	[0.35 - 5]
OBSS	in project	next decade	[12 - 21]	10^9	[0.012 - 0.35]

systems with separations up to 6 arcsec are excluded, as well as all stars with no or poor proper motion. The completeness of UCAC3 will be much improved in all these respects.

2.1.3. USNO-B1.0

The USNO-B1.0 catalogue (Monet et al. 2003) is an all-sky catalogue obtained from scans of 7435 Schmidt plates taken during the last 50 years, i.e. all entries were detected in the digitized images of the major photographic sky surveys (POSS, SERC, ESO and AAO). It contains positions, proper motions, magnitudes in various optical passbands, and star/galaxy estimators for more than a billion objects in the magnitude range 12-21. It is claimed to be complete up to $V = 21$, and provides J2000 positions with an accuracy of $0\farcs2$ at epoch 2000.0, relative proper motions, magnitudes in three colours (up to five in some fields) with an accuracy of 0.3 mag, and star/galaxy estimators. The accuracy for distinguishing stars from nonstellar objects is estimated to be of the order of 85%. A few caveats are given by the authors as a warning to the users 1) objects with proper motions larger than 1 arcsec/yr are unreliable, particularly those that are at the faint limit of detection in any of the plate, as there are possible misidentifications, 2) the astrometry (and the photometry) of objects in dense fields, in regions with nebulosity or around bright stars is not well defined, and there is an increased probability of misidentification in these areas, 3) the USNO-B1.0 catalogue is not a reliable source of information for bright stars.

2.1.4. Other ground-based catalogues

There are some other extensive astrometric catalogues either in some zones of the sky, for example from Meridian Circle observations, or compilations of *best* astrometric data. A few of them are quoted here:

- CMC14, Carlsberg Meridian Catalogue 14, released in December 2005 (www.ast.cam.ac.uk/~dwe/SRF/cmc14.html). This catalogue is the result of Meridian Circle observations carried out from March 1999 to October 2005. It is an astrometric and photometric catalogue of nearly 100 million stars in the red (SDSS r’) magnitude range 9 to 17, and covering the declination range $-30°$ to $+50°$. It is mostly complete to 95% down to r’ = 16, and the astrometric accuracy at the epoch of observation is 20-60 mas as

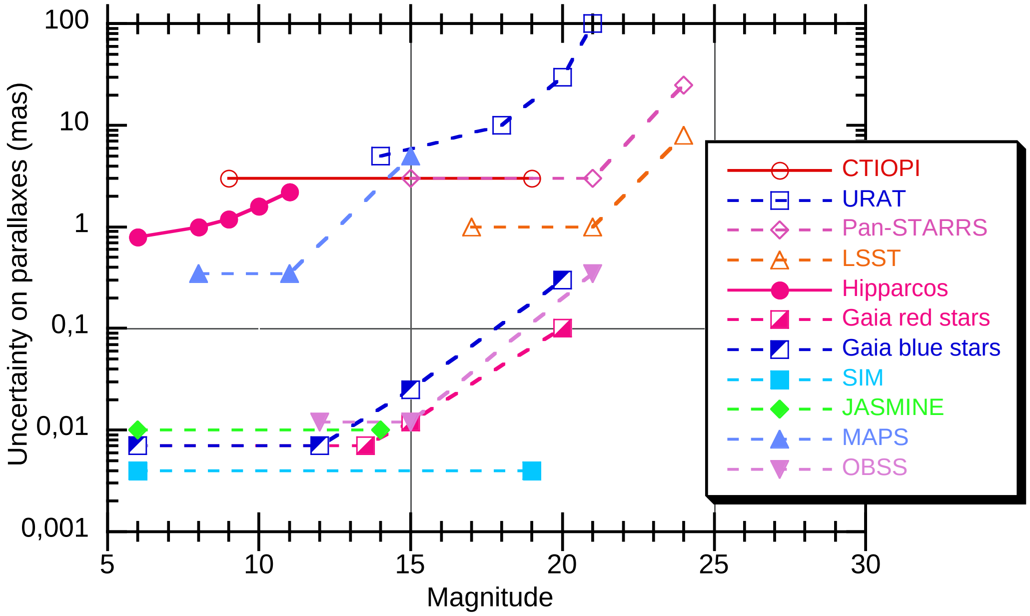

Fig. 1. Parallax precision of the astrometric surveys as a function of star magnitude

a function of magnitude. There is no proper motion.

- PM2000, Bordeaux Proper Motion catalogue (Ducourant et al. 2006). This catalogue includes proper motions for 2.7 million stars in the declination zone +11° to +18°. Proper motions were derived from the comparison of Bordeaux meridian circle observations with positions derived from the reduction of 512 Carte du Ciel plates of the Bordeaux zone (scanned at the APM Cambridge) and a number of other intermediate astrometric catalogues. The catalogue is complete down to $V = 15.4$, and the precision of proper motions varies from 1.5 mas/yr to 6 mas/yr.

- NOMAD (www.nofs.navy.mil/nomad/) is a compilation of the *best* astrometric data for more than a billion stars. For bright stars, astrometric data are taken from Hipparcos, Tycho-2, and then from UCAC-2. For fainter stars, astrometric data are taken from Hipparcos, UCAC-2, Tycho-2, USNO-B1, YB6, and then from 2MASS.

In addition to astrometric catalogues, there are two photometric/spectrocopic survey catalogues which positional accuracy is better than 100 mas: 2MASS, 2 Micron All Sky Survey (Skrutskie et al. 2006), and SDSS, Sloan Digital Sky Survey (Adelman-McCarthy et al. 2006; Ivezić 2006). These catalogues are being used in combination with astrometric catalogues to determine proper motions and make systematic detections of various types of objects (Open cluster membership, detections of halo streams, tidal debris, warps, cool stars and brown dwarfs, etc.). Moreover, a proper motion catalogue have been obtained by combining USNO-B and SDSS (Munn et al. 2004). It is 90% complete down to $g > 19.7$, and the proper motion statistical errors are in the range 3-3.5 mas/yr.

2.2. Future ground-based surveys

Three very ambitious all-sky surveys, using robotic instruments are under way or under consideration. Even though their first science drivers are not necessarily galactic astronomy, each of them should provide huge amounts of astrometric data which would greatly impact on galactic studies.

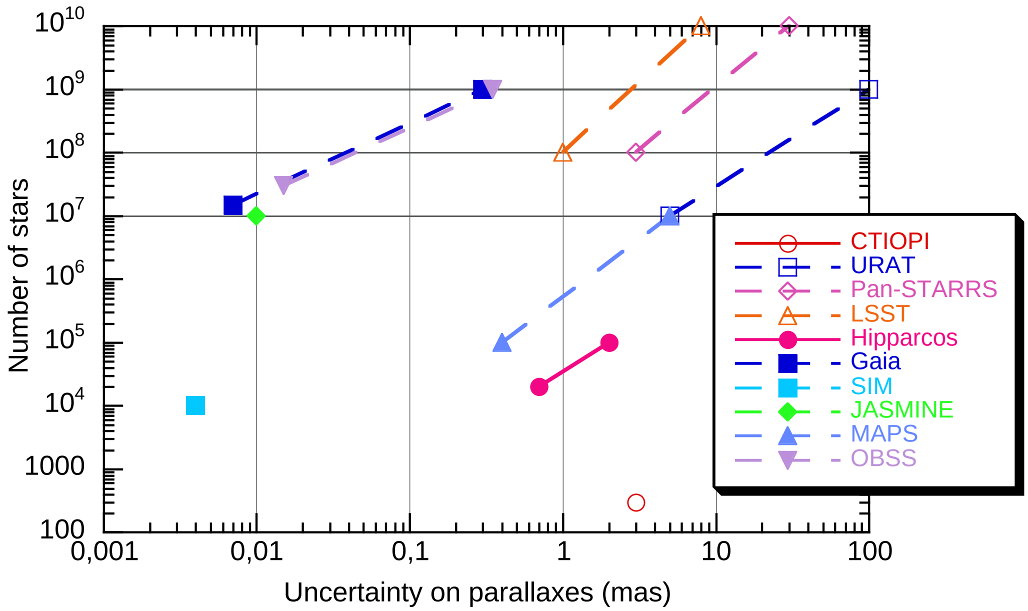

Fig. 2. Number of stars with a given parallax precision for the astrometric surveys

2.2.1. URAT

USNO Robotic Astrometric Telescope (URAT) is a new astrometric instrument developed at USNO (Zacharias et al. 2006, 2005), aiming at an all sky astrometric survey of about a billion objects in the magnitude range 14 to 21. The main science drivers are the densification of the stellar reference frame, galactic dynamics in the pre-Gaia era, and unbiased observations of parallaxes in the Solar neighbourhood. With systematic observations of one hemisphere 6 times per year, the expected products are positions, absolute proper motions and parallaxes on the 5-10 mas level for stars in the 14 to 18 mag range. A prototype camera is expected by the end 2006.

2.2.2. Pan-STARRS

The primary goal of Pan-STARRS (Panoramic Survey Telescope and Rapid Response System) is to survey potentially dangerous asteroids (Chambers 2005). The complete project will consist of four 1.8m telescopes, each with a 7 square degree field of view. It will be able to scan the entire visible sky (30 000 square degrees) to 24th magnitude in less than a week. Relative astrometry (positions, parallaxes and proper motions) are expected to a few mas with systematic errors of about 10 mas. The fundamental limitations to the astrometric accuracy are the knowledge of the atmospheric profile as a function of exposure time and angular separation, and the telescope axis encoders and mount model. The first, prototype, telescope will be operational by the mid-2007.

2.2.3. LSST

The four key science drivers of LSST (Large Synoptic Survey Telescope) are dark energy, a survey of solar system objects, optical transients, and mapping the stellar populations in the Galaxy. The project is a 8.4 m telescope, partly funded, which first light is expected by October 2012 for a lifetime 10 years. With a field of view of 9.6 square degrees and 15 sec exposures, it is aiming at surveying 20 000 square degrees in about 3 nights in six bands from 320nm to 1060nm (u, g, r, i, z, y). The expected outputs are relative astrometry (parallaxes and proper motions) in the magnitude range 17-24 with an accuracy of 1 mas on parallaxes and 0.2 mas/yr on proper motions. Many uncertainties should be addressed to assess the astrometric accuracy with such short exposures (Wolff 2005).

3. Space surveys

Observations in space opened a new era for astrometry by eliminating the effects of atmospheric seeing and instrumental distortions due to gravity or large thermal variations. Moreover, a unique instrument has access to the whole sky, which permits a direct linking of all observations. Hipparcos is the world's first, and up to now, only space astrometry satellite. It provided stellar and galactic astronomy with a wealth of high accuracy data, clearly demonstrating how powerful is the use of high accuracy parallaxes and proper motions for astrophysics. This great success has stimulated many proposals of new generation astrometric satellites.

3.1. Past and present space surveys

3.1.1. Hipparcos

The European Space Agency pioneer satellite Hipparcos was decided in 1980, operated between 1989 and 1993, and the resulting catalogue published in 1997 (Perryman et al. 1997; ESA 1997). Two fields of view and continuous scanning resulted in an optimum use of the available observing time and in a large number of observations per star (of the order of 110). 118 000 stars were preselected all over the sky representing a synthesis of the main science drivers (galactic structure and evolution, stellar structure and evolution, Solar neighbourhood) and of the observational and data reduction requirements (Turon et al. 1995). About half of the observing programme is a survey, complete up to $V = 7.3$ to 9 as a function of galactic latitude and spectral type. The results for stars with Hp (the Hipparcos magnitude) < 9 are a median accuracy smaller than 1 mas on absolute parallaxes, of 0.8 mas/yr on proper motions, with a link to ICRS to ± 0.6 mas. It has to be noted that the smallest error obtained with this 30 cm telescope equipped with a photometer (no space qualified CCDs at that epoch!) is 0.03 mas. In addition multi-epoch photometry to 0.001-0.005 mag is available for all programme stars.

3.1.2. Tycho-2

The Tycho catalogue was constructed by using the observations collected by the star mappers of the Hipparcos satellite (Høg et al. 1997). It resulted in a survey of a million stars 99% complete down to $V_T \approx 10$ with positions to 25 mas at epoch 1991.25, and two-colour photometry (V_T and B_T), close to the Johnson B and V, to 0.1 mag. The Tycho-2 catalogue (Høg et al. 2000) is a re-reduction of Tycho observations which led to a larger and more precise catalogue. The 2.5 million star survey is 99% complete to $V = 11.0$, the error on position is of about 7 mas for $V_T < 9$, and proper motions precise to about 2.5 mas/yr have been derived from the comparison of Tycho positions with the Astrographic Catalogue and 143 other ground-based astrometric catalogues reduced to the Hipparcos reference system.

3.2. Future space surveys

3.2.1. Gaia

Among the many new generation projects of astrometric satellites, the ESA's Gaia is the only one which is fully funded (Lindegren & Perryman 1996; Bailer-Jones 2006). Planned for a launch by the end of 2011 and a lifetime of 5-6 years, it will open the way to microacsecond astrometry. It is based of the successful principles of Hipparcos, a two fields of view scanning satellite which will survey the sky down to magnitude 20 and obtain multi-epoch astrometric, photometric and spectroscopic observations of a billion stars. Indeed, contrary to Hipparcos, the observations are made in a survey mode (no input catalogue), and the astrometric observations will be complemented by spectroscopic and multicolour photometric observations. The main science drivers are a stereoscopic and kinematic census of the Galaxy leading to a revolution in our understanding of the history of the Galaxy, dark matter distribution, stellar structure and evolution, cosmic distance scale, but also the astrometric and photometric systematic detection of exoplanets. As a result of the extreme astrometric accuracy of Gaia, no less than 150 million stars with have their distance known to less than 10%. In parallel to astrometric data, radial velocities will be obtained as well as a complete astrophysics diagnostics of all observed objects. The expected products are

- Absolute astrometry (position, trigonometric parallaxes and proper motions) to
  - 5 μas at $V < 10$
  - 8-20 μas at $V < 15$
  - 110-250 μas at $V < 20$
- Medium resolution spectra (R≈11000) for stars brighter than 16-17, providing
  - Radial velocity, with accuracy ranging from 1 km/s to 15 km/s
  - Rotational velocity and atmospheric parameters
  - Abundances for the brighter stars
- Spectrophotometry in the red and blue domain, providing
  - Atmospheric parameters
  - Abundances
  - Variability (80 observations per star)
- Duplicity (with the 3 instruments)

3.2.2. SIM PlanetQuest

SIM PlanetQuest is a NASA project currently in phase B, with a preliminary Design Review in 2007. The expected launch date is 2015, with a lifetime of 5 years (Unwin 2005, 2006). The instrument is a long baseline Michelson interferometer in optical wavelengths. The main scientific drivers are the search for planets down to a few Earth masses around the nearest stars, stellar luminosities and masses to 1%, the calibration of cosmic distance scale, the distribution of masses in the Galaxy, the formation of the halo. It is a pointed astrometric mission aiming at the observation of about 10 000 pre-selected targets. An accuracy of about 4 μas down to 19 mag for wide-angle astrometry (15°), and about 1 μas for narrow angle astrometry (1°) is expected.

3.2.3. JASMINE

JASMINE, Japan Astrometry Satellite Mission for Infrared (Gouda 2006), is a Japanese project that plan to observe 200 square degrees in the bulge of the Galaxy over 5 years in the infrared, with a launch in 2015. The goal is to obtain trigonometric parallaxes to 10 μas and proper motions to 4 μas/yr for 10 million stars brighter than $z = 14$ (0.9 μm). A precursor scanning microsatellite, Nano-Jasmine, similar to Hipparcos (two fields of view, less than 10 kg, telescope 5 cm), is planned for 2008, and expected to measure positions and proper motions to 1 mas for stars brighter than $z < 8.3$ mag (Kobayashi 2006).

3.2.4. MAPS

MAPS, Milli-Arcsecond Pathfinder Survey, is a micro-satellite studied at USNO for a launch in 2010. The concept of MAPS (Zacharias & Dorland 2006; Gaume et al. 2006) is a step and stare mission with a single aperture (15 cm) and a field of view of 1.5°. The main science drivers are the astrometric detection of planets in nearby systems, the search for Galactic mergers and the kinematics of the solar neighbourhood. The expected product is an all-sky astrometric and photometric survey of about 10 million stars, covering the magnitude range from 3 to 15, with a 1 mas accuracy for positions, parallaxes and annual proper motions, 0.1 mas/yr proper motions for the Hipparcos stars. It is developed as a pathfinder for OBSS.

3.2.5. OBSS

The Origins Billion Star Survey, OBSS, is a USNO-JPL proposal to NASA (Origins roadmap AO 2004) for an expected launch in 2014 (Johnston et al. 2005; Zacharias & Dorland 2006). The main science drivers are the census of giant extrasolar planets within 200 pc from the Sun, the characterisation of stars in half of the Galaxy, the dynamics of the Galaxy, and the improvement of the reference frame. As MAPS, it is a step-stare astrometric mission with a single aperture (1.5m), and a field of view of 1.3°. Two observing modes are planned: an all sky survey with 36.5 sec cycles (all sky observed twice a month down to $V = 21$), and a targeted observation mode that could go as deep as $V = 24$ in selected areas. The expected products are absolute positions, parallaxes and proper motions for 1 billion stars at an accuracy of about 15 μas in the survey mode, reaching 10 μas in the targeted mode for stars of magnitude 15. In addition a low resolution spectrograph would provide stellar colours in 16 bands up to $V \approx 18$.

4. Conclusion

The following table and figures show a recapitulation of the projects which have or will provide trigonometric parallaxes.The figures illustrate two tendencies: ground-based projects are going towards larger and larger number of stars, space projects are mandatory to reach sub-millarcsec accuracy, and even micro-arcsec accuracy for stars brighter than about 15.

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