PART I

ASTROMETRY IN THE TWENTY-FIRST CENTURY

1 Opportunities and challenges for astrometry in the twenty-first century

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Introduction

The fundamental task of measuring stellar positions, and the derived properties of trigonometric distances and space motions, has preoccupied astronomers for centuries. As one of the oldest branches of astronomy, astrometry is concerned with measurement of the positions and motions of planets and other bodies within the Solar System, of stars within our Galaxy and, at least in principle, of galaxies and clusters of galaxies within the Universe as a whole.

While substantial advances have been made in many areas of astrometry over the past decades, the advent of astrometric measurements from space, pioneered by the European Space Agency's Hipparcos mission (operated between 1989 and 1993), has particularly revolutionized and reinvigorated the field. Considerable further progress in space and ground measurements over the next decade or so collectively promise enormous scientific advances from this fundamental technique.

At the very basic level, accurate star positions provide a celestial reference frame for representing moving objects, and for relating phenomena at different wavelengths. Determining the changing displacement of star positions with time then gives access to their motions through space. Additionally, determining their apparent annual motion as the Earth moves in its orbit around the Sun gives access to their distances through measurement of parallax. All of these quantities, and others, are accessed from high-accuracy measurements of the relative angular separation of stars. Repeated measurements over a long period of time essentially provide a stereoscopic map of the stars and their kinematic motions.

What follows, either directly from the observations or indirectly from modeling, are absolute physical stellar characteristics: stellar luminosities, radii, masses, and ages. The physical parameters are then used to understand their internal composition and structure. Space motions, derived from a combination of proper motions, radial velocities, and distances, are used to infer the Galaxy's kinematic and dynamical properties and, eventually, to explain in a rigorous and consistent manner how the Galaxy was originally formed, and how it will evolve in the future.

Crucially, stellar space motions reflect dynamical perturbations due to all other matter, visible or invisible. In a highly simplified picture, most of the visible mass of our Galaxy

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resides in the form of disk stars. To first order, these stars display a bulk rotation, while more detailed observations reveal a whole host of substructure. This includes spiral arms and a central stellar bar, both of which appear to arise from intrinsic instabilities in a rotating population. In our immediate neighbourhood, the stellar motions reveal thin and thick disk populations, coherent groupings of open clusters and stellar associations, and various other dissolving remnants of earlier structures. How these various populations originated, and indeed how our Galaxy as a whole formed, can be inferred from these detailed space motions.

Although the large-scale acquisition of astrometric data provides the crucial foundation for studies of stellar structure and evolution on the one hand, and Galactic structure, kinematics, and dynamics on the other, astrometry is in principle capable of measuring a whole host of more detailed or "higher-order" phenomena: at the milliarcsecond level, binary star signatures, general relativistic light bending, and the dynamical consequences of dark matter are already evident; at the microarcsecond level, targeted by the next generation of space astrometry missions currently under development, direct distance measurements will be extended across the Galaxy and to the Magellanic Clouds.

Other effects will become routinely measurable at the same time: perspective acceleration and secular parallax evolution, more subtle metric effects, planetary perturbations of the photocentric motion, and astrometric micro-lensing; and at the nanoarcsecond level, currently no more than an experimental concept, effects of optical interstellar scintillation, geometric cosmology, and ripples in space-time due to gravitational waves will become apparent. The bulk of this seething motion is largely below current observational capabilities, but it is there, waiting to be investigated.

1.1 Some history

It is useful to place the current state-of-the-art milliarcsecond astrometric measurements in a brief, albeit highly selective, historical context. Chapman (1990) provides a fascinating historical account of the development of angular measurements in astronomy between 1500 and 1850, on which this summary is based.

After the remarkable achievements of the ancient Greeks, including their first estimates of the sizes and distances of the Sun and Moon, the narrative intensifies 300–400 years ago, when three main scientific themes motivated the improvement of angular measurements: the navigational problems associated with the determination of longitude on the Earth's surface, the comprehension and acceptance of Newtonianism, and understanding the Earth's motion through space. Even before 1600, astronomers were in agreement that the crucial evidence needed to detect the Earth's motion was the measurement of trigonometric parallax, the tiny oscillation in a star's apparent position arising from the Earth's annual motion around the Sun. The early British Astronomers Royal, for example, appreciated the importance of measuring stellar distances, and were very much preoccupied with the task. But it was to take a further 250 years until this particular piece of observational evidence could be secured.

In 1718, Edmund Halley, who had been comparing contemporary observations with those that the Greek Hipparchus and others had made, announced that three stars, Aldebaran, Sirius, and Arcturus, were displaced from their expected positions by large fractions of a degree. He deduced that each star had its own distinct velocity across the line of sight, or proper motion: stars were moving through space.

By 1725, angular measurements had improved to a few arcseconds, making it possible for James Bradley, England's third Astronomer Royal, to detect stellar aberration, as a byproduct of his unsuccessful attempts to measure the distance to the bright star γ Draconis. This was an unexpected result: small positional displacements were detected, and correctly attributed to the vectorial addition of the velocity of light to that of the Earth's motion around the Sun. His observations provided the first direct proof that the Earth was moving through space, and thus a confirmation both of Copernican theory, and Roemer's discovery of the finite velocity of light 50 years earlier. It also confirmed Newton's hypothesis of the enormity of stellar distances, and showed that the measurement of parallax would pose a technical challenge of extraordinary delicacy.

During the eighteenth century, the motions of many more stars were announced, and in 1783 William Herschel found that he could partly explain these effects by assuming that the Sun itself was moving through space. Attempts to measure parallax intensified. Nevil Maskelyne, England's fifth Astronomer Royal, spent seven months on the island of St. Helena in 1761, using a zenith sector and plumb-line, in an unsuccessful attempt to measure the parallax of the bright star Sirius.

Criteria for probable proximity were developed and, after many unsuccessful attempts, the first stellar parallaxes were measured in the 1830s.

Friedrich Bessel is generally credited as being the first to publish a parallax, for 61 Cygni (Piazzi's Flying Star), from observations made between 1837 and 1838. Thomas Henderson published a parallax for α Centauri in 1839, derived from observations made in 1832–1833 at the Cape of Good Hope. In 1840, Wilhelm Struve presented his parallax for Vega from observations in 1835–1837. Confirmation that stars lay at very great but nevertheless finite distances represented a turning point in the understanding of the Universe. John Herschel, President of the Royal Astronomical Society at the time, congratulated Fellows that they had *'lived to see the day when the sounding line in the universe of stars had at last touched bottom'* (quoted by Hoskin, 1997, p. 219).

The following 150 years saw enormous progress, with the development of accurate fundamental catalogs, and a huge increase in quantity and quality of astrometric data based largely on meridian-circle and photographic-plate measurements.

1.2 The Hipparcos mission

By the second half of the twentieth century, however, measurements from ground were running into essentially insurmountable barriers to improvements in accuracy, especially for large-angle measurements and systematic terms; a review of the instrumental status shortly in advance of the Hipparcos satellite launch in 1989 is given by Monet (1988).

Problems were dominated by the effects of the Earth's atmosphere, but were compounded by complex optical terms, thermal and gravitational instrument flexures, and the absence of all-sky visibility. A proposal to make these exacting observations from space was first put forward in 1967.

The Hipparcos satellite was a space mission primarily targeting the uniform acquisition of milliarcsecond level astrometry (positions, parallaxes, and annual proper motions) for some 120 000 stars. The satellite was launched in August 1989 and operated until 1993. The data processing was finalized in 1996, and the results published by the European Space Agency (ESA) in June 1997 as a compilation of 17 hard-bound volumes, a celestial atlas, and six CDs, comprising the Hipparcos and Tycho Catalogues. The original Tycho Catalogue comprised some 1 million stars of lower accuracy than the Hipparcos Catalogue, while the Tycho-2 Catalogue, published in 2000, provided positions and accurate proper motions for some 2.5 million objects, through the combination of the satellite data with plate material from the early 1900s. Details of the satellite operation, the successive steps in the data analysis, and in the validation and description of the detailed data products, are included in the published catalogue.

The Hipparcos astrometric results impact a very broad range of astronomical research, which can be classified into three major themes

1.2.1 Provision of an accurate reference frame

This has allowed the consistent and rigorous re-reduction of a wide variety of historical and present-day astrometric measurements. The former category include Schmidt plate surveys, meridian-circle observations, 150 years of Earth-orientation measurements, and re-analysis of the 100-year-old Astrographic Catalogue (and the associated Carte du Ciel). The Astrographic Catalogue data, in particular, have yielded a dense reference framework reduced to the Hipparcos reference system propagated back to the early 1900s. Combined with the dense framework of 2.5 million star-mapper measurements from the satellite, this has yielded the high-accuracy long-term proper motions of the Tycho 2 Catalogue.

The dense network of the Tycho 2 Catalogue has, in turn, provided the reference system for the reduction of current state-of-the-art ground-based survey data: thus the dense UCAC 3 and USNO B2 catalogs are now provided on the same reference system, and the same is true for surveys such as SDSS and 2MASS. Other observations specifically reduced to the Hipparcos system are the SuperCOSMOS Sky Survey, major historical photographic surveys such as the AGK2 and the CPC2, and the more recent proper-motion programmes in the northern and southern hemispheres, NPM and SPM. Proper-motion surveys have been rejuvenated by the availability of an accurate optical reference frame, and amongst them are the revised NLTT (Luyten Two-Tenths) survey, and the Lépine–Shara proper-motion surveys (north and south). Many other proper-motion compilations have been generated based on the Hipparcos reference system, in turn yielding large data sets valuable for open cluster surveys, common-proper-motion surveys, etc.

The detection and characterization of double and multiple stars has been revolutionized by Hipparcos: in addition to binaries detected by the satellite, many others have been revealed through the difference between the Hipparcos (short-term) proper motion, and the long-term photocentric motion of long-period binary stars (referred to as $\Delta\mu$ binaries). New binary systems have been followed up through speckle and long-baseline optical interferometry from ground, through a re-analysis of the Hipparcos Intermediate Astrometric Data, or through a combined analysis of astrometric and ground-based radial-velocity data. Other binaries have been discovered as common-proper-motion systems in catalogues reaching fainter limiting magnitudes. Various research papers have together revised the analysis of more than 15 000 Hipparcos binary systems, providing new orbital solutions, or characterizing systems which were classified by Hipparcos as suspected double, acceleration solutions, or stochastic ("failed") solutions.

Other studies since 1997 have together presented radial velocities for more than 17 000 Hipparcos stars since the catalogue publication, not counting two papers presenting some 20 000 radial velocities from the Coravel database, and more than 70 000 RAVE (Radial Velocity Experiment) measurements including some Tycho stars. These radial-velocity measurements are of considerable importance for determining the three-dimensional space motions, as well as further detecting and characterizing the properties of binary stars.

More astrophysically, studies have been made of wide binaries, and their use as tracers of the mass concentrations during their Galactic orbits, and according to population. Numerous papers deal with improved mass estimates from the spectroscopic eclipsing systems, important individual systems such as the Cepheid binary Polaris, the enigmatic Arcturus, and favourable systems for detailed astrophysical investigations such as V1061 Cygni, HIP 50796, the mercury–manganese star ϕ Her, and the spectroscopic binary HR 6046. A number of papers have determined the statistical distributions of periods and eclipse depths for eclipsing binaries, and others have addressed their important application in determining the radiative flux and temperature scales. Studies of the distributions of detached and contact binaries (including W Ursa Majoris and symbiotic systems) have also been undertaken.

The accurate reference frame has in turn provided results in topics as diverse as the measurement of general relativistic light bending; Solar System science, including mass determinations of minor planets; applications of occultations and appulses; studies of Earth rotation and Chandler wobble over the last 100 years based on a re-analysis of data acquired over that period within the framework of studies of the Earth orientation; and consideration of non-precessional motion of the equinox.

1.2.2 Constraints on stellar evolutionary models

The accurate distances and luminosities of 100 000 stars has provided the most comprehensive and accurate data set relevant to stellar evolutionary modeling to date, providing new constraints on internal rotation, element diffusion, convective motions, and asteroseismology. Combined with theoretical models the accurate distances and luminosities yield evolutionary masses, radii, and stellar ages of large numbers and wide varieties of stars.

A substantial number of papers have used the distance information to determine absolute magnitude as a function of spectral type, with new calibrations extending across the Hertzsprung–Russell diagram: for example for OB stars, AFGK dwarfs, and GKM giants, with due attention given to the now more quantifiable effects of Malmquist and Lutz–Kelker biases. Other luminosity calibrations have used spectral lines, including the Ca II-based Wilson–Bappu effect, the equivalent width of O I, and calibrations based on interstellar lines.

A considerable Hipparcos-based literature deals with all aspects of the basic 'standard candles' and their revised luminosity calibration. Studies have investigated the Population I distance indicators, notably the Mira variables, and the Cepheid variables (including the period–luminosity relation, and their luminosity calibration using trigonometric parallaxes, Baade–Wesselink pulsational method, main-sequence fitting, and the possible effects of binarity). The Cepheids are also targets for Galactic kinematic studies, tracing out the Galactic rotation, and also the motion perpendicular to the Galactic plane.

Hipparcos has revolutionized the use of red clump giants as distance indicators, by providing accurate luminosities of hundreds of nearby systems, in sufficient detail that metallicity and evolutionary effects can be disentangled, and the objects then used as single-step distance indicators to the Large and Small Magellanic Clouds, and the Galactic bulge. Availability of these data has catalyzed the parallel theoretical modeling of the clump giants.

For the Population II distance indicators, a rather consistent picture has emerged in recent years based on subdwarf main-sequence fitting, and on the various estimates of the horizontal branch and RR Lyrae luminosities.

A number of different methods now provide distance estimates to the Large Magellanic Cloud, using both Population I and Population II tracers, including some not directly dependent on the Hipparcos results (such as the geometry of the supernova SN 1987A light echo, orbital parallaxes of eclipsing binaries, globular cluster dynamics, and white-dwarf cooling sequences). Together, a convincing consensus emerges, with a straight mean of several methods yielding a distance modulus of $(m - M)_0 = 18.49$ mag. Through the Cepheids, the Hipparcos data also provide good support for the value of the Hubble constant, $H_0 = 72 \pm 8$ km/s/Mpc, as derived by the Hubble Space Telescope key project, and similar values derived by the Wilkinson Microwave Anisotropy Probe (WMAP), gravitational-lensing experiments, and Sunyaev–Zel'dovich effect.

A huge range of other studies has made use of the Hipparcos data to provide constraints on stellar structure and evolution. Improvements have followed in terms of effective temperatures, metallicities, and surface gravities. Bolometric corrections for the *Hp* photometric band have opened the way for new and improved studies of the observational versus theoretical Hertzsprung–Russell diagram.

Many stellar evolutionary models have, of course, been developed and refined over the last few years, and Hipparcos provides an extensive testing ground for their validation and their astrophysical interpretation: these include specific models for pre- and post-main-sequence phases, and models which have progressively introduced effects such as convective overshooting, gravitational settling, rotation effects, binary tidal evolution, radiative acceleration, and effects of α-element abundance variations. These models have been applied to the understanding of the Hertzsprung–Russell diagram for nearby stars, the reality of the Böhm–Vitense gaps, the zero-age main sequence, the subdwarf main sequence, and the properties of later stages of evolution: the subgiant, first-ascent and asymptotic giant branch, the horizontal branch, and the effects of dredge-up and mass-loss. Studies of elemental abundance variations include the age–metallicity relation in the solar neighbourhood, and various questions related to particular elemental abundances such as lithium and helium. Other studies have characterized and interpreted effects of stellar rotation, surface magnetic fields, and observational consequences of asteroseismology, notably for solar-like objects, the high-amplitude δ Scuti radial pulsators, the β Cephei variables, and the rapidly oscillating Ap stars.

Many studies have focused on the pre-main-sequence stars, both the (lower-mass) T Tauri and the (higher-mass) Herbig Ae/Be stars, correlating their observational dependencies on rotation, X-ray emission, etc. The understanding of Be stars, chemically peculiar stars, X-ray emitters, and Wolf–Rayet stars have all been substantially effected by the Hipparcos data. Kinematic studies of runaway stars, produced either by supernova explosions or dynamical cluster ejection, have revealed many interesting properties of runaway stars, also connected with the problem of (young) B stars found far from the Galactic plane.

Dynamical orbits within the Galaxy have been calculated for planetary nebulae and, perhaps surprisingly given their large distances, for globular clusters. In these cases the provision of a reference frame at the 1 milliarcsecond accuracy level has allowed determination of their space motions and, through the use of a suitable Galactic potential, their Galactic orbits, with some interesting implications for Galactic structure, cluster disruption, and Galaxy formation.

One of the most curious of the Hipparcos results in this area is the improved determination of the empirical mass–radius relation of white dwarfs. At least three such objects appear to be too dense to be explicable in terms of carbon or oxygen cores, while iron cores seem difficult to generate from evolutionary models. “Strange matter” cores have been postulated, and studied by a number of groups.

1.2.3 Galactic structure and dynamics

The distances and uniform space motions have provided a substantial advance in understanding of the detailed kinematic and dynamical structure of the solar neighbourhood, ranging from the presence and evolution of clusters, associations and moving groups, the presence of resonance motions due to the Galaxy’s central bar and spiral arms, the parameters describing Galactic rotation, the height of the Sun above the Galactic mid-plane, the motions of the thin disk, thick disk and halo populations, and the evidence for halo accretion.

Many attempts have been made to further understand and characterize the solar motion based on Hipparcos data, and to redefine the large-scale properties of Galactic rotation in the solar neighbourhood. The latter has been traditionally described in terms of the Oort constants, but it is now evident that such a formulation is quite unsatisfactory in terms of describing the detailed local stellar kinematics. Attempts have been made to re-cast the problem into the nine-component tensor treatment of the Ogorodnikov–Milne formulation, analogous to the treatment of a viscous and compressible fluid by Stokes more than 150 years ago. The results of several such investigations have proved perplexing. The most recent and innovative approach has been a kinematic analysis based on vectorial harmonics, in which the velocity field is described in terms of (some unexpected) “electric” and “magnetic” harmonics. They reveal the warp at the same time, but in an opposite sense to the vector field expected from a stationary warp.

Kinematic analyses have tackled the issues of the mass density in the solar neighbourhood, and the associated force law perpendicular to the plane, the K_z relation. Estimates of the resulting vertical oscillation frequency in the Galaxy of around 80 Myr have been linked to cratering periodicities in the Earth's geological records. Related topics include studies of nearby stars, the stellar escape velocity, the associated initial mass function, and the star formation rate over the history of the Galaxy. Dynamical studies of the bar, of the spiral arms, and of the stellar warp, have all benefited. Studies of the baryon halo of the Galaxy have refined its mass and extent, its rotation, shape, and velocity dispersion, and have provided compelling evidence for its formation in terms of halo substructure, some of which is considered to be infalling, accreting material, still ongoing today.

New techniques have been developed and refined to search for phase-space structure (i.e. structure in positional and velocity space): these include convergent-point analysis, the "spaghetti" method, global convergence mapping, epicycle correction, and orbital back-tracking. An extensive literature has resulted on many aspects of the Hyades, the Pleiades, and other nearby open clusters, comprehensive searches for new clusters, and their application to problems as diverse as interstellar reddening determination, correlation with the nearby spiral arms, and the age dependence of their vertical distribution within the Galaxy: one surprising result is that this can be used to place constraints on the degree of convective overshooting by matching stellar evolutionary ages with cluster distances from the Galactic plane.

In addition to studying and characterizing open clusters, and young nearby associations of recent star formation, the Hipparcos data have revealed a wealth of structure in the nearby velocity distribution which is being variously interpreted in terms of open-cluster evaporation, resonant motions due to the central Galactic bar, scattering from nearby spiral arms, and the effects of young nearby kinematic groups, with several having been discovered from the Hipparcos data in the last 5 years.

The Hipparcos stars have been used as important (distance) tracers, determining the extent of the local "bubble", itself perhaps the result of one or more nearby supernova explosions in the last 5 Myr. The interstellar-medium morphology, extinction and reddening, grey extinction, polarization of star light, and the interstellar radiation field, have all been constrained by these new distance estimates of the Hipparcos stars.

1.2.4 Other applications

Superficially, it may seem surprising that the Hipparcos Catalogue has been used for a number of studies related to the Earth's climate. Studies of the passage of nearby stars and their possible interaction with the Oort Cloud have identified stars which came close to the Sun in the geologically recent past, and others which will do so in the relatively near future. Analysis of the Sun's Galactic orbit, and its resulting passage through the spiral arms, favour a particular spiral arm pattern speed in order to place the Sun within these arms during extended deep-glaciation epochs in the distant past. In this model, climatic variations are explained as resulting from an enhanced cosmic-ray flux in the Earth's atmosphere, leading to cloud condensation and a consequent lowering of temperature. A study of the Maunder Minimum, a period between 1645 and 1715 coinciding with the coldest excursion of the

"Little Ice Age," and a period of great hardship in Europe, was interpreted in the context of the number of solar-type stars out to 50–80 pc showing correspondingly decreased surface activity. Several studies have used the accurate distance data, accompanied by stellar evolutionary models, in an attempt to identify "solar twins" (stars which most closely resemble the Sun in all their characteristics, and which may be the optimum targets for searches for life in the future), and "solar analogs" (stars which resemble the Sun as it was at some past epoch or time in the future, and which therefore offer the best prospects for studying the Sun at different evolutionary stages).

Many studies have used the accurate photometric data, which can be derived from space observations in parallel with the positional information as part of the construction of absolute or bolometric magnitudes, or for their uniform colour indices. In addition, the extensive epoch photometry has been used for all sorts of variability analyses, including the rotation of minor planets, the study of eclipsing binaries, the complex pulsational properties of Cepheids, Mira variables, δ Scuti variables, slowly pulsating B stars, and many others.

In addition to all of these, the Hipparcos and Tycho Catalogues are now routinely used to point ground-based telescopes, navigate space missions, drive public planetaria, and provide search lists for programmes such as exo-planet surveys; one study has even shown how positions of nearby stars at the milliarcsecond level can be used to optimize search strategies for extraterrestrial intelligence.

More details of the Hipparcos scientific results are given by Perryman (2008), a book-length review covering the full range of the Hipparcos scientific findings. It offers an extensive summary and analysis of the scientific literature over the 10 years since the publication of the Hipparcos and Tycho Catalogues in 1997.

1.3 Other recent advances

While the Hipparcos satellite has represented a breakthrough in stellar astrometry in terms of numbers of stars and astrometric accuracy, many other projects have contributed to the advances in measurement and interpretation over the past 10–20 years. From space, the Fine Guidance Sensors of the Hubble Space Telescope have contributed accurate parallaxes of a small number of important objects. Various ground-based interferometers have also yielded small numbers of narrow-field astrometric measurements, which have been most notably targeted to the study of close binary systems showing orbital motion.

Radio astrometry has also provided a basic network of reference positions over the entire celestial sphere, as well as a small number of high-accuracy measurements of radio stars, masers, and the radio source in the centre of the Galaxy, Sgr A*. Digitized photographic-plate surveys and, more recently, large-scale CCD sky surveys, have provided a stellar reference system, with proper motions, for hundreds of millions of stars down to 20 mag. In turn, newly discovered high-proper-motion stars have been used as target lists for identifying low-luminosity stars in the solar neighbourhood.