THE SOLAR NEIGHBOURHOOD AND BEYOND

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ABSTRACT

In this paper, the impact of the results from Hipparcos, and the prospect from the proposed GAIA interferometric mission are reviewed. The combination of accurate parallaxes with proper motions will provide data for direct studies of the stellar density distribution and the population structure of the Galaxy to a distance of several kiloparsecs, particularly in regions with low interstellar absorption. In the galactic plane, and notably toward the galactic centre, only stars brighter than about $M_V = -2.5$ will be observable to ten percent accuracy in parallax, but these will enable spiral structure to be traced within 5 kpc, and the galactic rotation law outside the solar circle should be obtainable from proper motions to much greater distances. The parallaxes from GAIA will provide calibration of luminosities on the upper main sequence, which are poorly represented in Hipparcos, and also direct measurement of distances to the Magellanic Clouds. A kinematic distance to the LMC may also be derived by comparing the rotation law obtained from radial velocities and from proper motions.

Key words: solar neighbourhood, distance scale, stellar kinematics, galactic rotation, GAIA

1. INTRODUCTION

The 'solar neighbourhood' can been defined *de facto* by the volume contained within the radius to which reasonably accurate distances can be measured from trigonometric parallax observations. A relative accuracy of about ten percent has been achieved from ground-based measurements for less than a thousand stars, giving a radius of somewhere between ten and twenty parsecs. Parallaxes have been measured with lower accuracy for several thousand more stars within a nominal radius of 25 pc. Data for these nearby stars has included proper motions, radial velocities, photometry and spectroscopy, so that a reasonable picture of the overall stellar content and space velocities has been built up for this small volume. In particular the absolute Hertzsprung-Russell diagram, giving the correlation between luminosity and surface temperature for the common stars, has provided a fundamental basis for extending indirectly the distance scale within the Galaxy, and beyond. Extensive surveys of proper motions and radial velocities have also been used for studying the statistical properties of the velocities and space densities of stars within a wider volume extending to distances of a hundred parsecs or more.

The main limitation to these studies has been the difficulty of measuring large numbers of accurate trigonometric parallaxes. This situation will change dramatically in the very near future when the results of the Hipparcos astrometric satellite programme become available. Not only will the number of stars for which distances with relative accuracies of ten percent or better be vastly increased, but the limiting radius will be extended to up to a hundred parsecs, depending on magnitude, thus bringing within the scope of detailed investigation types of stars which are too rare to be represented within the smaller volume hitherto observable. This is well illustrated in a preliminary discussion of parallaxes and the Hertzsprung-Russell diagram from Hipparcos (Perryman et al., 1995) which extends the calibration of luminosities to many giants and upper main sequence stars, and shows that more than thirty percent of the stars which were previously thought to lie within 25 pc are in fact further away. Thus the detailed description of the stellar distribution and motions within even this very small radius will have to be substantially revised.

Although the Hipparcos data will provide a major extension of the solar neighbourhood, it is important to put this in perspective. The distance from the Sun to the centre of the Galaxy is thought to be about 8 kpc, so that, on the scale of the solar system with the Sun representing the galactic centre, the radius of the solar neighbourhood accessible to ground-base observations corresponds roughly to the radius of the Moon's orbit; even the range of Hipparcos represents an extension to only about one percent of the distance to the centre.

The situation could change dramatically with the proposed GAIA (Global Astrometric Interferometer for Astrophysics) mission. A description of the concept and aims for this new mission by the European Space Agency has been given elsewhere (Lindegren & Perryman, 1994, 1995). Two possible modes of operation are suggested, a 'baseline option' using modulating phase grids and CCD detectors, and 'direct fringe detection' which uses a detector with sufficient spatial resolution to replace the modulating grid. This latter mode gives higher performance than the baseline option, both in respect of limiting magnitude and astrometric accuracy, but requires development of a suitable detector, whereas the baseline option is based on existing technology.

The predicted parallax errors for GAIA in the baseline mode range from 0.002 mas, for $V = 10$ mag, to 0.02 mas at the limiting magnitude of $V = 16$ mag; these figures should be compared with the average parallax error achieved with Hipparcos of about 1.4 mas. Thus, even in the worst case of faint stars, the distance for which relative accuracy of ten percent can be obtained will be increased from about 60 pc to at least 5 kpc. The solar neighbourhood could in principle be extended to include a large fraction of the total volume of the Galaxy. In direct fringe detection mode parallax errors should not exceed 1 μas for stars brighter than $V = 12$ mag, rising to 12 μas at $V = 18$ mag and 30 μas at the limiting magnitude of $V = 20$ mag.

A feature of the proposed GAIA mission is that no *a priori* selection of stars will be required, so that selection effects, other than by apparent magnitude, which have hitherto bedevilled most statistical analyses of stellar data, will be avoided.

2. EXTENDING THE SOLAR NEIGHBOURHOOD

Our knowledge of the numbers and types of stars in the solar neighbourhood has been derived by counting the stars whose measured parallaxes indicate that they may be within some adopted distance limit. This procedure, though simple in concept, has two serious sources of error. In the first place, the measurement of parallaxes has been confined to those stars for which there is a reasonable likelihood of the parallax being large; this generally means selection according to size of proper motion, which gives a bias towards stars with high velocity, although late type dwarf stars can be selected spectrophotometrically, thus avoiding this kinematic bias for these stars. Secondly, in practice, the adopted distance limit has to be chosen according to the size of the observed parallax; thus any selection favours stars with positive observational errors over those with negative ones.

For a uniform space density, the number of stars per unit parallax ϖ, varies as ϖ^{-4}, so that many more stars will be erroneously included than excluded. The smaller the parallax errors, the less significant is this latter bias. In the case of Hipparcos, the relative accuracy at the distance of 20 pc ($\varpi = 50$ mas) is only about 3 percent, compared with 20 percent for ground-based parallaxes. For GAIA in baseline mode, 3 percent relative accuracy corresponds to a distance of 15 kpc at $V = 10$ mag and 1.5 kpc at $V = 16$ mag. Since 1.5 kpc corresponds to a distance modulus of about 11, this latter limit means that, in the absence of interstellar absorption, all stars for which $M_V \leq 5$ within this distance could be identified, with correspondingly larger distance limits for intrinsically brighter stars. In direct fringe detection mode, the parallax error of 30 μas at $V = 20$ mag corresponds to a limiting distance of 1 kpc for $M_V \leq 10$.

3. STELLAR POPULATIONS, DENSITY DISTRIBUTION AND KINEMATICS

Any density gradients within the immediate vicinity of the Sun, for example the volume studied from ground-based parallax observations, are generally assumed to be negligible. The majority of stars within this volume are normal stars belonging to the 'old' disk population, although there are a few sub-dwarf members of the halo population which have been detected by their high velocities and lower than normal metal abundance. As soon as the distance limit is increased, the variations of density with distance from the galactic plane, and also from the galactic centre, will become apparent. The estimated scale heights perpendicular to the galactic plane for various stellar types vary between about 50 pc for young objects, such as O stars and Cepheid variables, to several kpc for old halo objects in the spheroidal component of the Galaxy, such as RR Lyrae variables, for which accurate absolute magnitude calibrations as a function of metal abundance will be obtained from the parallaxes. Although the integrated densities of particular stellar types can be estimated, the partition into discrete populations is a matter of controversy. The large majority of stars appear to be distributed in the old disk with scale height of about 300 pc, but some authors contend that a few percent of the stars belong to a 'thick disk' (e.g. Gilmore & Wyse, 1987) with scale height of some 1.3 kpc. All these estimates depend on analyses of star counts, and indirect determinations of distances, mostly from photometric parallaxes calibrated from the nearby stars, which cannot be accurate to better than about 25 percent.

Different stellar populations are characterized by chemical composition and by kinematics, both of which presumably depend on age. The main kinematic effects may be expected to be an increase in velocity dispersion and a decrease in the rotation speed around the Galaxy, with increasing scale height. The velocities and dispersions for stars in the immediate solar neighbourhood have been reasonably well determined from the radial velocities, and transverse velocities obtained from proper motions and parallaxes.

For more distant stars, some proper motion surveys are available, but the main kinematic data come from radial velocities. The normal nearby stars have velocity dispersions of the order of 25 km/s and a rotational lag of about 10 km/s relative to the circular velocity at the Sun (the local standard of rest), whereas the dispersions in the extreme halo is of the order 100 km/s and the lag about 200 km/s. The accurate proper motions, coupled with the distances, obtained by GAIA, will provide very powerful evidence for the population structure, particularly in regions of high galactic latitude where absorption is low and where the proper motions contain a large component of the velocity parallel to the galactic plane. Indeed, the chief limitation to the complete description of the stellar densities and kinematics will be the lack of radial velocity data.

4. THE GALACTIC PLANE AND ROTATION LAW

Studies of galactic rotation depend critically on the measurement of distances in the plane, particularly those to very young and intrinsically bright objects such as Cepheid variables and luminous stars on the upper main sequence, which can be detected at large distances from the Sun. Hitherto the distances to these objects have had to be estimated photometrically, in the case of Cepheids, from the period-luminosity law, and for O-B supergiants, from their position on the adopted zero-age main sequence in the Hertzsprung-Russell diagram.

The calibration of these distances has depended ultimately on the lower main sequence calibrated by trigonometric parallaxes, augmented by the indirect procedure of fitting the main sequences of galactic clusters of various ages. The parallax results from Hipparcos will provide direct calibration of the main sequence for stars with $M_V \geq -1$. but there are only very few more luminous stars, and no Cepheids, with sufficiently accurate parallaxes in the Hipparcos catalogue. A further complication in estimating distances photometrically is the presence of absorbing matter.

In principle, in its baseline mode, GAIA will be able to measure parallaxes with an accuracy of ten percent or better to a distance of 5 kpc, for stars with $V = 16$ mag. This represents a distance modulus of 13.5. In the absence of interstellar absorption the observable stars at this distance would have $M_V = 2.5$; but since a reasonable average value for the absorption is about 1 mag/kpc, the actual absolute magnitude observable at this distance, in the galactic plane, would be about $M_V = -2.5$. Of course there will be 'windows' in the absorption through which brighter and more distance stars will be observable, but it is safe to say that within 5 kpc it will be possible to map the distribution of stars brighter than this limit, and hence to delineate the spiral structure optically with many more objects than has hitherto been possible.

Differential galactic rotation within about a kiloparsec of the Sun is described by Oort's constants A, B and the distance from the Sun to the galactic centre, R_0. These can be obtained from radial velocities and from proper motions of objects for which distances can be estimated. The galactic rotation curve at greater distances has only been derived from radio observations if the 21 cm line of neutral hydrogen, involving assumptions of symmetry in the distribution of hydrogen, and adopting values for R_0, A and B. This procedure is only possible within the solar circle, i.e. for galactocentric distances less than R_0. With GAIA, not only the parallaxes, but also proper motions of large numbers of stars in the plane will be measured, with relative accuracies similar to those of the parallaxes. Provided that radial velocities are also measured, it will thus be possible to map directly the space velocities within 5 kpc of the Sun. A topic of current interest is whether the rate of rotation increases for galactocentric distances greater than R_0; if it does, then the implication is that there is a large amount of mass in the Galaxy exterior to R_0.

5. BEYOND THE GALAXY

The cosmic distance scale is based primarily on the period-luminosity law of the Cepheid variables. This law was first discovered through observations of the variables in the Magellanic Clouds. It has hitherto been calibrated from the absolute magnitudes of Cepheids in the Galaxy, derived from analyses of proper motions and radial velocities, and also from Cepheids which belong to some galactic clusters whose distances have been estimated by the main-sequence fitting procedure. GAIA will provide direct calibration of galactic Cepheids from trigonometric parallaxes, thus putting the distance scale on a much more secure foundation.

The distance to the the nearest external galaxy, the Large Magellanic Cloud, is about 50 kpc, which corresponds to a parallax of 20 μas. In order to measure this to an accuracy of a few percent, it will be necessary to measure several hundred stars, which will be quite possible with GAIA. There is however another possibility of measuring the distance to the LMC, by means of proper motions. The predicted accuracy of proper motions from GAIA in baseline mode range from 1 μas/yr at $V = 10$ mag to 12 μas/yr at $V = 16$ mag; these correspond to velocities of 5 km/s/Mpc and 60 km/s/Mpc respectively. Thus at 50 kpc even the faintest stars will be measured with an accuracy of only 3 km/s. The LMC is a flattened system inclined at about 27° to the plane of sky. Its rotation curve has been determined from radial velocity observations of supergiant stars, bright gaseous nebulae, and from 21 cm radio observations, and has been shown to have an amplitude of about ± 100 km/s (Feast, 1964). The projected effect of this rotation in the plane of the sky is therefore about 90 km/s, which should be easily detectable in the GAIA proper motions. Thus, by comparing the rotation curves derived from radial velocities and from proper motions, we can derive a kinematic distance to the LMC, in addition to the trigonometric parallax, which will be independent of any assumptions about the luminosities of the Cepheids. Furthermore, since the LMC contains many stars brighter than $V = 16$ mag, it should be possible to derive a rather detailed velocity map, thus giving information on the mass distribution and its dynamical structure.

As has already been remarked, the proper motion accuracy from GAIA in baseline mode will be about about 60 km/s/Mpc or better, which is of the order of the Hubble constant. It is of interest to speculate that proper motions of bright quasars may also be of this order of magnitude, in which case the current definition of the cosmic inertial reference frame may have to be modified.

CONCLUSIONS

In this paper we have indicated only a few of the topics in galactic and extra-galactic astronomy to which GAIA, even in its baseline mode, will contribute very dramatically; we have intentionally concentrated only on the baseline observing mode to show what will be possible even with existing detector technology. Lack of astrometric data will no longer be the critical factor in any investigation of stars brighter than $V = 16$ mag; indeed, as has been remarked above, the absence of radial velocity data with corresponding accuracy for large numbers of stars will be the main limitation.

The final publication of the results from Hipparcos will be a major leap forward in galactic astronomy, but this will be nothing compared to the impact which GAIA could have for the next generation of astronomers.

REFERENCES

Feast, M.W., 1964, MNRAS, 127, 195

Gilmore, G., Wyse, R.F.G., 1987, 'The Galaxy', Gilmore, G. & Carswell, B. (eds), Reidel, 247

Lindegren, L., & Perryman, M.A.C., 1994, Supplementary information submitted to the ESA Horizon 2000+ Survey Committee

Lindegren, L., & Perryman, M.A.C., 1995, ESA SP-379, this volume

Perryman, M.A.C., et al. 1995, A&A, in press