PROPER MOTIONS WITH RESPECT TO GALAXIES

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Abstract. The Lick proper motion program with respect to galaxies is summarized. The subject of extragalactic astrometry is introduced with estimates of proper motions for selected members of the Local Group of galaxies and more distant systems. The problems of measuring proper motions for the Magellanic Clouds is described in more detail.

I. INTRODUCTION

The subject of proper motions measured with respect to galaxies, taken with its broadest implications, promises to become a vital part of optical and radio astrometry through the rest of the present century and continuing forward into the twenty-first century. Traditionally the term has referred to conventional wide-field photographic techniques, such as currently being conducted at Lick, Yale, and other observatories. However, the broader view takes account of the probability of future measurements of the nearer extragalactic systems referred to still more distant objects conducted at the submilliarc second per year level by new techniques, some of which are now in developmental stages. This report considers some of the exciting problems of extragalactic astrometry without being restricted by the practical questions of exactly how the measurements will be made. The observational facilities provided by the Hubble Space Telescope will likely contribute strongly to programs of extragalactic astrometry.

II. GENERAL PROPER MOTION PROGRAMS WITH RESPECT TO GALAXIES

At present there are two major Western proper motion programs for the measurement of galactic stars using faint galaxies as a quasi-inertial reference frame (Vasilevskis 1973). These include the Lick Northern Proper Motion (NPM) Program and the Yale (with National University of San Juan, San Juan, Argentina) Southern Proper Motion (SPM) Program. The upcoming repetition of the Palomar Schmidt Sky Survey and its astrometric potential is noted here, as well as the future value of the southern hemisphere Schmidt surveys. In addition, there is the broadly-based Soviet program involving numerous collaborating institutions.

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The Lick NPM and Yale SPM complement one another in that the NPM treats the northern sky from declination +90° to -23° (with Southern Supplement to -33°), while the SPM extends from -90° to -17° with partial sky coverage to about +20°. Both programs make use of 0.5-m double astrographs with similar blue lenses and identical yellow lenses (Vasilevskis 1964), which cover fields 6° x 6° to blue magnitude about 19, with astrometrically usable images 1-2 magnitudes brighter. The exposure information and pattern of field centers, which is shared by both programs, is given by Shane and Wirtanen (1967). Currently, the work of the Lick NPM program is being carried out by Jones, Klemola and Hanson. The present report represents this joint effort.

The core of the NPM program is defined by an input catalogue of 40-50 thousand stars of special interest selected from the literature on the basis of probable astrophysical or kinematical interest (see Tables III and IV in Deutsch and Klemola 1974). Included also are photometric standard stars, bridge stars (magnitude 10-13) to attach the system of short exposure to the long one, and faint anonymous stars (magnitude 13-17) for computing relative proper motion plate constants. Up to 100 faint galaxies (magnitude 15-18) are measured on each plate for the zero-point correction of relative to absolute proper motion. All classes of selected stars will be available for studies of stellar motions and statistical luminosity calibrations where appropriate.

Second-epoch photography is complete for 93% of the 1246 fields down to declination -23°. Measurements, currently restricted to the 75% (908 fields) of the sky outside the Milky Way, are completed for about 650 fields in the declination band -3° to +73°. Reduction programs are approaching final versions and will be applied to the measured fields.

Some idea of the internal errors can be gained from comparison of results from faint stars (magnitude 14-17) and galaxies measured on overlapping plates. In Table I, prepared by Hanson, we note that epoch differences extend from under 20 years to over 35 years. Moreover, we note the steady decline in mean error for centennial proper motion of a single star, amounting to 0".1/century for each five year increment in epoch difference. For a mean epoch of 28 years for the NPM program, we expect an overall internal error of 0".5/cent for faint stars. This figure does not consider the possible degradation in accuracy for brightest stars at magnitude 7-9, which are far removed from the magnitude of the reference galaxies and may also suffer from blending effects with the nearby overexposed long-exposure images.

Table I. Mean Errors for a Single Star in Lick NPM Program

Epoch Difference (years)	20	25	30	35
Mean Error ("/cent)	0.7	0.6	0.5	0.4

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The formal uncertainty in zero-point correction, defined by the galaxies on a single plate, is about 0".2/cent for average epoch difference approaching 28 years, as found by Hanson from a study of galaxies on overlapping plates. Extrapolation of these mean errors as well as those in Table I to an epoch difference of fifty years, corresponding to the year 2000, emphasizes the growing value of the Lick NPM program plates in the future.

III. EXTRAGALACTIC ASTROMETRY

The subject of transverse motions of stellar systems lying beyond the boundaries of our galaxy has received scant attention. However, with increasing attention being devoted to experiments in the technological basis of ground- and space-based measurements, in both optical and other parts of the electromagnetic spectrum, it is becoming valid to explore hitherto ignored or vaguely discussed applications. Conceptually these applications are simple and direct but so far have been unattainable because of the smallness of the expected proper motions and faintness of the extragalactic stars and reference objects. In particular we consider the feasibility of measuring proper motions for the nearest galaxies, starting with the nearby Magellanic Clouds and then galaxies at larger distances.

Measurement of proper motion of a galaxy requires the selection of some specific members to represent its motion as a whole. This means identifying stellar or near-stellar objects or essentially point-like radio sources as members of a galaxy. It appears that remote near point-like objects, like the QSOs, will provide the operationally-defined reference frame. Although the distribution of QSOs with apparent magnitude is still somewhat uncertain, it appears that by magnitude 23 the extragalactic objects, which include a significant QSO component, constitute most of the observed background at higher latitudes (Shanks 1983). Other than for the nearer members of the Local Group of galaxies, the remainder of the applications described here must be relegated to the domain of twenty-first century astrometry.

1. Members of the Local Group of Galaxies

The question of proper motions of galaxies has come up on various occasions since their recognition as a class (see, e.g., Shapley 1943). With astrometric technology undergoing developments directed to measurements made eventually at the submilliarc second level, it seems worthwhile to expand our discussion to include motions of the nearer galaxies. As a guide to planning possible future measurements, Table II contains computed values of proper motions for a standard value T=100 km-s^{-1} for the tangential velocity. This corresponds to the observed peculiar motions, which are in the low hundreds of kilometers per second. Since internal motions lie at the low tens of kilometers per second level, the table may also serve as a guide for planning such programs if the listed motions are diminished by one order of magnitude.

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Table II. Computed Proper Motions for Selected Members of Local Group

Galaxy	r (Ref) kpc	P ("/cent)$_{T=100\ km\text{-}s}^{-1}$	Galaxy	r (Ref) kpc	P ("/cent)$_{T=100\ km\text{-}s}^{-1}$
LMC	52 (1)	0".041	NGC 147	570 (8)	0".004
SMC	59 (1)	0.036	NGC 185	570 (8)	0.004
UMi	63 (2)	0.034	NGC 205	651 (9)	0.003
Draco	76 (3)	0.028	NGC 211	651 (9)	0.003
Sculptor	78 (4)	0.027	M31	651 (9)	0.003
Fornax	150 (5)	0.014	IC 1613	760 (10)	0.002
Leo I	230 (6)	0.009	LGS 3	900 (11)	0.002
Leo II	230 (6)	0.009	M33	1100 (12)	0.002
NGC 6822	400 (7)	0.005			

(1) McNamara and Feltz (1980)
(2) van Agt (1967)
(3) Stetson (1980)
(4) Kunkel and Demers (1977)
(5) Verner et al. (1981)
(6) Sandage (1961)
(7) van den Bergh and Humphreys (1979)
(8) Abell (1969)
(9) de Vaucouleurs (1978)
(10) van den Bergh (1979)
(11) Christian and Tully (1983)
(12) Sandage (1983)

The galaxies listed in Table II fall into three groups on the basis of expected proper motions. The five nearest galaxies, comprising LMC, SMC, LMi, Draco, and Sculptor, present the most promising chance for successful measurement of proper motions. Their computed motions are 0".03-0".04/cent, which is within the capability of current photographic astrometric measurements, such as those of Chiu (1980) and Cudworth (1979). The Fornax, Leo I, and Leo II dwarf galaxies form a middle group with motion 0".01/cent, which is at the limit of current measurements. The remaining galaxies form a third group representing a much more difficult level of astrometric measurements for the future.

Both the high degree of resolution into stars and the presence of background galaxies is evident on photographs of the UMi (van Agt 1967), Draco (Stetson 1979, 1980), Sculptor (Kunkel and Demers 1977), Fornax (Demers and Kunkel 1979; Verner, et al. (1981), and IC 1613 (Volders and Högbom 1961; van den Bergh 1979) dwarf galaxies. In fact, van den Bergh (1979) notes that IC 1613 appears projected onto a fairly rich cluster of galaxies. It appears that an extragalactic reference frame can be identified for most of the members of the Local Group of galaxies, if visibility of galaxies is regarded as a measure of detectability of QSOs.

The Sculptor dwarf galaxy offers a particularly important test of recent developments in dynamical astronomy by Innanen and Papp (1979), which concerns the stability of stellar motions to a distance beyond the nominal tidal radius, if the orbital motions for the outer stars are retrograde to the rotation of the spherical galaxy. The Sculptor dwarf galaxy has outlying RR Lyr stars which may possess the expected

retrograde orbits, with Keplerian velocities up to 10 km-s^{-1}. This velocity translates into a proper motion of 0".002/century.

The high degree of resolution of both M31 and M33 make these objects interesting for future astrometric measurements. Surveys for faint blue objects (Richter and Meinunger 1972; Richter 1974) and compact galaxies (Sharov 1974) in the halo of M31, which extends up to 9° (Sargent et al. 1977; also de Vaucouleurs and Ruta 1978), deserve examination for QSOs useful for defining the astrometric reference frame. The astrometric frame appears well defined for M33, where a density 200 galaxies per square degree to magnitude V=19.8 is noted in one field (Christian and Schommer 1982).

2. Outside the Local Group of Galaxies

Although the large distances for galaxies beyond the Local Group point to small proper motions, the observed dispersion of peculiar motions of $\pm$650 km-s^{-1}, derived from measurements of radial velocities for galaxies with redshifts less than 0.03 (Gross 1977), makes it useful to consider briefly the level of expected proper motions. A distance-limited full-count sample of 179 galaxies to 10 mpc, compiled by Kraan-Korteweg and Tammann (1979), is useful as a starting point for estimating the expected level of proper motions. A large fraction is resolved into stars (see, e.g., Hubble 1936). At a distance of one megaparsec a tangential velocity of 650 km-s^{-1} corresponds to a proper motion of 0".014/cent, while at the limit of the sample at ten megaparsecs the motion is only 0".0014/cent.

The sample also includes the Sculptor Group with at least seven members, as the closest group of galaxies to the Local Group. Its basic properties include distance of 3.0 mpc, radial velocity of mass centroid of 224 km-s^{-1}, and r.m.s. velocity dispersion of 149 km-s^{-1} (Lewis and Robinson 1973). If we assume a tangential velocity comparable to the radial component, we compute proper motion of 0".0016/cent, also placing this system in the microsecond of arc category.

It is illuminating to consider one case of a still more distant extragalactic system, such as the Virgo cluster of galaxies at a distance of 20 mpc, with mean redshift near +1100 km-s^{-1} and range +500 to +1500 km-s^{-1} (Fig. 1 in Sulentic 1977). Using the mean radial component for its tangential motion, we compute a proper motion of 0".001/cent, and a total range of internal motion of comparable value for the members. Similar calculations may be made for other clusters of galaxies as needed. Clearly these are astrometric programs for the twenty-first century.

Although we are not concerned here with the details of the required measurements, it appears likely that the Hubble Space Telescope will play an important role in the problems of extragalactic astrometry to very faint levels of magnitude for at least the nearer systems.

3. Special Case of the Magellanic Clouds

Early astrometric consideration of the Clouds (Hertzsprung 1920, 1923) and measurements (Luyten 1928a, 1928b; Woolley 1963, 1965), demonstrate the value of continued measurements for relative proper motions as a means of complementing current objective-prism spectral and radial-velocity surveys employed to the similar purpose of segregating Cloud members from galactic field stars and for kinematical studies of the stars themselves. Valuable early plate collections certainly exist in various observatory files, which are suitable for astrometric measurements.

The measurement of the proper motions of the Clouds against the extragalactic reference frame represents a most valuable venture, permitting the study of the kinematical history of the Magellanic Clouds and their possible interactions with our galaxy. The measured motions should contribute to the eventual resolution of several problems: (1) orbits of the SMC and LMC, (2) possibility that the Clouds are breaking up, (3) the existence of the Galactic halo, (4) the origin of the Magellanic Stream, (5) account for observed structural features and deformations resulting from possible tidal interactions, and (6) mass of our galaxy.

Recent studies provide guidelines as to the feasibility of measuring proper motions of the Clouds. These provide estimates of direction (Feitzinger et al. 1977) and value of 0".2/cent (Lin and Lynden-Bell 1982) for the proper motion. Although this is a small motion, it lies within current abilities of photographic astrometry, provided that a suitable reference frame can be identified. Some of the most precise proper motion measurements based on long-focus telescopes, such as the works of Chiu (1980), Cudworth (1979), Stetson (1980), and some trigonometric parallax series, show that very small errors can now be reached which are almost an order of magnitude smaller than required for the Clouds. Let us consider possible approaches to the problem of measurement of absolute proper motions.

The brightest member stars start at V=9.8 for the LMC (Mendoza 1970) and at V=10.2 for the SMC (Mendoza 1970; Osmer 1973). Although stars from the FK4, N30, GC, and SRS catalogues are found on or near the Clouds, none are members. Even if fundamental stars could be attached to the Clouds, there is question whether the FK5 system can be defined to the required 0".05/cent level or less for this part of the sky.

Although the brightest stars lie within the expected faint limit of the Hipparcos Astrometry Satellite program, the problem of interference by bright stellar neighbors may be one limiting factor for arriving at proper motions for Cloud members. Feitzinger (1980) compares the nominal error of 0".2/cent with his estimated motion of 0".03-0".05/cent for the Clouds. Hubble Space Telescope observations will depend on identification of suitable QSOs for measurement of motions for fainter members.

The photographic technique of measuring fainter Cloud members against an extragalactic reference frame defined by faint galaxies and QSOs offers promise for measuring proper motions. Surveys for the distribution of background galaxies in the fields of the Clouds (Shapley 1951, 1957; Hodge 1974, 1977; Hodge and Snow 1975) provide a guide to selection of useful fields. This author has examined deep Michigan Schmidt plates of the Clouds taken at CTIO, kindly loaned by Dr. Merle Walker. For the LMC the band lying west of right ascension 4^h40^m between declination -65° and -72° (1975) is most promising for abundant faint galaxies. This band deserves attention for surveys for QSOs. For the SMC the region of the outlying cluster NGC 121 offers moderately rich background galaxies. These regions lie within the halos of the Clouds, as defined by de Vaucouleurs (1955), Brück and Marşoğlu (1978), Tifft (1963), Brück (1980), and Stryker, et al. (1981).

A program is in progress at the Lick Observatory which has as its goal the measurement of the absolute proper motion of stars in the halo of the SMC using faint galaxies and later, if possible, QSOs as a quasi-inertial reference frame (Klemola and Lin 1984). The extensive series of plates taken in 1970-1971 by Graham (1975) for his RR Lyr star survey in the field centered on the SMC halo cluster NGC 121 was identified as a potentially valuable first-epoch series for measurement of absolute proper motions. Second-epoch plates were taken in 1981 with the Cerro Tololo 1.5-m reflector, to match the early set kindly offered by Dr. John Graham.

Radio source surveys (Wall and Cannon 1973; Bolton and Butler 1975; Bolton and Savage 1977; Clark et al. 1976) offer promise for defining the reference frame of motions through optical identifications of the QSO component. Particularly important would be the identification of a QSO with a Cloud member located inside the aplanatic patch of 2-3 arcseconds, so that such blended or near-blended pairs may be observed for relative proper motion by the speckle interferometer technique normally applied to close double stars. Surveys for radio-quiet QSOs in and near the Clouds also deserve consideration as near-stellar reference points.

The galactic globular cluster 47 Tuc, at a distance of only 5 kpc, is projected onto the halo of the SMC. This fortunate circumstance permits measurement of relative proper motions for segregation of membership and for determination of galactocentric motion, once the motion of the SMC is attached to the extragalactic frame. The Bok-Bok stellar group, at a distance of only 400 pc (Philip 1973; also Sanduleak and Philip 1968), is projected onto the LMC. The astrometric study for membership by Murray et al. (1969) deserves extension, using early collections of plates likely to reside in various observatories, to strengthen the determination of stellar membership and galactocentric orbit of the group.

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Discussion:

MURRAY: Will you have enough galaxies in your Magellanic Cloud fields to provide an absolute reference frame to better than 0".001/year?
KLEMOLA: The number of astrometrically useful galaxies in the field of NGC 121 is small. We consider also the possibility of finding first QSO's in the galaxy-rich parts of the clouds. We do the best we can at this time.
GLIESE: Is it possible to compare the Lick programs with the work done in the Soviet Union at Pulkovo and at Tashkent?
KLEMOLA: Yes. We have taken a representative sample of stars in each of the Soviet fields, so that ultimately we can make a star-by-star comparison.