THE RELATIONSHIPS BETWEEN VARIOUS TECHNIQUES FOR OBTAINING PROPER MOTIONS

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1. Introduction

In many problems of galactic kinematics we need to know the proper motions of faint stars, as well as bright stars, within some well-defined reference frame. Generally speaking, the accuracy required is greater for faint stars on account of their larger distances. Techniques at present used for determining proper motions vary according to apparent magnitude, and it is clearly desirable that all methods should give results which are capable of reduction to a common frame.

2. Fundamental Proper Motions

Approximations to an absolute frame of reference are given by proper motions derived ultimately from long series of meridian observations, as e.g. the FK4 and its extension to intermediate magnitudes, the AGK3. It is important to remember, however, that, apart from their own peculiar systematic errors, all catalogues of fundamental proper motions depend on a conventional value of the constant of precession which, with the motion of the equinox, can at present only be derived by making assumptions about the systematic motions of stars. This may not have much importance in discussion of stellar motions in the immediate solar neighbourhood ($\sim$100 parsec, say), but it becomes increasingly significant at larger distances.

3. Extragalactic Reference Frame

We have already seen the preliminary results from the KSZ programme, and within the next few years we can hope to see also results from the Lick programme, for referring fundamental proper motions to extragalactic nebulae.

In principle the Lick programme (Wright, 1950) should enable the systematic errors in the AGK3 proper motions outside the galactic zone, and also the precessional motions, to be determined directly without any appeal to stellar kinematics. However, it will be several decades before the Southern extension of the programme, now being carried out by the Yale-Columbia Southern Observatory at El Leoncito, will enable the whole sky to be covered.

In the KSZ programme (Dejč, 1954) the systematic motions of reference stars at

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m_{pg}14–15 will be measured relative to galaxies at the same apparent magnitude, and also relative to KSZ stars for which fundamental proper motions on the FKSZ system will be known. Interpolation between fields containing galaxies and fields centered on KSZ stars will be achieved by making statistical assumptions about the average proper motions of the reference stars. While the KSZ programme is not as fundamental as the Lick programme for determining precession and errors in the fundamental system of proper motions, it will give valuable information about the motions of the reference stars themselves relative to the frame of reference defined by the galaxies.

4. 'Kinematic' Reduction to Absolute Proper Motion

An alternative method for deriving absolute proper motions is to assume a model of galactic kinematics from which the systematic motion of any particular selection of reference stars can be predicted. There is a natural tendency among fundamental astronomers to regard this 'kinematic' method as a regrettable second-best. Its importance, however, lies in the fact that, for magnitudes fainter than about $m_{pg}=13$, it is the only generally practicable method. Furthermore, it will still have to be used at brighter magnitudes over much of the sky, until the results of the current large-scale photographic and meridian programmes become available. The characteristics of the kinematic model have to be derived from assumptions about stellar motions, and in this sense the kinematic method is no less 'fundamental' than the fundamental method itself.

It is in principle possible to measure absolute proper motions in any field directly with respect to extragalactic objects, provided that a sufficient number of these can be identified and measured. But at $m_{pg}=16$, the average apparent magnitude of galaxies to be measured in the Lick programme (Vasilevskis, 1953), there will be far too few measurable galaxies in fields of the order $1° \times 1°$, even outside the zone of avoidance. In larger fields, and at fainter magnitudes, such as in Luyten's repetition of the Palomar Sky Survey plates (Luyten, 1963), it may well be possible to use galaxies directly as reference objects; but in general, for faint objects photographed with long-focus telescopes, we shall always need to rely on kinematic methods of reduction. It is, therefore, an important task for fundamental astrometry to provide the data necessary for application of the kinematic method.

The parameters required for the kinematic method can be obtained either from fundamental proper motions alone (solar apex, secular parallaxes), or from an assumed solar motion, together with mean parallaxes derived from a comparison between relative proper motion dispersions and a velocity model derived from radial velocity observations, as first proposed by Oort (1936), and later improved by Binnendijk (1943). As Clube has recently pointed out (1966), this latter approach can in principle lead to a proper motion system which is virtually independent of any fundamental system, provided that sufficient radial velocity and spectroscopic data are available for the construction of the velocity model. At the present time, radial velocity data for stars fainter than about $m_{pg} = 9$ are very scarce, and the model has to be built up from an extrapolation from bright star observations, with assumptions about the average population of stars at a given apparent magnitude. The model may well be adequate down to $m_{pg} \approx 12$, but at fainter magnitudes there is likely to be an increasing number of distant halo stars, such as was found in the field of M 67 (Murray, 1968), which will affect the mean proper motions, and dispersions. For this reason, any further extrapolation is dangerous.

In addition to the parallactic motion, we also need to know systematic motion of the centroid of any selection of reference stars due to differential galactic rotation, and to the total rotation of the co-ordinate system arising from the circular velocity of the 'local standard of rest'. The differential rotation is usually allowed for by adopting a value of Oort's constant, A, which can be determined satisfactorily from radial velocities; higher-order approximations can also be obtained, in principle, from radial velocity observations of very distant objects. The total rotation on the other hand, corresponding to Oort's A-B, is more difficult to determine. In theory it can only be obtained from absolute proper motions, with assumptions about the systematic motions of stars, but Clube (1966) has argued that a value can be assigned to it, within tolerable limits, from the radial velocity of the Sun relative to very old objects in the Galaxy, and relative to the galaxies in the local group.

Oort's constants are frequently obtained from the motions of early-type stars, and A-B derived in this way must represent the rotation of the extreme Population-I system. On the average, however, reference stars in any particular field will be older, and it is therefore important to determine the appropriate parameters representing rotation and differential rotation for these older stars.

5. Accuracy of Fundamental and Kinematic Reduction to Absolute Proper Motion

With the publication of AGK3, the Northern hemisphere will have a network of stars down to $m_{pg} \approx 11$ whose fundamental proper motions will be known with a mean error of $\pm 0\overset{''}{.}008/a$ (Dieckvoss, 1960). This will be entirely adequate for deriving proper motions from Astrographic Catalogue plates. However, when we consider fields photographed with long-focus telescopes, of the order of $1° \times 1°$ say, we can only expect an average of 9 AGK3 stars; in some fields there will be rather fewer. The reduction to the FK4 system at the centre of a $1° \times 1°$ field will thus have a statistical error of about $\pm 0\overset{''}{.}003/a$ or worse.

The accuracy attainable in the kinematic method depends partly on the cosmical dispersion of the proper motion of the reference stars which, at $m_{pg} = 11$, is roughly the same as the mean error of AGK3 stars (e.g. Vyssotsky, 1954) over much of the sky. At this magnitude, the formal accuracy of the two methods is therefore similar, but in the kinematic method it may always be possible to measure more stars in any particular field. The real errors may, however, be much larger than this on account of imperfections in the assumed kinematic model. The usual assumption of a unique solar apex and velocity, applicable to all stars, is, of course, over-simplified; but as long as we have no independent spectroscopic or photometric information for the reference stars, there seems to be no real justification for a more complicated model.

Vyssotsky and Williams (1948) have shown clearly that the direction to the solar apex varies over more than 20° for different spectral types, at both bright and intermediate magnitudes, due to systematic variation of mean orbital eccentricity (*ibid.*, p. 51) or age. This uncertainty in the apex can introduce a systematic error of up to $''\!.007$/a in proper motions referred to high-latitude stars with a centennial secular parallax of 2″.

It has been claimed by Clube (1966) that the mean error of an absolute proper motion derived by the kinematic method from about 20 reference stars with $10 < m_{pg} < 12$, is about $\pm''\!.005/a$. For some problems, e.g. study of the kinematics of RR Lyrae stars at distances of the order of 1 kpc, this accuracy is sufficient, but there are many problems, such as the motions of distant clusters and Population-I objects, for which it is quite inadequate.

It goes without saying that if one requires higher accuracy one must be prepared to pay the price by measuring more stars. However, with modern techniques of measurement and computation this is quite feasible. The systematic errors introduced by imperfections in the kinematic model cannot of course be eliminated merely by increasing the number of reference stars, but they may be appreciably reduced if accurate two-colour or spectroscopic data are available. A recent study in the field of M 67, carried out at Herstmonceux, has shown that an accuracy of at least $\pm''\!.002/a$ can be obtained without any *a priori* assumption about the solar apex (Murray, 1968).

6. Future Requirements and Programmes

A task for the immediate future is the improvement of our knowledge of the kinematics of stars so that a more satisfactory kinematic model can be built up.

In the first place, the publication of AGK3 will make available the proper motions of 180000 stars, albeit only in the Northern hemisphere. This is six times the number of stars in the two McCormick catalogues, discussed by Vyssotsky and Williams, on which so much of our present knowledge of kinematics of stars down to $m_{pg} \sim 12$ is based. It will provide an unrivalled source of data for kinematic studies, which will be even more valuable when the data from current Southern hemisphere programmes become available.

The KSZ and Lick programmes will give important information on the systematic motions of fainter stars, relative to the extragalactic frame of reference. On account of the relatively small scale and short baseline, however, the accuracy of some of the individual proper motions relative to nebulae measured at Lick will only be about

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$\pm 0''.007/a$ (m.e.) after 20 years (Vasilevskis, 1953). This is greater than the intrinsic proper motion dispersions of many classes of faint stars, so that for more detailed studies of the dispersions it will be necessary to supplement the Lick data with more accurate relative proper motions.

Much observational material is available for deriving very accurate relative proper motions in the Northern Kapteyn Selected Areas. The mean error of an individual proper motion from a combination of the Radcliffe (Knox-Shaw and Barrett, 1934) and Pulkovo (Dejč, 1940) catalogues is about $0''.004/a$. But even the second epoch of the Radcliffe catalogue is now about 40 years old, and a repetition of the whole Radcliffe material now would increase the weight of the proper motions by at least a factor of 20. The Radcliffe refractor, and plates, are at present at the University of London Observatory, but it is unfortunately impracticable to repeat the whole programme on this telescope. However, the 26-inch refractor at Herstmonceux is a very similar instrument, and recent tests have shown that plates taken simultaneously on the two telescopes give systematically the same results over at least four magnitudes. It is planned to repeat the bulk of the Radcliffe plates at Herstmonceux, but to have a selection taken at London; in this way it should be possible to control any systematic errors existing now between the two telescopes. The repetition of the Radcliffe material is being supplemented from plates obtained over 50 years ago on the 26-inch refractor at Greenwich, for photometry; most of the Northern areas were covered, and repetition of these plates is nearly complete.

It will be several years before we have the results of all these observational programmes, but we can expect that with the increasing use of automatic and digitized measuring equipment, it will be possible to complete fairly rapidly the large amount of measurement and computation involved.

We can confidently hope that, within the next decade, we shall have far superior data on stellar motions than has hitherto been available, for the determination of absolute proper motions of faint stars.

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