GAIA AND BEYOND:
THE PERSPECTIVE FROM THE MILLIARCSECONDS OF HUBBLE AND HIPPARCOS

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ABSTRACT

Astrometry with the Hubble Space Telescope and Hipparcos have pushed optical astrometric accuracies to the milliarcsec level. GAIA and other proposed optical interferometry space missions would push the optical astrometric accuracies to 10 microarcsec or better. First a catalogue figure of merit is defined which allows a simple quantitative comparison among astrometric catalogues. Second, using two specific astrophysical problems the level of the expected scientific contribution from a GAIA type mission is assessed. The two problems are: (1) the question of the age of the globular clusters vs the age of the universe, and (2) the question of possible fluctuations in the initial mass function compared with fluctuations in the star formation rate with time.

Key words: space astrometry, Hipparcos, GAIA, interferometry, catalogues, globular clusters, star formation rate

1. INTRODUCTION

Astrometry has reached the milliarcsec level of accuracy, and is pushing the sub-milliarcsec level. Hipparcos has produced positions, parallaxes and proper motions with mean accuracies around 1.7 mas, while extensive observations with the Fine Guidance Sensors of the Hubble Space Telescope have demonstrated an accuracy of a few milliarcsec in single observations and formal errors of 0.5 milliarcsec in the measurement of parallax and proper motion (Benedict et al., 1994). Ground-based parallaxes are also pushing these limits, although global astrometry from the ground seems to be limited at about the mas level due to unmodelable phase path fluctuations in the atmosphere over large angles. The contribution of Hipparcos to our knowledge of galactic structure and evolution will be enormous, but it will be limited to a region relatively close to the sun, on a galactic distance scale. Therefore, the contribution of GAIA, reaching an accuracy of 10 mas and a limiting magnitude beyond 15 mag, will be to define the stellar population within a kiloparsec, and to allow stellar kinematics and dynamics to be studied outside the local neighborhood for the first time.

This paper will discuss two aspects of the proposed GAIA mission: first, a simple 'figure of merit' for star catalogues will be defined, which will demonstrate the affective improvement of GAIA over Hipparcos and some previous catalogues. Second, two astrophysical problems will be outlined on which GAIA will have a profound impact.

2. CATALOGUE FIGURE OF MERIT

Programmes to measure positions and motions of celestial objects usually result in catalogues which then are distributed to users. Such catalogues usually result from massive amounts of effort on the part of large numbers of people from various disciplines. The resulting catalogues have different specific uses depending on the typical accuracy of the catalogue and the number and distribution of objects in the catalogue. I will define here a simple 'figure of merit' of a positional catalogue at the catalogue mean epoch, which indicates its general usefulness. As is typical of such 'global' numbers, it is more or less meaningful depending on the context in which it is used.

A catalogue will be more useful if its 'typical error' (can be the formal mean error of a single position, for example) is smaller rather than larger. (Actually, the arial error is more meaningful than the error along one axis.) It will also be more useful if the number of stars is larger rather than smaller. Therefore, define the 'figure of merit' as $Q = n/(\sigma_\alpha \sigma_\delta)$, where n is the number of objects in the catalogue and the σ are the 'typical' errors in each coordinate.

For catalogues of the last part of the twentieth century, milliarcsec are appropriate units, so that Q, in units of mas^2, is an appropriate measure. Table 1 gives Q for some representative catalogues. Obviously, only catalogues within the same broad wavelength bands should be compared directly.

Table 1. Figure of merit for representative catalogues. N gives the number of objects in the given catalogue, 'error' a typical positional error in milliarcsec, and Q the figure of merit (as defined in the text).

Catalogue	N	Error	Q
Optical:			
FK4	1500	50	6.0×10^{-1}
FK5	5000	20	$1.2 \times 10^{+1}$
SAO	300000	50	1.2×10^{0}
GSSS	18000000	500	7.2×10^{1}
HIP	120000	2	$3.0 \times 10^{+4}$
Tycho	400000	15	$1.8 \times 10^{+3}$
GAIA	18000000	0.01	1.8×10^{11}
Radio:			
3CR	475	60000	1.3×10^{-7}
UTRAO	75000	1500	3.3×10^{-2}
VLBI-IERS	200	1	$2.0 \times 10^{+2}$

Two points are worth noting:

(1) The usefulness of catalogues alternates between 'fundamental' catalogues with relatively small numbers of objects, and then their extension to large numbers of fainter objects. One would think that GAIA would provide an exception to this trend, but the extension of the GAIA reference system to 22 mag or fainter is a real possibility, to cover small field CCD frames or imaging interferometer 'frames' in the centres of globular clusters, galaxies, QSOs, just for example.

(2) Optical positions were once used to calibrate radio source positions because the radio positions were much worse than 1 arcsec. Now the radio IERS-VLBI reference system is being used as the standard for the optical Hipparcos positions. With GAIA, looking at QSOs directly, we may revert to the former condition. However, with the increasing sophistication of infrared interferometry, we may very well come to a stage when the IR defines the reference system.

3. TWO ASTROPHYSICAL PROBLEMS

3.1. The Star Formation Rate

Old studies indicate that F stars show a local concentration around the sun (see McCuskey 1965 for a review.) Some hints exist that the star formation rate OR the initial mass function may have variations. Barry (1988) has used chromospheric age determinations of G and later stars within 20 pc to look at their frequency distribution as a function of age. He concluded that the most likely explanation of the distribution is a variable star formation rate, with three bursts indicated in the last billion years, the latest being within the last 4×10^8 years. Noh & Scalo (1990) find evidence for a burst of star formation within the last 3×10^8 years from the white dwarf luminosity function and the theoretical white dwarf cooling rates, but discrepancies exist between the numbers of expected and observed white dwarfs at the cool end of the white dwarf sequence. The question arises as to whether the observations of an enhancement (bump) in the white dwarf luminosity function was caused by a burst of star formation which is cooling its way down the white dwarf luminosity function or whether it was caused by a bump in the initial mass function.

The question will begin to be addressed by determining whether or not the local grouping of A and F stars is real. The distribution of the stars will be determined by looking at their parallaxes from Hipparcos and analyzing their motions, and determining if they were formed in a burst of star formation around $3 - 4 \times 10^8$ years ago, as indicated by their kinematics and observed photometric properties. If the group does not exist; i.e., if the distribution of A and F stars is uniform around the sun, then there is no empirical evidence for a burst of star formation from the actual distribution around the sun, and a bump in the initial mass function is implicated as the source of the bump in the white dwarf luminosity function. However, the space density distribution apparently drops off on average by a factor of two at about 400 pc. Therefore, Hipparcos parallaxes will be insufficiently accurate to make a definitive statement about the distribution of these stars, even if the complete sample stars out to 1 kpc were available. The best guess absolute V magnitude for F stars of luminosity classes III-V is 2.3. Therefore, the F stars down to 13 mag should have their parallaxes measured to better than 100 microarcsec (10 per cent accuracy per star) to map out the F stars within 1 kpc of the sun, a programme which will automatically be accomplished with the currently proposed GAIA parameters.

3.2. Cluster-Universe Age Problem

Clusters in general and globular clusters in particular are test particles with unique ages and initial chemical compositions that can be used to trace the development of the formation of the Milky Way, and test our theories of stellar evolution at the same time. While these two functions have been recognized for a long time, the combination of them to determine the ages of globular clusters as a function of metalicity, for example, has led to a possible discrepancy with the age of the Universe: some age determinations of the metal-poor globulars result in ages that are older than some ages determined for the Universe. Whether or not significant age differences exist among the globulars in the Milky Way is still a question, partly because of inaccuracies of the various measurements that go into fitting a real globular to a theoretical model, and partly to our uncertainties in the theoretical models, due to affects such as diffusion in the core complicating the evolution itself, and diffusion in the atmosphere complicating the abundance analyses.

The determination of the ages of the globular clusters relies on several steps, but the crux of the observational problem is determining the turn-off point of the main sequence, which should be only a function of the mass of the stars at that point, their initial chemical composition, and their age. In order to determine the turnoff point, the absolute magnitude of the main sequence must be determined. For sample isochrones, a difference of 10^9 years corresponds to an absolute magnitude difference of 0.063 mag. Therefore, if the absolute ages are to be accurate to a billion years, the contribution to the error from the parallax determination of the cluster must be significantly less than 0.063 mag in the distance modulus, or significantly less than 3 per cent in the parallax. Therefore, the objective of an observational programme would be to measure the parallaxes of objects which will allow the determination of the distance of a number of globular clusters in the galaxy to the 3 per cent level rms individually or the 1 per cent level in the fitting of the main sequence. The three groups of objects considered are:

(a) the parallaxes of the globular clusters themselves, with the measurement of the parallax of the nine brightest stars in each of 15 globular clusters. The magnitudes would range from 12–15 mag. The expected accuracies would therefore be a factor of three better than the quoted error for a single parallax, aside from systematic effects. Because of the distances of the globulars, the direct parallax measurements would probably not provide the most reliable distance measurements until a significant number of parallaxes can be measured at the 10 microarcsec level.

(b) the RR Lyrae field stars which are used to determine the absolute magnitudes of the horizontal branches of the globulars. Note that an error of 0.022 mag in the distance modulus is equivalent to 1 per cent error in the parallax. The trigonometric parallaxes of the n brightest (closest) RR Lyrae stars must be determined in order to calibrate the absolute magnitude as a function of period, and metalicity if the relation between the field and cluster RR Lyrae stars is to be used at the 1 per cent level. Here the magnitudes range from 7.66 to 14.0 mag. At 14 mag, a measurement error of 10 mircoarcsec corresponds to an error in the parallax of 5 per cent.

(c) 'subdwarfs' which are used to define the absolute magnitude of the main sequences of the globulars. Carney (1980) gives 78 subdwarfs ranging in magnitude down to 12.0 mag. The range in $B-V$ is 0.37 to 0.87. The range of these objects could give an excellent calibration of the subdwarf sequence to which the globular cluster main sequences could be fit. The problem would be transferred to the relationships between the physical parameters and the observed parameters, about which a great deal has been discussed, and certainly more will be needed before we understand the absolute ages of the clusters at the billion year level of accuracy.

The third 'programme' would measure the parallaxes of as many of the brightest 90 subdwarfs as possible. The stars are bright enough (7–12 mag) and close enough so that GAIA calibration of the absolute magnitude of the sample stars as a function of colour, metalicity, and other parameters would be impeccable. The problem would then come in making the assumption that the subdwarfs are a representative sample of the globular cluster main sequence population *at the level of accuracy* of the parallax data or determining from physical observations and models exactly what is the relationship. But the question of the absolute magnitudes of the field subdwarfs would be unconditionally solved.

4. SOME THOUGHTS AND CONCLUSIONS

When space astrometry was first contemplated, milliarcsec accuracy was a dream far from reality. However, through perseverance and careful planning, milliarcsec astrometry with both the Hubble Space Telescope and Hipparcos came to fruition. Both projects had unforeseen problems all along the way; sometimes they seemed insurmountable. Both projects overcame those problems to the vast benefit of astronomy as a science.

By going to the microarcsec level of accuracy, the questions to be addressed will be of a fundamentally different character than the questions addressed by the milliarcsec capability. The signals at the milliarcsec and 100 microarcsec levels will become systematic effects which must be removed from the data. The technical challenges described elsewhere in this volume may change significantly the direction of an actual GAIA mission. What can be said is that the problems will be more surprising and more challenging than anything encountered in either Hubble or Hipparcos, but with perseverance, planning, and good fortune, global microarcsec astrometry will become a reality.

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REFERENCES

Barry, D.C., 1988, Ap. J., 334, 436

Benedict, G.F. et al., 1994, Bull. Amer. Astron. Soc., 26, 930

Carney, B, 1990, Ap. J. Suppl., 42, 481

McCuskey, S.W., 1965, in *Galactic Structure*, (A. Blaauw & M. Schmidt, eds), Univ. of Chicago Press

Noh, H., Scalo, J., 1990, Ap. J., 352, 605