ASTROMETRY OF STAR CLUSTERS: PROBLEMS, TECHNIQUES, AND OPPORTUNITIES

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The astrophysical problems that can be attacked via proper motions in star clusters are set forth and current techniques and opportunities are described. Cluster membership work continues to progress with recent work mixing plates from various telescopes, including large reflectors. More and better internal motion studies are needed to have a significant impact on the dynamical models. Absolute proper motions of clusters present a very difficult problem, but for globulars, at least, the data are desperately needed.

I. INTRODUCTION

Proper motion work in star clusters probably has a more immediate impact on the rest of astrophysics than any other area of astrometry. This results, of course, from the fundamental importance of star clusters in such studies as stellar evolution, stellar dynamics, and Galactic evolution. The past several years have seen a significant increase in photometry and spectroscopy in star clusters addressing questions of Galactic evolution and of details of stellar evolution. Dynamics in star clusters will be the topic of IAU Symposium 113 in May, 1984.

This paper will deal with some of the current astrophysical problems which can be attacked via proper motion work in star clusters, the current state of relevant astrometric techniques, and some opportunities available because of improvements in techniques over the past several years. No attempt will be made to thoroughly review the literature on proper motions in star clusters. The emphasis will be on studying clusters as such. Thus the critical question of distance scale calibration via the Hyades convergent point and main sequence fitting is only mentioned in passing. A recent review of the Hyades questions can be found in Hanson (1980). One goal of this paper is to encourage more

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cluster proper motion work. The requests from photometrists, spectroscopists, and dynamicists are numerous and the necessary first epoch plates are often readily available.

The advent of rapid, accurate, automatic measuring machines has affected all of photographic astrometry. Cluster studies involving hundreds, or even thousands, of stars on ten or twenty plates are not especially difficult today and the necessary reductions can be done on essentially any modern minicomputer. Machines such as the PDS microdensitometers produce first rate photographic photometry as well as astrometry.

Cluster proper motion work has long been done photographically and this seems unlikely to change soon. Ronchi grating devices are unable to handle the large numbers of stars generally encountered in cluster problems, though one exception to the large numbers will be noted below. Astrometry with CCD's should now be considered a proven technique (Monet and Dahn 1983) but the detector size is simply too small for many cluster problems, though a network of overlapped CCD exposures could cover a small cluster in less telescope time than a single photographic exposure. The overlap reduction may prove to be difficult, but I expect to see this technique used within the next few years. The remainder of this paper will generally assume photographic plates, however.

It is useful to divide what follows into the same three general catagories discussed in Vasilevskis' (1962) fundamental review: cluster membership, internal motions, and absolute motions. In each catagory I will first review briefly the astrophysical questions being addressed, and then discuss the astrometric techniques and opportunities.

II. CLUSTER MEMBERSHIP

The basic goal of astrometric cluster membership studies is the production of a color-magnitude diagram (CMD) with reduced field star contamination. Very often one seeks to confirm (or reject) the cluster membership of unusual stars, presumably those in short-lived stages of stellar evolution. In open clusters these may include pre-main-sequence stars, supergiants, Cepheids or other variables, or blue stragglers. In globulars the stars in question may be UV-bright stars, spectroscopically peculiar giants, variables, or blue stragglers. Spectroscopists interested in faint cluster members often would like membership information before observing to avoid integrating for hours on field stars, but the data are often not available. Questions of the existence and characteristics of cluster halos also generally require membership information, as do luminosity functions.

Cluster membership techniques have recently been applied to two nearby galaxies and more such work is in progress (Stetson 1980; Schommer, Olszewski, and Cudworth, 1981). The purpose, of course, is to clean the CMD's by removing the foreground field stars that could confuse the study of the stellar population of the neighboring galaxy. A resolved galaxy (ie. one in or near the local group) hardly differs from a star cluster as far as astrometry is concerned. One added benefit is that the galaxy being studied will specify a quite good absolute zero proper motion for kinematical studies of the foreground field stars.

Cluster membership studies require only relative proper motions: usually the cluster itself provides the zero point. Standard errors of $\pm$ 0."1 cent^{-1} will yield a fairly good membership segregation for "bright" stars down to m ~ 15. Such errors can be obtained with two plate pairs at a scale of 10"/mm (Yerkes refractor) and an epoch difference of only 10-15 years. At these magnitudes much older plates are often available from various refractors, leading to excellent segregation of cluster- and field stars. At fainter magnitudes, especially at low galactic latitude, more accurate motions are needed to yield good membership information. These precision requirements can be relaxed somewhat for the nearest clusters (eg. Hyades, Pleiades, and Praesepe) since their proper motions are significantly different from the mean of field star motions in their directions. Thus plates from short-focus telescopes are easily usable for the nearby clusters, but can only be useful for more distant clusters if the epoch differences are very long or many plates are available.

An exciting development in this area has been the use of plates from various large reflectors to yield good proper motions. Chiu (1976) derived distortion coefficients for, and combined plates from, the Hale 5-m, Kitt Peak 4-m, and Lick 3-m. Stetson (1980) and Cudworth (Schommer et al. 1981) used Hale 5-m plates as the first epoch and Kitt Peak 4-m as the second in their studies of dwarf spheroidal galaxies to V $\gtrsim$ 20. In these studies blue and yellow plates have routinely been combined. In summary, any plate with reasonably good images is probably usable. This, of course, opens up enormous opportunities. For example, most clusters with published CMD's based on plates taken before ~ 1970 are probably now ripe for membership. The original photometric plates can usually be located and borrowed without great difficulty and new plates can be taken with any telescope of reasonable scale that can reach the desired magnitude limit.

It is best if the selection of images to be measured is not biased by previous knowledge of the CMD or other information. Central overlap reductions (Eichhorn and Jefferys 1971) are preferable to plate pairs and can be handled by nearly any modern computer. In combining plates from different telescopes, and sometimes even those from the same telescope, one must try reduction terms such as color, color magnification, and coma, in addition to linear and quadratic terms in the coordinates and in magnitude. In using plates from the large reflectors one generally pre-corrects the gross distortion and then includes distortion terms in the differential plate constants as well.

Stars with very large motions should be identified via trial reductions and then removed from the first plate constant solution or they will bias the plate constants. Subsequent iterations will not necessarily recover from such initial bias (Cudworth 1976a), though these stars can be included in the star constant reduction.

Since the work of Vasilevskis and his co-workers (Vasilevskis, et al. 1958, Vasilevskis 1962) it has become standard to derive membership probabilities from the proper motions. Sanders (1971) and van Altena and Jones (1972) have introduced automated fitting procedures in the probability solution. Recently, de Graeve (1979) combined the spatial distribution of cluster stars with proper motions to improve the probabilities when astrometric precision is low. While acceptable for cleaning a CMD, such probabilities cannot later be used to study the structure of the cluster. De Graeve also introduced an improved method for treating proper motions of different precision in the probabilitity solution.

This is not the place to discuss photometry in detail, but with "photometric" plates increasingly being used for astrometry, and being measured so as to yield photometry as well as positions, a few remarks are in order. First, photometry from a PDS microdensitometer is better than what was previously available for most clusters. Thus a combined photometric/astrometric study is generally preferable to simply applying membership probabilities to an old CMD. Second, it is the author's experience that photographic photometry is easier to reduce than astrometry.

The number of clusters with useful old plate material is now very large; we need no longer select clusters for study merely because old plates are readily available. We should instead base our cluster selection on the astrophysical importance of the cluster and then seek out the best plates.

III. INTERNAL MOTIONS

Stellar dynamics in open and globular clusters were reviewed by King (1980) and Heggie (1980). The general goal of proper motion studies of internal motions is to test stellar dynamical models and to guide further calculations. If one barely detects the internal velocity dispersion one may only be able to estimate the cluster mass, but we should aim to go further. Questions to address include isotropy or anisotropy of the velocity dispersion and how this varies with radius and stellar mass and with cluster age and cluster mass.

Among open clusters the Pleiades is probably the most studied. The study by Jones (1970) and that by Vasilevskis, et al. (1979) do not agree well regarding the internal motions. McNamara is planning a study of M35 which will address dynamical questions in a cluster of similar age, but more clusters of other ages also need to be studied.

Globulars are probably more similar to one another than are open clusters. The internal velocity dispersion has been detected in several (Cudworth 1980) and anisotropy reliably investigated in two or three. Much more information should soon be available at IAU Symposium 113.

When internal motions in a cluster have been measured via both proper motions and radial velocities one can derive the cluster distance using statistical parallax, independent of any standard candle or main sequence fitting. This requires some evidence for isotropy of the velocity dispersions. To my knowledge this has been done only once, with low precision, (Cudworth 1979), but one or two more are currently in progress.

The astrometric techniques for internal motion studies are simply an extension of those for membership. Relative proper motions are adequate but higher precision is required. The standard errors must be comparable to the velocity dispersion to detect the latter, and smaller errors are obviously required to investigate thoroughly. Open cluster velocity dispersions are generally $\lesssim$ 1 km/sec, corresponding to $\lesssim 0\overset{''}{.}02$ cent^{-1} at 1 kpc. The astrometric problem is essentially the same for globulars, since the velocity dispersions and the distances are both larger by about an order of magnitude.

If the proper motions can be reduced to a non-rotating and non-expanding frame with adequate accuracy one can investigate questions of cluster rotation and expansion. The velocities in question are unlikely to be greater than the internal velocity dispersions discussed above. It is not clear that this has been done reliably for any cluster, but it may be possible to detect rotation of a globular cluster using currently available plate material if several extra-galactic objects can be measured to establish the non-rotating frame. In most cluster studies the plate constants remove most of the rotation or expansion. The field stars, of course, should show no net rotation or expansion, but their proper motion dispersion is large enough that they do not generally define an adequate zero rotation or expansion.

Strand (1958) derived an expansion of the Orion nebula cluster which has been highly controversial. This has neither been confirmed nor thoroughly refuted, though we hope to be able to do so at Yerkes in a few years. We have a set of plates double-exposed on Orion and a control field. The control exposure will be used to monitor expansion (and rotation) due to instrumental effects.

IV. ABSOLUTE CLUSTER MOTIONS

One would like to investigate the kinematics of clusters as a function of age (for open clusters) or metal abundance (for globulars).

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A great deal has been done using radial velocities alone, but more could be done if tangential velocites were also available. While no surprises are likely from open clusters in this regard, some surprising claims have been made of correlations between metal abundance and orbital eccentricity for globulars (Seitzer and Freeman 1981). To investigate this thoroughly will require tangential velocites for a substantial number of globulars. Clearly such questions are crucial in discussions of Galactic evolution. The kinematics of globular clusters can also be expected to yield significant information about the gravitational potential of the Galaxy at large distances from the Galactic center.

This is the primary cluster problem requiring proper motions in an absolute frame. Useful results require tangential velocity errors $\lesssim$ 5 km/sec for open clusters and $\lesssim$ 50 km/sec for globulars ($\sim \pm$ 0″.1 cent^{-1} at 1 kpc or 10 kpc respectively). For some open clusters, the proper motions can be directly tied to the AGK3 or other catalogs. Except for a few nearby clusters, however, the errors of such catalogs exceed the velocities sought. HIPPARCOS observations may yield useful absolute motions for more open clusters. Most open clusters lie in the Galactic plane where there is no hope of tying directly to an extragalactic reference frame, but for many globulars, and some open clusters, one can find galaxies, or better yet, QSO's, in the field. Plates from large reflectors are almost essential to reach faint enough with adequate scale. On these plates the galaxies are often not measurable with high precision but at m $\gtrsim$ 19, QSO's should generally be available. Since one need not measure large numbers of cluster stars or of QSO's for such a project, this may be the place where non-photographic devices are most useful in cluster astrometry.

One can also reduce proper motions to an absolute frame via secular parallaxes of the field stars, if one believes that the secular parallaxes, solar apex, and Galactic rotation are known sufficiently well. In some parts of the sky the uncertainties in such a reduction are small enough to yield a useful absolute motion for the cluster. This situation may be improved when the Lick proper motions relative to galaxies are completed. If one has enough (> 200) field stars one can follow the lead of Murray (1968) and Cudworth (1972, 1976b) in a statistical analysis of the field star motions and photometry which eventually yields a reasonable estimate for the absolute zero point of the motions. Such indirect methods should not be a first choice, but they are worth trying when nothing else is available.

V. CONCLUSIONS

In his review, Vasilevskis (1962) took a pessimistic view of most cluster proper motion work up to that time. Due in large part to his ideas and encouragement, a good deal of high quality cluster membership work has been done in the past two decades, and opportunities for more have multiplied in recent years. Internal motions studies have improved, but additional careful work will be required before proper motions make a really major contribution to dynamical modelling of clusters. Rather little real progress has been made in the area of absolute motions, but here the prospects look encouraging, at least.

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Discussion:

MURRAY: Would it be feasible to use the wide field camera on Space Telescope to study infrared transverse motions in globular clusters?

CUDWORTH: This is strictly a differential problem; van Altena has thought more about this than I have, and I defer to him for an answer.

van ALTENA: There are suggestions that this be done, but the field is very small and it seems one must get enough stars into the field to get good accuracy.

STRAND: I'd like to mention Hertzsprung's measurements of the AC plates of the Pleiades. Those would be worth measuring with better machines and a better computer to determine the internal motions in the Pleiades.

MURRAY: Floor van Leeuwen has carried out an extensive study of Pleiades using old and modern Leiden plates. These results are continued in his Ph.D. thesis.

YE: In China we also work especially on the problem of the membership of the Orion cluster. We would like to exchange material.

de VEGT: If there are cluster members which are radio stars, these could be used to establish a connection between the optical and the radio proper motion systems.