SUB–MILLIARCSECOND ASTROMETRY OF STAR CLUSTERS AND ASSOCIATIONS

FLOOR VAN LEEUWEN
Royal Greenwich Observatory
Madingley Road, Cambridge, UK

Abstract. Some of the possibilities created by sub–milliarcsecond astrometry in the study of both nearby and distant star clusters are presented.

1. Introduction

Sub–milliarcsecond astrometry can bring a much larger number of clusters and associations within the range of direct distance determinations, thus contributing very significantly to the study of star formation (mass-functions) and stellar evolution. The spatial resolution of some nearby clusters and associations will create the possibility of observing the 3–dimensional distributions of mass, radial kinetic energy and angular momentum. For those clusters it will remove the noise on the HR–diagram due to spread in distance moduli and make it possible to detect escaped former cluster and association members on the basis of 3-d positions and velocities. In the more distant future, sub–milliarcsecond astrometry opens the way to measuring accelerations in nearby star clusters, thus making it possible to measure their masses.

2. Distances for clusters and associations

Measuring parallaxes to an accuracy level of 1 to 10 microarcsec brings the order of 1000 open clusters, several associations and a number of globular clusters within range of a direct distance determination. Currently, differences in metal abundances, reddening corrections and age produce serious uncertainties in cluster distances (Lyngå, 1980). Figure 1 shows the impact of improvements in accuracy on absolute magnitudes at various distances

E. Høg and P. K. Seidelmann (eds.),
Astronomical and Astrophysical Objectives of Sub-Milliarcsecond Optical Astrometry, 227–232.

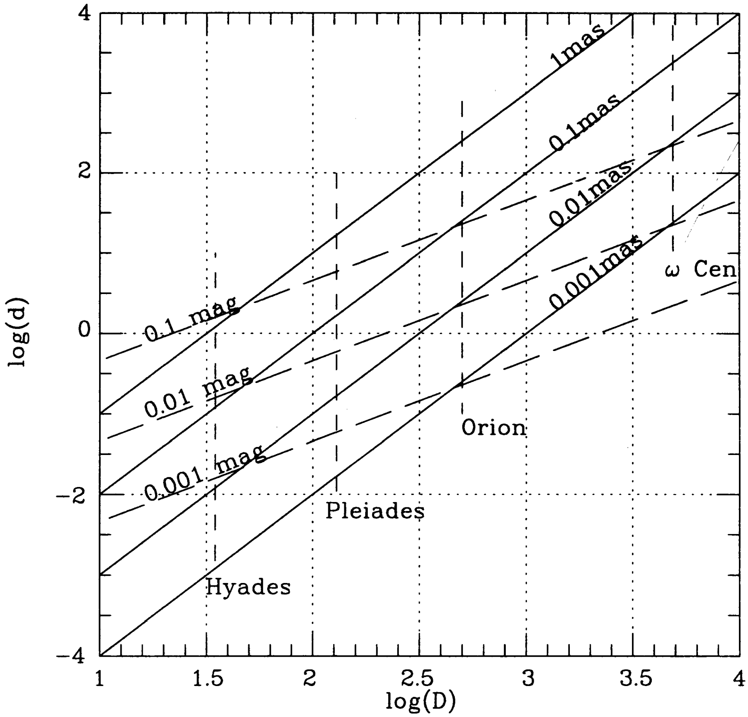

Figure 1. Relations between accuracies in parallax (solid lines), distance moduli (long–dash lines), the spatial resolution (d) and the distances (D) of clusters and associations. The 1 mas parallax accuracy is obtained with Hipparcos, 0.01 mas could be obtained with the revised ROEMER and GAIA concepts.

from the sun. The positions of some clusters and associations are shown in comparison. It is clear from Fig.1 that even though the impact of Hipparcos has been enormous, there is still a considerable improvement needed to make it possible to use the clusters and associations in the detailed calibrations of the HR–diagram: the HR-diagram constructed from preliminary Hipparcos results indicates a considerable intrinsic spread in absolute magnitudes for very nearby stars with the same $(B-V)$ colour index (Perryman and Heger, 1993).

In a concept like the ROEMER or the GAIA satellite (Lindegren et al, 1993, Høg, 1994), where high accuracy astrometry is combined with intermediate band-width photometry, it will become possible to calibrate the variations in luminosity as a function of age and metallicity using interstellar reddening corrections obtained from two-colour diagrams, provided the photometric passbands are carefully chosen and can be reproduced on the ground. A detailed HR-diagram thus obtained can then be used as the observational basis for the study of stellar evolution over ages ranging from less than a million years in some associations to 15 billion years in some globular clusters, taking into account fully differences in metallicity.

The nearby younger star clusters and associations will provide data on the mass spectrum of star formation processes using observed luminosity functions that include the detection of members in the cluster halo (Kholopov and Artyukhina, 1972, Van Leeuwen, 1980). Due to mass segregation, even by an age of 10^8 years a strong gradient in the mass spectrum may be observed between the cluster centre and the halo. Observations of the mass spectrum based only on data from the projected cluster centres can thus lead to wrong conclusions (Taff, 1974). This is further complicated by the escape of cluster members, for which the probability depends on the mass of the star and its chance of passing through the cluster centre.

Combined high precision astrometric and photometric studies of both young and old star clusters and associations are essential for filling in the details in the stellar evolution theories. The same applies for clusters with different metal abundances. The comparisons between clusters of different ages can show how their mass functions change due to the dynamical evolution of these systems, and thus also how the clusters and associations populate the galaxy with new stars.

3. Spatially resolved systems

The nearest clusters are well studied down to magnitude 14 to 16. The limit is set by the availability of early photographic plates. Accuracies in (relative) proper motions have reached levels of 0.1 to 0.2 mas/year (Vasilevskis et al, 1979), allowing the study of internal motions. Two main problems remain: the relative positions of cluster stars are only known projected along the line of sight, and for the fainter stars the proper motions are no longer sufficient to clearly distinguish members from non-members. The effect of the first problem is that a considerable uncertainty remains in the interpretation of the kinematics: it is necessary to deconvolve the observed projected proper motion dispersions with the density distribution of the cluster, which itself has been derived from differentiation of the projected density distribution. This would not be too bad if the number of stars involved were large, but in open clusters these numbers are small, leaving considerable uncertainties in matters like the actual presence of low mass stars in the cluster centre (Van Leeuwen, 1983). A lively discussion on this problem in the Pleiades can be found in Kholopov, 1971a, Mirzoyan and Mnatsakanian, 1971, Kholopov, 1971b and Mirzoyan et al, 1980.

The uncertainty in the number of faint members and their masses causes problems in the determination of the mass-function and therefore also in the potential energy function of the cluster. The difficulties currently existing for fainter cluster members are illustrated by the discrepant results between proper motion surveys of the Pleiades halo and flare star studies (Jones, 1980).

With the improvement of parallax accuracies to a level of 1 to 10 μas the positions of individual stars in a nearby cluster or association can be mapped in 3-dimensions, eliminating partly the need for a selection of members on the basis of proper motions only. Within the area of an open cluster there will always be a few tens of stars (comparable to the number of stars within 10 pc from the sun) that are not cluster members, but simply passers by. These can be distinguished on the basis of their relative space velocity. Assuming radial velocities can be obtained at accuracies of $0.1km/s$, the three positional and three velocity coordinates of each cluster star can be obtained. This also applies of course to all other stars in and around the cluster. Members which are in the process of escaping fast as the result of three body interactions or which are slowly drifting away as the result of interactions with much heavier members can also be located, thus making the reconstruction of the mass function more complete. The improvement of parallaxes will also remove the intrinsic spread in distance moduli which at the moment still confuses the Pleiades HR-diagram with a noise of 0.015 magnitudes.

The space density distribution of the cluster stars can be translated into a potential energy distribution, provided all the mass in the cluster is known. It is thus important that membership probabilities are obtained as far as possible down the mass spectrum. An additional problem, as well as a unique source of information on pre-main sequence stellar evolution, is that the faintest stars of a cluster have often not yet evolved into main sequence objects, causing uncertainties in the mass–luminosity relations. The observed velocities and the potential energy distribution provide an estimate of the total kinematic energy of the star, and thus of the distribution of energy over stars of various masses. Comparisons between different mass-groups should reveal the extent to which exchange of energy has taken place in older systems, or for very young systems, whether there are differences in the energy distribution for stars of different masses that would reflect differences in primordial conditions. This information is supplemented by the energies from the escaping stars, where some of the fast escaping stars might possibly pinpoint the binary system they left behind.

The angular momentum of a cluster star determines the chance of stars paying a visit to the cluster centre, and exchange a little energy. The radial energy determines how frequently this will happen. As was shown by Van Leeuwen (1983) and Terlevich (1984), the angular momentum dispersion for stars in the cluster halo increases with time due to the galactic gravity

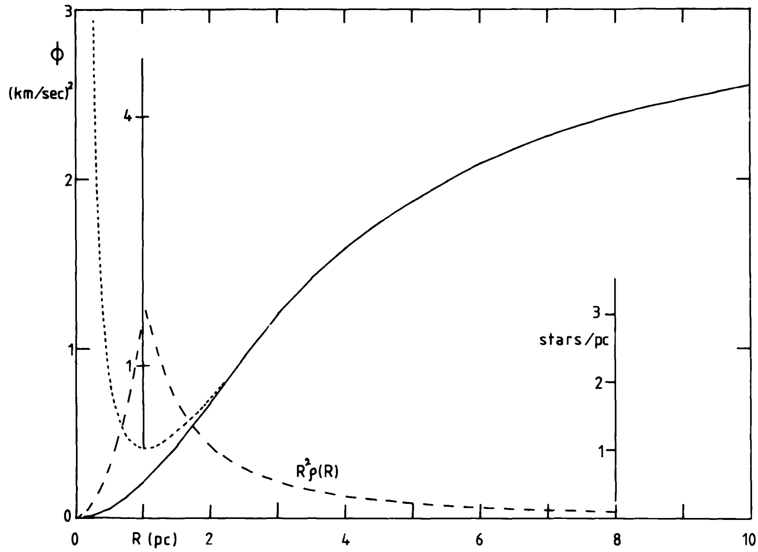

Figure 2. The radial potential energy distribution (dotted line) for a star with a transverse velocity of $0.44 km/s$ at $1 pc$ from the centre in an open cluster of 1000 solar mass, compared with the radial distribution of B and A type stars in the Pleiades (dashed line). The vertical line starting from the minimum of the effective potential energy distribution compares the radial kinetic energy per unit mass with the observed squared velocity dispersion in the cluster centre, $0.49(km/s)^2$ (Van Leeuwen, 1983)

gradient over the cluster. This leads, together with mass segregation in the cluster centre, to under–population of the cluster centre in low mass stars and makes the distribution of these stars, after a while, almost unaffected by short distance interactions with other members in the cluster centre. In this (temporary) state of quasi–equilibrium the observed density distribution of the low mass stars and their observed angular momentum and kinetic energy distribution are related through the potential energy distribution function. The agreement between the potential energy distribution, as derived from the total density distribution and as derived from the faint stars, should indicate whether the total mass distribution in the cluster is determined entirely by the known cluster stars, or whether there is the need for additional (dark) matter.

https://doi.org/10.1017/S0074180900228118 Published online by Cambridge University Press

4. Accelerations

If it were possible to measure the radial accelerations in a star cluster, then the distribution of mass in the cluster could be measured. Figure 2 shows that accelerations (the derivative of the solid line) in the halo of the Pleiades are expected to range up to $10^{-11} m/s^2$ (equivalent to $6 \times 10^{-8} AU/yr^2$). Much higher accelerations will be found close to the centre of the cluster, but these do not reflect the cluster's mass distribution but rather are the result of pericentre accelerations in the stellar orbits.

It can be shown that given observations with positional accuracy σ_p, spanning an interval T and evenly spaced at intervals of Δt, the accuracy of the acceleration measurements approximates:

$$\sigma_{acc} = 13.4 \sigma_p T^{-2.5} \Delta t^{0.5}$$

For a 5–year GAIA mission, this could lead to accuracies of $0.6 \mu as/yr^2$. However, the main gain will be later in the next century, when the full effect of the factor $T^{-2.5}$ is felt. This is similar to the situation that started 100 years ago: the positions in star clusters and associations recorded from that time onwards on photographic plates enable us today to study the kinematics of these systems. A mission such as GAIA or ROEMER can act as a first epoch for the determination of accelerations in the next century and thus lay the basis for direct measurements of masses of stellar systems, in a way comparable to the current use of the earliest photographic plates in studies of cluster dynamics. Until such a project is properly finished, however, the study of the dynamics of star clusters, and to some extent associations also, will depend on the availability of (old) photographic material.

References

Høg, E. (1994) present volume
Jones, B.F. (1980) **Astron.Journ.** 86, 2, p290
Kholopov, P.N. (1971a) **Sov. Astr.–AJ**, Vol 15, No.3, 415
Kholopov, P.N. (1971b) **IBVS** 566
Kholopov, P.N. and Artyukhina, N.M. (1972) **Sov. Astr.–AJ**, Vol 15, No.5, 760
Van Leeuwen, F. (1980) in **Star Clusters**, p157, ed. J.E.Hesser, Reidel, Dordrecht.
Van Leeuwen, F. (1983) PhD Thesis, Leiden University
Lindegren, L. (1993) GAIA proposal for ESA post Horizon 2000 program
Lyngå, G. (1980) in **Star Clusters**, p13, ed. J.E.Hesser, Reidel, Dordrecht.
Mirzoyan, L.V. and Mnatsakanian, M.A. (1971) **IBVS** 528
Mirzoyan, L.V., Mnatsakanian, M.A. and Oganyan, G.B. (1980) in **Stellar physics and Evolution**, ed. L.V.Mirzoyan, Yerevan
Perryman, M.A.C. and Heger, D. (1993) in **ESA Bulletin** No 75, p7
Taff, L.G. (1974) in **Astron.Journ.** 79, 11, p1280
Terlevich, E. (1984) PhD Thesis, Cambridge University
Vasilevskis, S., Van Leeuwen, F., Nicholson, W., and Murray, C.A. (1979) **Astron.Astroph.Suppl.** 37, 333