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Astrometry with Schmidt Telescopes for Probing the Galaxy

C. Andrew Murray

12 Derwent Road, Eastbourne, Sussex BN20 7PH, England (formerly at Royal Greenwich Observatory)

Abstract. The use of proper motions and parallaxes for large numbers of stars, obtainable from a combination of Schmidt telescopes and automatic plate scanners, is discussed. The importance of deriving the zero points of both absolute proper motion, and of parallactic motion, is emphasised. Calibrations of proper motion and of parallaxes should be based on dispersions of proper motion. These methods are illustrated by results from a study in the South Galactic Cap.

1. Introduction

More than thirty years ago, the late Professor R. O. Redman of Cambridge proposed the so-called "Schmidt Problem", which was to extract all the astronomical information contained in a photograph taken with a Schmidt telescope. A plate taken with a classical long focus telescope may have some tens, or perhaps several hundreds of images, whereas a Schmidt plate typically contains many thousands. The first solution to this problem was the development by P. G. Fellgett (1970), of a large automatic plate scanner which was known as GALAXY. Being in the days when acronyms had a literal significance, this stood for "General Automatic Luminosity and X Y" measuring machine. Since GALAXY was developed in the late 1960s, technology has moved on and there are now several large scanners in regular use. I do not want to discuss here the relative merits of such instruments, nor the technicalities of data reduction, which vary from instrument to instrument, but rather to concentrate on one particular area for which GALAXY and its successors were devised, namely the study of our own Galaxy from Schmidt plates. In particular I shall discuss some of the galactic problems which can be addressed by means of proper motions and trigonometric parallaxes.

2. Astrometric Data

Any study of the spatial or kinematic structure of the Galaxy depends on data for statistically significant samples of stars over a range of distances, and it is here that the wide field of a Schmidt telescope has the advantage over even the most powerful large telescopes. The accuracy obtainable for individual stars is less important than overall systematic accuracy for large samples.

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Much of what I have to say will be illustrated by an investigation of a region in the South Galactic Cap which was carried out during the 1980s at the Royal Greenwich Observatory, using plates taken with the UK Schmidt telescope on Siding Spring. This work has been described in two papers, Murray, Argyle and Corben (1986) and Murray (1986); for brevity these will be referred to below as SGCII and SGCIII respectively. It was based on two series, 40 unfiltered IIaO plates taken between 1975.0 and 1977.0, and 33 IIa-D plates with a GG495 filter, taken between 1978.6 and 1981.0, all of which were measured on GALAXY.

Schmidt plates are now regularly used for measurement of proper motions (Evans 1989; Reid 1990, 1992; Soubiran 1992; Chareton et al. 1993). It was demonstrated in SGCII that, in addition to obtaining proper motions from a large number of plates extending over only a few years, it is also possible to measure trigonometric parallaxes with moderate accuracy *en masse.*

But the reduction of the raw measurements to give the astrometric parameters, relative proper motion and parallax, for large numbers of stars, is only a first step; these must be reduced to an absolute system. It is also essential to have properly calibrated magnitudes in at least two colours for each star.

3. The System of Proper Motions

Although extra-galactic objects in principle define a standard of rest, they cannot generally be measured with the same accuracy as stars, and there are sometimes too few of them anyway to provide an adequate primary frame. In general, therefore, the data reduction provides proper motions relative to some arbitrary frame and zero point, 0, which are defined by a subset of the stars. It should be remembered that, in addition to defining a zero point, these selected stars fix the systematic characteristics of all the proper motions; for example if they happen to belong to an expanding system, or are perturbed by a few outliers which distort the system, then a spurious "cosmic" dispersion will be introduced into the proper motions. Stars defining the ordinary frame should therefore be chosen with some care.

When a sufficient number of extra-galactic objects have been measured, an estimate of the absolute zero point of proper motions, A, can be obtained directly and spurious cosmic dispersion in the proper motions can be minimized. But even in this case, it is still necessary to derive the zero point of parallactic motion, Z, which corresponds to the local standard of rest in the Galaxy, as defined by the common stars in the solar neighbourhood. As a first approximation, the displacement of Z from A represents a velocity which increases linearly with distance, such as a shear or rigid rotation. In general, the Oort-Lindblad model of differential galactic rotation, as described by Oort's constants A and B, gives rise to such an offset of Z from A; but one of the aims of statistical analyses of proper motions must be to measure both Z and A in many lines of sight, and hence to build up a model of the large-scale motions in our part of the Galaxy.

3.1. Parallactic Motion

By its very nature, solar motion is a somewhat imprecise concept since it depends on the particular selection of stars adopted for its definition. In the century or so following William Herschel's detection of solar motion relative to a few bright

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stars, astronomers sought to refine it by increasing the size of the sample and accuracy of the data. But all such investigations were limited to bright stars observed with meridian circles, and therefore within about a hundred parsecs of the Sun.

A convenient method for analysing proper motions in a Schmidt field is to bin the data according to photometric criteria. For example, in SGCIII Fig. 2, parallactic motion is evident in a large number of bins with $B - V > 0.65$; furthermore, its direction, projected on to the galactic plane, is virtually identical to that of the so-called standard solar motion relative to disc stars in the solar neighbourhood. Evidence for parallactic motion in the standard direction was also found by Evans (loc. cit.) and Reid (1990).

Identifying the parallactic motion vector in the $\mu_x \, \mu_y$ plane is only part of the story. By definition, the point Z must lie somewhere on this vector, but its location depends on calibrating the (linear) scale of parallax along it.

A possible strategy is to assign mean parallaxes to the various bins according to their mean apparent magnitude and colour, that is to assume mean absolute magnitudes to be assigned to each bin, but there are several objections to this. While it is probable that many bins will consist entirely of a homogeneous population of, say, main sequence stars, some will contain a mixture of luminosities, and in any general direction the estimation of mean photometric parallaxes will be complicated by interstellar absorption and reddening. Furthermore, since one of the aims of such an investigation is to determine the luminosity and space distribution of stars using astrometric data, it rather begs the question if one has to rely on mean parallaxes derived from photometry.

An alternative approach is to use dispersion of proper motion as a measure of parallax. Within a bin defined by a reasonably narrow range of colour and apparent magnitude, the proper motion dispersion is independent of zero point and of likely systematic astrometric errors. The calibration depends on assuming that the projected mean solar velocity, $\overline{T}$, and average velocity dispersion, σ_T, are known from stars in the immediate solar neighbourhood. Strictly speaking, one should derive the complete dispersion ellipse of proper motions in a bin, and compare it with the projection of the three-dimensional velocity distribution, but it is sufficient to take the root mean square of the dispersions in the two coordinates. This technique was used with some success in SGCII to define the point Z, although the observed proper motion dispersions of faint stars appeared to be too large. This could be due to an unexplained error contribution, or, as I now think, evidence for increase in velocity dispersion with distance from the galactic plane.

3.2. A "Hyades" Stream?

One unexpected phenomenon, which was found in the proper motions in SGCIII, was a population of stars, with $B - V < 0.65$, which seem to share the parallactic motion associated with the Hyades cluster. Similar, but less striking evidence for such a kinematic group, was found by Reid (1990) near the North Galactic Pole. It has long been recognised (Eggen 1958) that there are stars in the solar neighbourhood which appear to share the motion of the Hyades. That these might extend to several hundred parsecs was suggested some years ago (Murray, Dickens & Walker 1969) by the discovery that the motion of an anonymous galactic cluster of similar age to the Hyades, projected on to the Large Magellanic Cloud (Bok & Bok 1960), also had the same motion.

This illustrates a cardinal principle which should govern all investigations such as the present one, namely that one should look not only for what one expects to find, but also be prepared for the unexpected.

3.3. Shears in the Velocity Field

As has already been remarked, if sufficient extra-galactic objects, galaxies or quasars, have been measured, the absolute zero point of proper motions, A, in the $\mu_x\,\mu_y$ plane is readily determined. This is not always the case. In low galactic latitudes, for example in the galactic anti-centre direction (Chareton et al. loc. cit.), no galaxies were found because of interstellar extinction. In SGCIII the absolute zero point, A, had to be derived indirectly by assuming kinematics of faint stars, which clearly did not partake of the standard parallactic motion.

According to the Oort-Lindblad model, in the directions of the galactic poles the points Z and A should coincide. But in SGCIII a significant offset of Z from A was found; this was explained by postulating a shear in the velocity field in the direction of galactic rotation of about −36 km/s/kpc. A similar shear was found by Evans (loc. cit.) who, however, obtained a smaller value of −21 km/s/kpc. In his work in the North Galactic Cap, Reid (1990) found a shear of −17 km/s/kpc, but not exactly aligned with galactic rotation. As he rightly pointed out, the precise evaluation of the shear depends very critically on the determination of the proper motion zero point.

Recently, Guo et al. (1993) have determined the absolute proper motion relative to galaxies of the globular cluster NGC 288. Since the proper motion of this cluster was also measured in SGCIII, we can use this new result to re-determine the proper motion zero point. With this revision, the shear in the direction of the south Galactic Cap reduces to −23 km/s/kpc in the direction of galactic rotation but with a significant component in the orthogonal direction.

But it is premature to argue about precise numerical values at the present time. My point is that we have here an example of a kinematic phenomenon which is additional to the Oort-Lindblad model, although its description as a linear shear may well be oversimplified. Furthermore, it is entirely reasonable that an increase in velocity dispersion will be associated with larger mean velocity, which is exactly what is seen in the excess proper motion dispersion of faint stars.

4. Trigonometric Parallaxes

For much of the present century, the measurement of trigonometric parallaxes has been something of a black art, practised in a very few observatories. Although great improvements in accuracy over photographic plates have recently been obtained with the use of CCDs, the numbers of stars for which parallaxes have been measured from the ground is still only a few thousand. The situation will soon be greatly improved when the final results of the HIPPARCOS programme become available. But in all ground-based programmes the stars for which parallaxes are measured have to be pre-selected, primarily on size of proper motion. Thus any attempt at statistical evaluation of parallax samples is bedevilled by selection effects. One of the aims of SGCII was to test whether parallaxes with moderate accuracy could be measured for a large number of stars simultaneously. Only in this way would it be possible to detect nearby stars having small proper motions.

It is clearly desirable in principle to choose epochs of observation for which the parallactic shift is extreme, in order to maximise the displacements to be measured. In the case of SGCII this meant taking plates at large hour angles, on opposite sides of the meridian for the "morning" and "evening" exposures. This broke one of the cardinal rules for classical parallax observations, that all plates should be taken close to the meridian in order to minimise differential effects of refraction and instrument flexure. Furthermore it was clearly not possible to introduce compensation for images of stars of different magnitudes.

Thus the raw parallax measurements must be regarded as strictly relative, not only in respect of an arbitrary overall zero point, but also within restricted bands of magnitude and perhaps also colour. In SGCII a satisfactory calibration of the parallaxes was obtained by comparing the bin means with the corresponding mean kinematic parallaxes obtained from the parallactic motions (SGCII Fig. 3).

The formal errors of the parallaxes ranged between $\pm 0.012''$ and $\pm 0.017''$, according to magnitude, and are comparable with those obtained from measurements made in the large classical pre-war programmes in the first half of this century. These internal errors are satisfactorily confirmed by probability plots of the actual parallaxes in various magnitude and colour ranges (SGCII Fig. 5).

There were no real surprises among the individual parallaxes. The only two stars in the field for which parallaxes had previously been measured were duly recovered, and there were one or two possible candidates within 25 parsec, for which further observations are desirable. This rather negative result is reassuring in suggesting that our knowledge of the population in the immediate solar neighbourhood is not seriously incomplete, but clearly much more work along these lines needs to be done.

5. Absolute Magnitudes and Space Density

In any field we can in principle obtain apparent magnitude, colour index, proper motion and even trigonometric parallax, for very large samples of stars. These data contain much useful information on the distribution of stars along the line of sight, and in luminosity. In SGCIII, the data were divided into bins defined by bands of colour index and ranges of apparent magnitude within each band. The adopted statistical model consisted of an exponential distribution of distance r with scale parallax p, a Gaussian distribution of transverse speed T, with mean $\overline{T}$ and dispersion σ_T and a Gaussian luminosity function with mean $\overline{M}$ and dispersion σ_M

Assuming values of $\overline{T}$ and σ_T in each bin, the likelihood function for the joint distribution of the observed total proper motion, μ_*, parallax, Π_*, and apparent magnitude, m, was maximised to give p, M and σ_M.

The various bins of colour and apparent magnitude were analysed in three main groups, according to the assumed values of the kinematic parameters. The majority of bins were presumed to be dominated by stars with the disc velocity

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distribution, $\overline{T} = 3.93$ AU yr^{-1} and $\sigma_T = 5.04$ AU yr^{-1}, and for a few bins, containing suspected members of a Hyades stream, $\overline{T} = 9.17$ AU yr^{-1} was adopted. The third group was assumed to have halo-like kinematics, $\overline{T} = 45$ AU yr^{-1} and $\sigma_T = 30$ AU yr^{-1}.

5.1. High Velocity Stars

Some of the most interesting stars are those which do not fit the majority population in any bin, primarily because of abnormally large proper motion. Nearly a hundred were identified relatively easily in plots of the logarithm of the likelihood for each star versus apparent magnitude (e.g. SGCIII, Fig. 1). Spectroscopic observations of 63 of these stars have been made subsequently by Reid, who showed them to be mostly halo subdwarfs with a few metal rich high velocity stars (Reid & Murray 1992).

5.2. Colour-magnitude Diagram and Luminosity Function

This analysis is fully described in SGCIII. The results are illustrated in a colour-magnitude diagram (SGCIII Fig. 3) and luminosity function (SGCIII Fig. 9). The agreement between $\overline{M}_v$, B−V derived for the various bins, and the standard main sequence and old disc giant branch, is very satisfactory. Also, apart from obvious selection effects among the bright and faint stars, the observed luminosity function is consistent with that obtained from nearby stars. Furthermore, the average scale height found for the disc stars, 311 ± 7 parsec, is very reasonable. All this evidence suggests that the hypotheses underlying the analysis are basically correct.

6. Summary

In this paper I have attempted to indicate the rich harvest which can be reaped from a detailed examination and analysis of astrometric data obtainable now from a combination of Schmidt telescopes and automatic plate scanners.

Careful analysis of the proper motion zero points in many different directions can extend to three dimensions the two-dimensional Oort-Lindblad model of the motions in the galactic plane. Dispersions of proper motions can be used as indicators of distance which are independent of any assumptions about absolute luminosities.

One should always be on the alert for possible deviations from expected kinematic behaviour, such as the suspected Hyades stream. Similar phenomena within the immediate solar neighbourhood have been known for many years, but if they can be shown to exist on a larger scale they could provide important clues to the evolution of the Galaxy.

Furthermore, the large number statistics which can be obtained from Schmidt plates give a good chance for serendipitous detection of minority objects such as subdwarfs and stars having large parallax but small proper motion.

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Over a number of years I have had interesting and useful discussions on these topics with Dr Neill Reid and Dr Dafydd Evans, to both of whom I am most grateful. In particular, the follow-up observations and discussion of the high velocity stars in the South Galactic Cap were entirely due to the initiative of Dr Reid. Finally I would like to thank Dr R. D. Cannon and the organisers of this Colloquium for making it possible for me to attend; additional thanks are due to Dr Cannon for helping in the selection of the field for the SGC investigation some twenty years ago, when he was in charge of the UK Schmidt Telescope.

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Discussion

Cannon: It has always seemed to me that there must be very strong arguments for repeating what you did at the South Galactic Pole in several more fields. Can you comment on that? Is progress limited by the telescope time required, the work involved in measuring the plates or the subsequent analysis of the data?

Murray: I would certainly like to see this work repeated in more fields. I seem to recall that plates on at least one other UKSTU field were measured on GALAXY, but the continuation of the programme became a casualty of the demise of GALAXY and the move of the RGO. Plate measurement on GALAXY was a long process. Each Schmidt plate was measured in two opposite orientations, and each measuring run took almost twelve hours. Modern plate scanners would probably be much faster than this, but I do not have experience of them and so cannot comment further.