2.2 Hipparcos

Introduction

A great deal of our knowledge about the Universe has been derived from the precise measurement of star positions. For more than two thousand years this astronomical discipline, technically referred to as astrometry, has therefore been an important scientific tool. For a significant part of the last 300-400 years, progressively greater accuracy in the measurement of star positions has led to a greatly improved picture and comprehension of our place in our Galaxy. Directly and indirectly, the accurate measurement of star positions has provided profound insights into the content and structure of the Universe as a whole. Astrometry is again at the forefront of astronomical research with the availability of the Hipparcos and Tycho star catalogues created with the data from ESA's Hipparcos space astrometry mission.

It was the glaring shortfall of precise observations to match the increasing sophistication of theories of stellar and Galactic physics that led ESA's scientific advisers in 1980 to recommend adoption of the Hipparcos space astrometry mission. The satellite was launched on an Ariane 4 from French Guiana in August 1989. With the launch, European scientists embarked on an entirely new chapter in the exploration and understanding of our Universe: to measure the positions of the stars to an unprecedented degree, and thereby to set in motion scientific investigations that are expected to yield important astronomical advances in the months and years ahead.

Publication of the Hipparcos and Tycho Catalogues

Hipparcos completed its unusual measurement programme in 1993, a little over 4 years after the launch. Following a huge scientific analysis phase, ESA published the results of this formidable star-mapping project on behalf of all of the scientific collaborators in June 1997: a 17-volume catalogue containing the positions, distances, movements, and many other properties of more than 100 000 stars. This highly complex programme called for the participation of some 200 European scientists for its successful execution. In the words of the Director of the American Association of Variable Star Observers, 'Perhaps the most inspiring aspect of this effort is the staggering degree of human cooperation required.' Notwithstanding the great size and complexity of the data analysis, and the many inevitable problems encountered during such a unique programme, the Hipparcos consortia succeeded in releasing the final results of their catalogue compilation to the scientific community 3 years after the end of the satellite operations. This almost exactly followed the schedule targeted by the Hipparcos Science Team, as endorsed by the ESA advisory committees, before

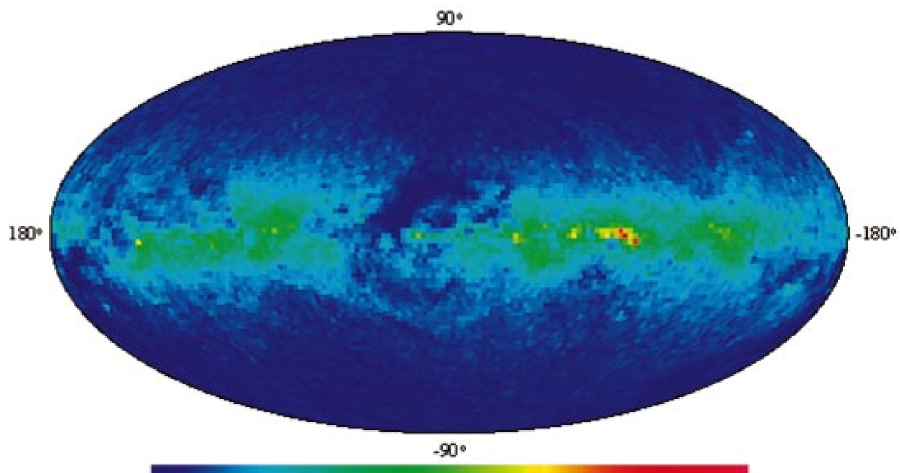


Figure 2.1.1. The Tycho Catalogue: number of observed stars per square degree, in galactic coordinates (cell size 2×2°). (All figures are from The Hipparcos and Tycho Catalogues, ESA SP-1200, Volume 1, Part 3).

For further information, see http://astro.estec.esa.nl/Hipparcos

Figure 2.1.2. Hipparcos Catalogue: median number of great-circle abscissae used for astrometry, in ecliptic coordinates (cell size 2×2°).

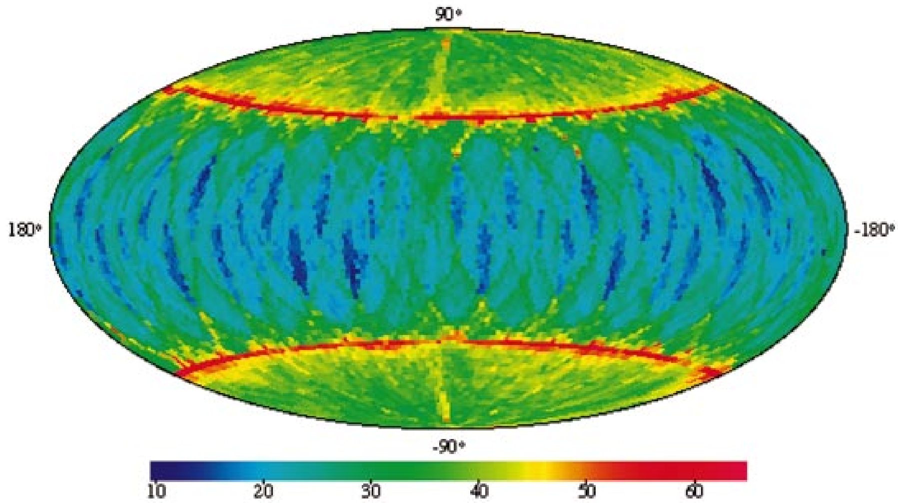
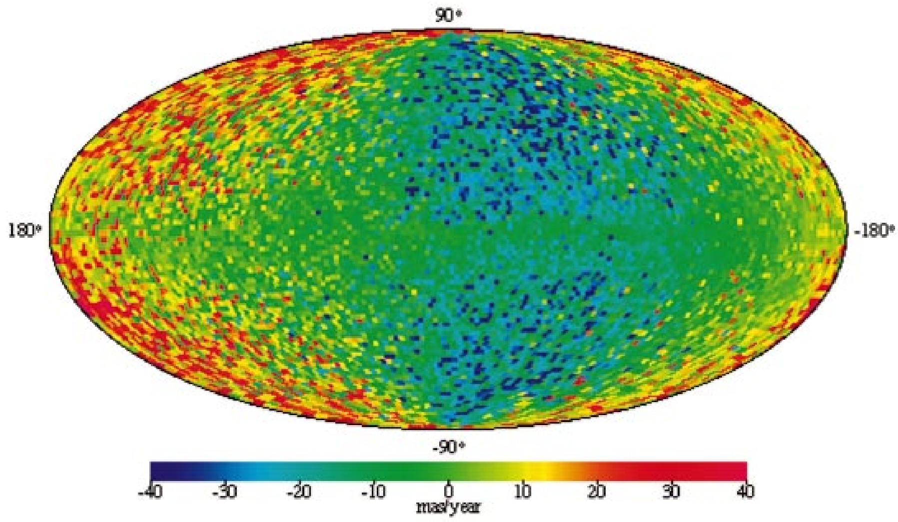


Figure 2.1.3. Hipparcos Catalogue: median proper motion in galactic longitude, in galactic coordinates (cell size 2×2°). The bipolar structure of the plot results from the motion of the solar system towards the apex.



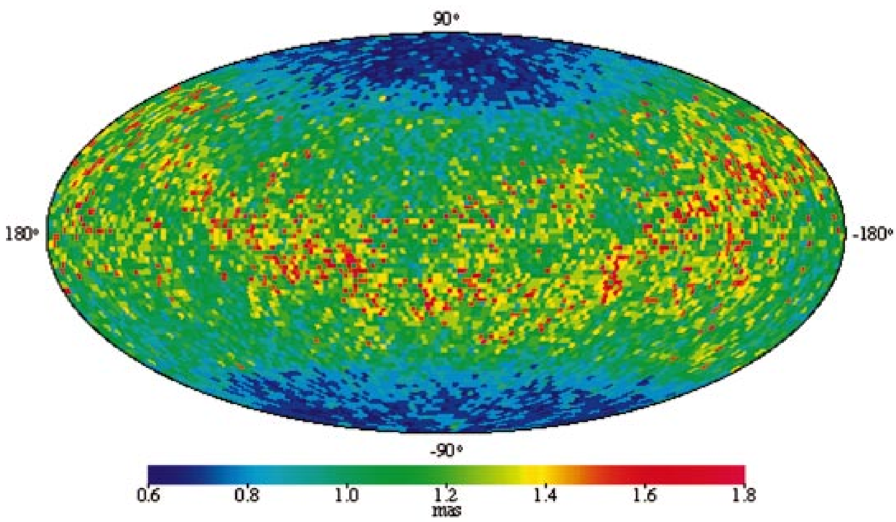


Figure 2.1.4. Hipparcos Catalogue: median parallax standard error in ecliptic coordinates (cell size 2×2°).

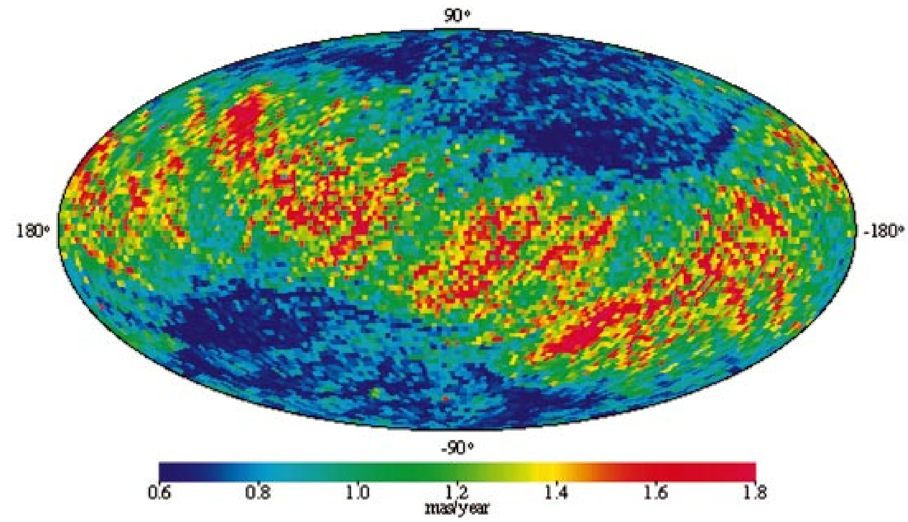


Figure 2.1.5. Hipparcos Catalogue: median standard error of the proper motion in right ascension, in equatorial coordinates (cell size 2×2°).

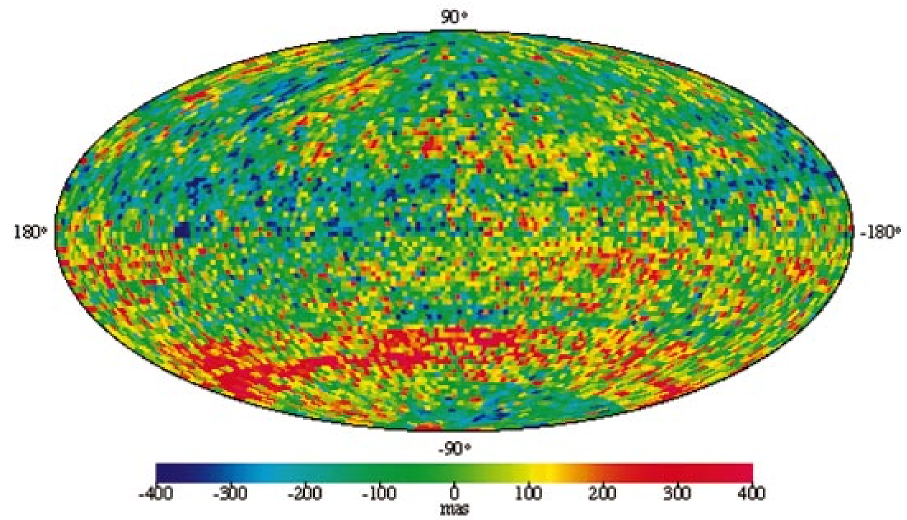


Figure 2.1.6. Median difference between right ascension from the Hipparcos Input Catalogue and from the Hipparcos Catalogue, in equatorial coordinates (cell size 2×2°).

launch. Perhaps even more remarkably, completion of the accompanying Tycho Catalogue of more than 10^6 stars was brought forward by 1 year, and eventually released and published on the same schedule as for the Hipparcos Catalogue.

The Hipparcos satellite essentially provided a network of very precise angular measurements, each star slotting into this grid at the level of about 0.001 arcsec. From this coordinate network, encompassing the entire celestial sphere, stellar distances out to several hundred light-years, and stellar motions, along with other related properties (including binarity and variability) could be established with unprecedented accuracy. The procedures are described fully in the published catalogue.

Between the first release of the final data to the scientists with proprietary data access in June 1996, and the publication of the printed and CD-ROM catalogue versions by ESA in June 1997, scientists with early access to the data proceeded with their scientific exploitation, while the main effort of the Hipparcos scientific teams was devoted to the task of preparing and documenting the catalogues for general distribution. The result is the unique 17-volume publication ESA SP-1200, which includes not only the major catalogue data and annexes in printed form, but also four volumes documenting the catalogue contents, explaining how to use the data, and describing details of the satellite operations and the methodology and tests employed during the creation of the Hipparcos and Tycho Catalogues.

A magnificent visualisation of the entire Hipparcos and Tycho Catalogues is included as Volumes 14-16 of the printed catalogues in the form of a 3-volume 1548-chart atlas of the sky. This production arose out of a remarkable collaboration between ESA and the Hipparcos scientific teams on the one hand, and Sky Publishing Corporation and its leader of this programme, Roger W. Sinnott, on the other. The result is a visually dramatic sky atlas, showing the stellar objects observed by the Hipparcos satellite, some of their main characteristics, such as variability, high proper motion, variability, duplicity and distance; it also includes many non-stellar objects, galaxies and nebulae. These three catalogue volumes mirror the 3-volume Millennium Star Atlas published separately by Sky Publishing Corp.

In May 1997 a major colloquium was held in the Fondazione Cine, and 300 scientists met on the small island of S. Giorgio, Venice, to celebrate the completion of the Hipparcos programme, to hear of the early results from the scientific exploitation, and to consider plans for follow-on missions that promise access to the microarcsec positional regime. The 800-page proceedings were published by ESA as ESA SP-402 in September 1997, 4 months after the colloquium.

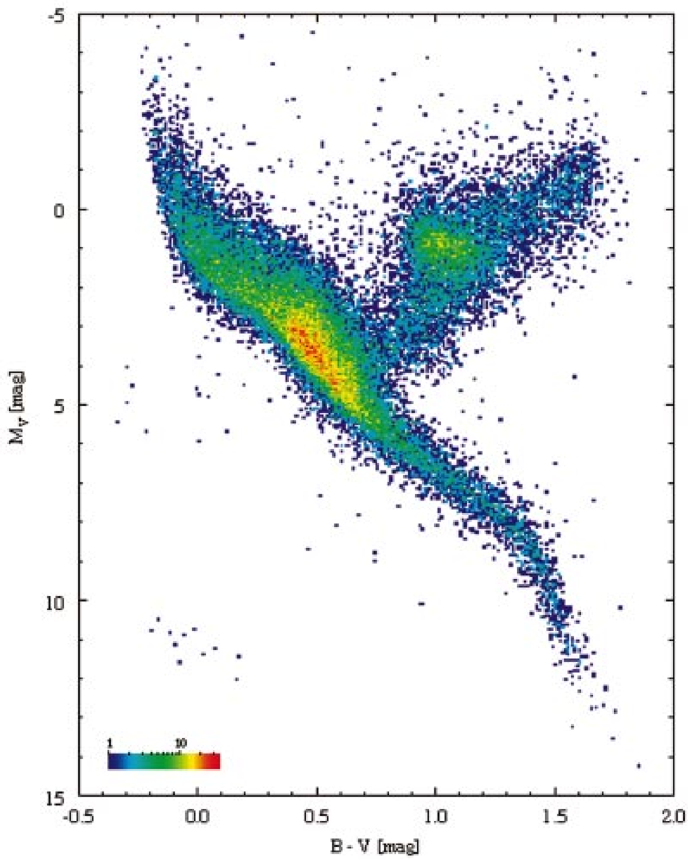
A comprehensive WWW site has been established by the Space Science Department in ESA, giving the community easy and detailed access to the catalogue data, documentation, animations, news, and recent scientific results.

Some scientific results

In the Hipparcos Catalogue, more than 20 000 stars out to a range of 200-300 light years now have their distances known to better than 10%, and another 30 000 are known to better than 20%. An interesting by-product of the Hipparcos positional measurements is the confirmation of gravitational light bending by the Sun to about one part in a thousand, the most precise test of this prediction of General Relativity made to date. The deflection of light, which amounts to more than 1.7 arcsec at the solar limb, has been easily and convincingly measured by Hipparcos over the entire celestial sphere.

Scientific results from the mission are now appearing regularly in the scientific literature, with around 200 papers having appeared in print during 1997 based directly on the Hipparcos results. A topical example of the use of the Hipparcos data comes from the emerging discipline of asteroseismology, in which stars other than our Sun are scrutinised for observational signatures of solar-like oscillations. Formulae predicting the frequencies of the low-degree modes, for example, involve the sound travel time across the stellar diameter, conditions near the stellar surface, and correction terms depending on conditions within the stellar core. Detailed stellar modelling predicts the star's luminosity and hence, from its apparent magnitude, its distance, which may then be compared to the Hipparcos trigonometric determination. The Hipparcos parallax for Eta Boo, at 88.17–0.75 milliarcsec, places the star at a distance of 11.3 pc with a distance uncertainty of just under 1%. This distance agrees perfectly with the current model predictions, and serves as an important validation of the asteroseismic analysis.

The limited knowledge of distances and motions of stars in the pre-Hipparcos era is well illustrated by comparing the 'Catalogue of Nearby Stars' with the Hipparcos results. This catalogue has been maintained by astronomers in Heidelberg since Wilhelm Gliese established his first such catalogue census there in 1957. Extending out to a distance of 25 pc, and cataloguing some 2000 stars, the pre-Hipparcos



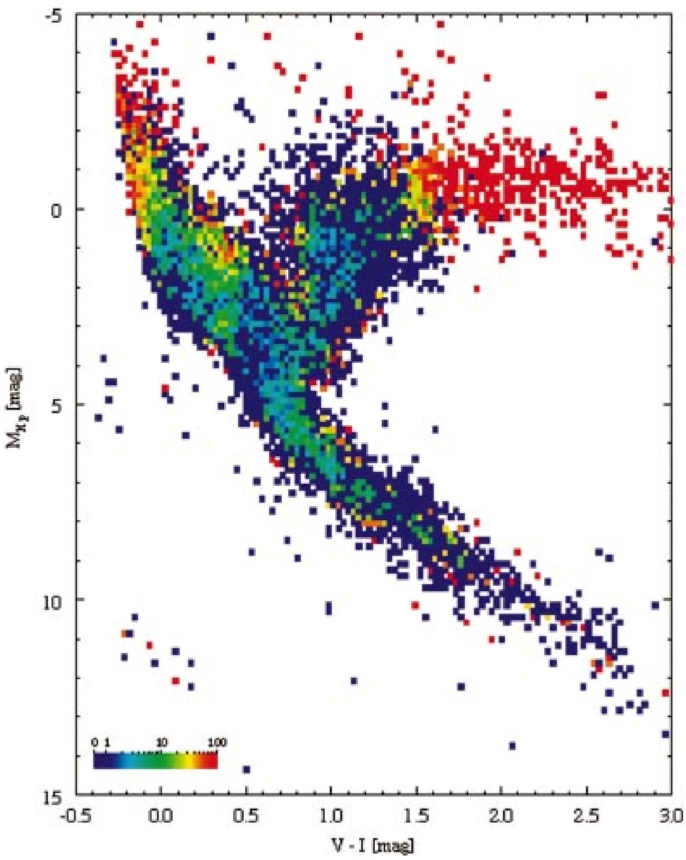


Figure 7 (left). The Hertzsprung-Russell diagram of the 41 704 single stars from the Hipparcos Catalogue with a relative distance precision better than 20%. The colour scale indicates the number of stars in a cell of 0.01 mag in the colour index, B-V (horizontal axis), and 0.05 mag in the absolute magnitude (vertical axis).

Figure 8 (right). The fraction of stars from the Hipparcos Catalogue that are variable, in the HR diagram. In each cell of 0.03 mag in V-I and 0.15 mag in absolute magnitude, the percentage of variable stars is coded according to the colour scale.

compilation had to draw on distance information obtained from painstaking ground-based parallax determinations extending over about a century, assembled from observations made at many different observatories. These trigonometric parallax measurements were supplemented by distances inferred from a variety of spectroscopic or photometric estimates. The goal in such a census is to identify, from the 2-dimensional projection of the many millions of stars on the celestial sphere, that small subset lying within 25 pc. Seeing nearby space with the superb stereoscopic vision provided by Hipparcos, the impact on our understanding of even these nearest stars has been enormous. Around 200 'new' nearby stars have become apparent, the nearest of these lying at a distance of only 5.5 pc. Several hundred stars previously suspected of being nearer than the 25 pc distance horizon of the ground-based census are now known to lie much further away. There are fewer main sequence stars, a reduction in the number of giant stars within 20 pc by almost a factor of two, and one white dwarf leaving the 5 pc sphere. And 37 previously unknown binary companions of nearby stars were discovered, including a probable brown dwarf companion to the star Gliese 433. One key number emerging from this study is the local stellar mass density, amongst other things an important parameter for placing limits on the presence of dark matter in the Galactic disc. This density has 'decreased' to a value of about 0.039 solar masses/pc^3.

Several lines of evidence suggest that all of the gravitating mass in the Universe cannot be simply in visible form. So it is important to be able to establish the presence of matter, independently of its visibility. Stars can act as suitable kinematic tracers, probing the gravitational signature of material irrespective of its physical manifestation. Determination of the density of matter in the solar neighbourhood is an issue well-known in Galactic dynamics. Usually referred to as the ‘K-z problem’, it aims to characterise the force law perpendicular to the Galactic plane. The Hipparcos sample of A stars provides the first volume-limited and absolute magnitude-limited homogeneous tracer of stellar density and velocity distributions in the solar neighbourhood. Results of recent Hipparcos work indicate that the local dynamical volume density is 0.076 – 0.015 solar masses/pc^3, a value well below all previous determinations, but nevertheless compatible with all existing observations of known matter. Significantly, the results support a growing consensus concerning the main structural parameters of the Galactic disc populations (such as their scale length and scale height), although there is no agreement as to their precise composition. Even more importantly, they imply that there is no room left for any significant disc-shaped component of dark matter, although a nearly spherical halo of dark matter is still needed to explain the flat rotation curve of the Galaxy beyond the solar Galactic radius.

The distance to the Hyades cluster has been the subject of intense interest and investigation by astronomers over a very long period. Astronomers’ preoccupation with the Hyades has its roots in the central role the cluster has played in defining the entire distance scale used in astronomy. More generally, clusters are important because they represent a gravitationally bound collection of typically a few hundred stars, born at the same time, and with a given chemical composition. The development of this coeval system, both dynamically and with respect to the individual stellar properties such a stemperature and luminosity, therefore provides an ideal laboratory for testing models of stellar evolution. These open clusters are subject to ‘evaporation’ and eventual disruption over timescales of tens or hundreds of millions of years due to gravitational encounters between stars within the cluster, or between the cluster and the Galactic disc or giant molecular clouds. A wide variety of creative methods has been brought to bear on the Hyades distance determination problem over the last hundred years, with tantalisingly discordant results – scientifically enigmatic for a cluster of stars at a distance of ‘only’ some 40 pc, or a little more than 120 light-years. Hipparcos has provided unambiguous results on this important system, providing the first truly reliable direct distance measurements to about 200 stars in the cluster, while also allowing its internal structure, internal motion, mass segregation, and disintegration processes to be observed.

The problem of the determination of distances to objects throughout our Galaxy and beyond is one of the central themes in present-day astronomy. On the largest scales, distances to other galaxies affect our knowledge of the Hubble constant. Already in early 1997, Feast & Catchpole argued for a Hipparcos-derived Cepheid distance modulus for the Large Magellanic Cloud of 18.70 – 0.10 mag, corresponding to a distance of almost precisely 55 kpc. This represented an upward revision in the measured distance to this galaxy, by an amount which would have the effect of increasing the extragalactic distance scale by nearly 10%. Other researchers have since examined the distance to the Large Magellanic Cloud using a variety of other routes, using different information contained in the Hipparcos Catalogue (for example, the RR Lyrae and Mira variables) and considering the Cepheid distance calibrations from slightly different perspectives. While no consensus has yet emerged, the general trend has been to increase the estimated age of the Universe, by invoking cosmological arguments related to the increased value of the Hubble constant.

Meanwhile, Hipparcos-based investigations attempting to date the oldest stellar populations in our Galaxy, the globular clusters, have suggested a revised age of perhaps 12-14 Gyr, although not all investigators are in agreement. Pre-Hipparcos estimates had put some globular cluster ages as high as 18 Gyr, older than the cosmological age estimates of the Universe itself. It would be a triumph if so soon after its release the results from Hipparcos could have eliminated a long-standing cosmological age conflict that has confounded researchers for many years – that the age of the Universe appeared to be smaller than some of its constituent stars. Alternatively, if further examination of the Hipparcos results fails to resolve this question unambiguously, theoretical cosmology on the one hand and stellar observation and theory on the other, will need further extensive scrutiny to establish exactly where this inadmissible inconsistency originates. Some further surprises concerning the self-consistency of the various Galactic distance scale indicators, and their ages, may still be awaiting us.