ASTROMETRY OF EXTRAGALACTIC OBJECTS FROM THE *PALOMAR SKY ATLAS* PRINTS

BY A. H. BRIDLE AND R. E. GOODSON
Queen's University, Kingston, Ontario

ABSTRACT

Recent developments in radio interferometry allow optical astrometry of extragalactic objects to play a new role in making unbiased optical identifications of radio sources. We describe the equipment and reduction procedure used to obtain optical positions with random errors as low as $\sim 0''.35$ and systematic errors $\lesssim 0''.15$ from the *Palomar Sky Atlas* prints at Queen's University. The accuracy of our measurements is demonstrated by comparisons with the AGK3 positions of 112 stars and with other astrometry of 33 quasars.

1. *Introduction*. A program of astrometry of the optical counterparts of extragalactic radio sources is being undertaken at Queen's University. This paper describes the motivation for this work and the method used to obtain positions accurate to $\lesssim 0''.4$ from a print copy of the *Palomar Sky Survey*.

2. *Accurate Positions and Unbiased Optical Identifications*. There is still no general method for estimating distances to extragalactic radio sources by purely radio means, so optical identifications of the sources remain the link between radio astronomy and extragalactic astrophysics. Distances to sources identified with giant elliptical galaxies are inferred from the galaxy redshifts, or (somewhat more crudely) from their apparent magnitudes by assuming that the identifications conform to the average magnitude versus redshift plot for radio galaxies. Distances to sources identified with unusual (e.g. compact or bright-nucleus) galaxies, or with quasars, must be estimated from the redshifts with the still controversial assumption that these are due solely to the expansion of the Universe (see Field *et al*. 1973). As most optical counterparts of extragalactic sources are fainter than 16^m, the redshift measurements are time-consuming; a *reliable* procedure for selecting identification candidates is therefore very necessary if valuable observing time at large optical instruments is not to be wasted.

Until the 1970's very few radio source positions had been measured to better than a few arc-seconds (even for small-diameter sources) so optical identifications had to be based a) on *rough* positional coincidence between source and identification candidate and b) on the degree of peculiarity of the candidate itself. The additional criteria of peculiarity were needed to reduce the probability that proposed identifications lay near the directions to the radio sources purely by chance. Identifications were more acceptable if the candidates were blue starlike objects at high galactic latitudes, or bright or unusual galaxies, than if they were more commonplace, e.g., neutral-coloured or red starlike objects, or faint galaxies. As the more extended radio sources (whose angular sizes range from a few arc-seconds to many arc-minutes) might cover an area of sky containing many optical images, their identifications were based *mainly* on criteria of optical peculiarity or of closeness of the identification candidate to the centre (or centroid) of the radio emission. The latter criterion was particularly dangerous as it had no *astrophysical* basis; indeed it is not hard to envisage situations in which it could be systematically violated.

Recent improvements in radio interferometry are making these peripheral identification criteria unnecessary. There are now several interferometers operating at centimetre or decimetre wavelengths (for recent reviews see Wade (1974) and Counselman (1976)) capable of measuring positions of compact radio sources to much better than one arc-second. Furthermore, many of the extended "double" radio sources have now been found to contain weak compact components which coincide with an optical object (e.g. figure 1). The odds suggest (e.g. Riley and Pooley 1975, Guindon 1976) that the majority of these systems are "triples" whose inner component directly marks the optical identification of the outer "double" regardless of the identification's colour, brightness or location relative to the outer components.

These advances in radio interferometry have led to the discovery of neutral-coloured and red quasars (e.g. Gent *et al*. 1973, Wills *et al*. 1973) and to the recognition of astrophysically significant classes of radio sources in which the radio emission is asymmetrically distributed around the associated optical object (e.g. Rudnick and Owen 1976). With modest improvements in the sensitivity of high-frequency radio interferometers, it may be possible to base most optical identifications (even those of extended radio sources) on simple positional coincidence between radio components and optical objects. If this could indeed be done, the identification process would be freed from bias towards objects of particular colour, etc. and parameters such as the symmetry properties of radio sources would become impartial *output* from the identification procedure and not assumed *input* to it. This would allow the departures of radio sources from simple double symmetry to be used as probes of source physics.

The accuracy of the best radio positions cannot be fully exploited unless the optical positions of identification candidates are also known to better than one arc-second. Conventional optical astrometric instruments cannot

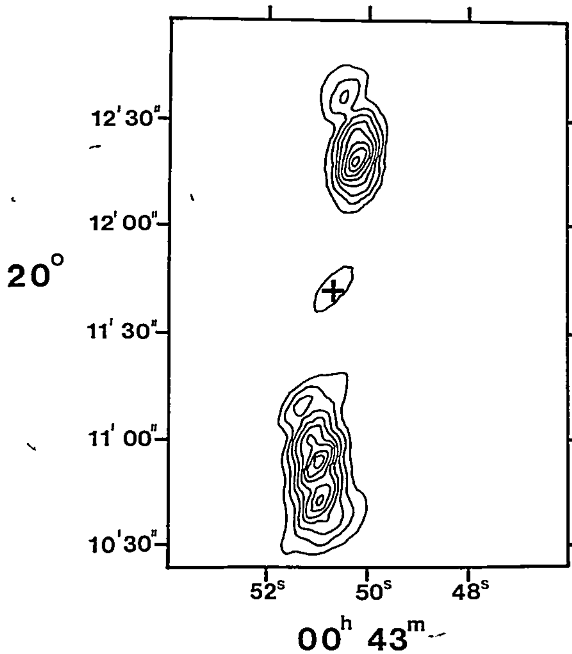

FIG. 1—Radio contour map of the "double" source PK 0043+20, made with a half-power beamwidth 15″.2 × 6″.1 in position angle −38° using the NRAO three-element interferometer at 2.7 GHz. The contours are at intervals of 5.5 mJy per beam area. The + marks our optical position for the centre of a $16^{m}.5$ elliptical galaxy in the rich cluster Abell 98. The central radio component (flux density ~ 7mJy) coincides with our optical position to within the errors of measurement.

satisfy radio astronomers' needs for accurate positions for large samples of putative identification candidates, as most candidate objects are too faint. Indeed the only body of optical data covering the entire northern sky to the limiting magnitudes which must be reached for useful identification work is the *National Geographic Society-Palomar Observatory Sky Survey* (usually referred to as the *Palomar Sky Survey*).

The *Palomar Sky Survey* was carried out with the 48-in Schmidt camera at the Hale Observatories between 1949 and 1958. The survey comprises red-sensitive (Kodak 103a-E) and blue-sensitive (Kodak 103a-O) plates of 936 fields covering the whole sky north of $\delta = -33°$ and red-sensitive plates only for a further 100 fields at $-33° > \delta > -45°$ (the "Whiteoak Extension"). The red plates generally reach to $\sim 20^{m}$ and the blue to $\sim 21^{m}$. Each plate covers a square area of sky about 6°.5 on each side at a nominal scale of

67″.14 per mm; true scales differ by about 0.5 percent in X and Y from this nominal value (Lund and Dixon 1973, Véron and Véron 1975).

Contact print copies of this survey (known collectively as the *Palomar Sky Atlas*) are held by most radio observatories. It was therefore of great interest to radio astronomers when Hunstead (1971, 1974) showed that the print medium is sufficiently stable that image coordinates can be measured relative to those of nearby bright reference stars to an accuracy of order 0″.35 using a high-quality two-dimensional coordinate measuring microscope.

3. *Equipment*. We measure image positions on the *Sky Atlas* prints at Queen's using a Gaertner two-screw vertical coordinate cathetometer (Type M1236-33). The vertical-plane engine saves in space and initial cost (relative to a comparable horizontal-plane engine) at no significant penalty in performance (see Section 6). The usable travel in both X (horizontal) and Y (vertical) is 75 mm (corresponding to a field ~84 arc-minutes square on the *Sky Survey*) and the rated accuracy of the lead screws across this field is one micron. The measurement accuracy is limited in practice by the judgement of the operator in setting the crosshairs onto an extended image, which introduces an rms error of ~two microns for measurements of reference stars. The engine is normally used with a linear magnification of $\times 10$.

The print being measured is held flat against a sheet aluminum backing by pressure of an aluminum-framed cover glass 74 cm by 47 cm and 3 mm thick which is screwed to the backing. The backing and cover glass fold to a near-horizontal position so that the print can conveniently be inserted and adjusted to bring the radio position near the centre of the working area of the measuring engine. The print holder locks into a vertical position that repeats relative to the measuring plane to better than ten microns and is stable to within the resolution of the engine.

4. *Measurement Procedure*. The X-Y image positions of identification candidates are measured relative to those of adjacent bright (~8^m to 11^m) stars whose accurate sky coordinates are known from standard astronometric work. These accurate reference star positions are normally taken from the AGK3 catalogue (Dieckvoss *et al*. 1975), correcting for proper motion to the epoch of the Palomar plate. The reference stars are initially located on the prints by means of computer-generated transparent overlays drawn to the mean print scale. These overlays (rms accuracy ~4″) are also used to locate the print area containing the radio source during the initial search for identification candidates.

From six to nine reference stars are measured, depending on the density of AGK3 stars in the field of interest and on their distribution around the radio position. The ideal distribution has at least one star in every quadrant within about 20′ of the radio position. Where possible, reference stars are chosen whose proper motions are <5″ per century so that the proper motion corrections are small (the difference in epochs between the *Sky Survey* and the AGK3 data range from one to 14 yrs). Fainter stars are also preferred to brighter; if the reference stars are too bright their diffraction patterns cover many tens of arc-seconds on the prints and their positions must be measured by aligning the outer crosshairs of the measuring microscope with the diffraction spikes, a procedure which could systematically deviate from that of aligning the inner crosshairs with the fainter and smaller images of identification candidates.

The AGK3 star closest to the radio position is treated as a "test star" to monitor the accuracy of the final reduction of the *X*-*Y* measurements to sky coordinates. For each field the reference stars, test star and identification candidates are measured using each of the four possible combinations of motions of the measuring engine (*X* left and *Y* up, *X* left and *Y* down, etc.). Measuring four independent *X*-*Y* pairs for each image reduces random setting errors but cannot eliminate systematic errors such as might be introduced by variations in the calibration of the lead screws along their length or by deformation of the microscope crosshairs. We give evidence in Section 6 that systematic errors in our system are in fact small.

5. *Reduction from X-Y to Sky Coordinates*. The measured *X*-*Y* positions are reduced to equatorial coordinates using the method of dependences introduced by Schlesinger (1911, 1926) and described by Smart (1962). A set of approximate "standard" coordinates for the reference stars derived from the nominal print scale using the Schmidt equations (Dixon 1962) is adjusted to obtain the best fit to the measured *X*-*Y* positions. The modified coordinate system is then used to solve for the sky coordinates of the unknown objects, i.e. the identification candidates. The computing facilities required are modest: our basic reduction program uses only 2K of core in a Hewlett-Packard Model 9830A desktop computer, and the entire program (including interactive program control and data modification) runs in under 6K in this machine. The main elements of the reduction are as follows:

i) *Detection of Setting Errors*. The measured *X*-*Y* pairs for the reference stars are checked for unusually large internal discrepancies (which might indicate operator error) by comparison with standard values of the setting residuals and screw backlash derived from many measurements made with our engine.

ii) *Reference-Star Rejection*. Each reference star in turn is excluded from the computations while the effective plate constants are determined using the averages of the four pairs of X-Y settings on the remaining stars. The mean right ascension and declination residuals (catalogued minus fitted positions) of the reference stars are computed with each star in turn excluded. These residuals are typically $\lesssim 0\overset{''}{.}2$; their detailed values depend on the number of stars and their distribution. If one reference star is significantly distorting the fit, the mean residuals for the solutions including that star are significantly greater than those for the one solution in which that star is withheld. This allows "bad" star positions (or X-Y measurements) to be diagnosed and discarded from subsequent analysis. Such discards are rare (<five percent of all reductions). They could arise for a number of reasons, including a) occasional un-noticed confusion of the image of an AGK3 star with a fainter image, which could bias our setting on the Palomar print relative to that of the AGK3 observers on their plates, b) occasional local anomalies in the print scale due either to real distortions near the extreme edge of the plates or to the handling history of our particular prints, c) occasional quasi-systematic operator error at the measuring engine or d) proper motion components that were not detected when AGK3 positions were compared with the AGK2 (see Dieckvoss *et al.* 1975). The rarity of the discards suggests that they do not represent a *systematic* limitation to astrometry from the *Sky Atlas* prints, but the fact that we discard reference stars at all leads us to believe that it *is* worthwhile to measure more stars per field than are strictly necessary for a plate solution.

iii) *Solution for Unknown and Test-Star Positions*. After any reference stars incriminated by the above test have been discarded, the four sets of X-Y measurements are reduced independently to four estimates of the sky coordinates of the identification candidates and of the test star. The scatter among these estimates measures the uncertainties in the final positions due to random errors of measurement, and the discrepancy between the fitted position of the test star and its AGK3 position provides an external consistency check (see Section 6).

iv) *Accurate Location of Source Position on the Sky Atlas*. It is useful to predict the print coordinates of a given right ascension and declination, to ensure that all significant optical objects in a radio field have been measured while the print remains in its calibrated position in the holder. An inversion of Schlesinger's procedure is used to infer the X and Y coordinates of the microscope which bring a given sky position to the measuring crosshairs. This procedure is ~ ten times more accurate in each coordinate than the standard overlays used for the initial print inspection. It is valuable in that it can be used to ensure that radio sources (or components of sources) are not erroneously classified as "blank fields" (no object visible on the *Sky Atlas*) as a result of errors in overlay production.

6. *The Accuracy of the Measured Positions*.

i) *Internal Errors*. The position finally adopted for each image measured is the average of those computed from the four independent sets of X-Y measurements. The scatter among the four sets is used to estimate the internal random errors of measurement; these estimates range from ~ 0''2 for well-defined symmetrical images to three or four times this for very bright objects (large images), very faint or very asymmetric objects. Less than 0''1 of this uncertainty should arise from our random error in the determination of the mean AGK3 reference frame on the print; the major component is the uncertainty in setting on the unknown image itself, which can be estimated on an object-by-object basis.

ii) *External Errors*. It is harder to assess the external, or systematic, errors of measurement on a print-by-print basis. As our measurements are referenced to the mean frame defined locally on the print by the AGK3 stars, our positions contain an uncertainty related to the uncertainty in the AGK3 positions themselves. The estimated standard errors for stars of various magnitudes in AGK3 (Dieckvoss *et al*. 1975) imply that the *mean* standard error in the AGK3 positions for our reference stars is close to 0''22. The contribution of this "AGK3 error" to the external uncertainty in our mean frame, based on n AGK3 stars, is ~ $0''22/\sqrt{n}$ — typically ~ 0''1 for our reductions. In the absence of further external errors the overall uncertainty in our positions for well-defined images would therefore be $\lesssim$0''3 (~0''1 from the AGK3 errors and ~0''2 from our internal errors).

Over a large number of our measurements (though not field by field) this estimate can be checked by examining the discrepancies between our positions for the test stars and their positions in AGK3. For test stars within ~ 10′ of the identification candidates and with low proper motions, the scatter of these discrepancies should reflect our typical errors in combination with those of *single* AGK3 positions (the random errors in our measurements and in the AGK3 measurements can of course conspire to make the apparent discrepancy smaller or larger than average for any individual test star). For test stars much more than 10′ from the identification candi-

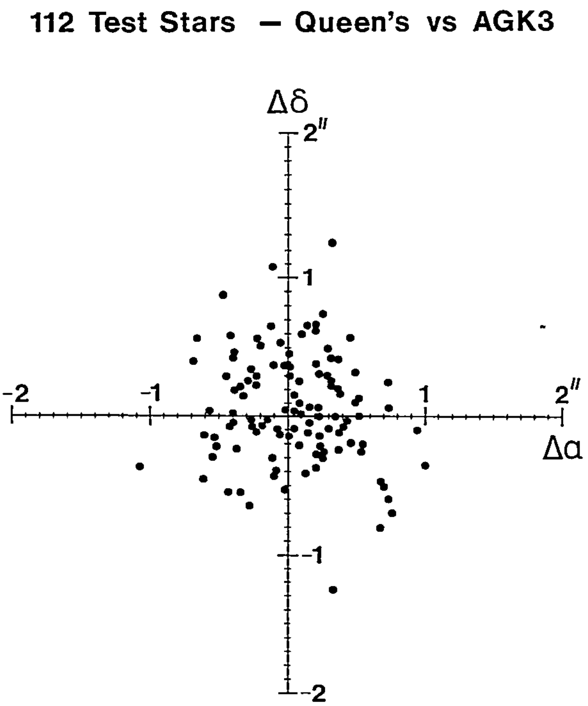

FIG. 2—Target diagram of the discrepancies in arc-seconds (Queen's minus AGK3 position) for 112 test stars between 8^m and 11^m. This distribution may be non-Gaussian because some test stars are more than 10′ from the field centres (see text). There is no significant bias in either coordinate and the standard deviation in each coordinate is ~ 0″.4.

dates, the distribution of reference stars around the test star is often worse than the distribution around the unknown; the test star discrepancies are then *pessimistic* indicators of the uncertainties in the positions of the unknowns. Figure 2 shows a target diagram of the discrepancies with AGK3 for 112 test stars. The mean discrepancies and their standard errors in right ascension and declination are +0″.056 ± 0″.037 and +0″.066 ± 0″.039 respectively; these are not significantly different from zero, verifying that there is no systematic error in our reduction algorithm. The standard deviations of the discrepancies in right ascension and declination are 0″.39 and 0″.41 respectively; these are consistent with a standard deviation in each coordinate of ~ 0″.33 in our test star measurements (allowing for the ~0″.22 uncertainties in the AGK3 positions), in good agreement with our expected internal errors.

The typical reference (or test) star is, however, 8^m to 10^m brighter than the typical identification candidate. As the star images are usually bright enough to show clear diffraction patterns on the *Sky Atlas* while the identification candidates are not, effects such as the intensity distributions in the diffraction patterns or distortions of our microscopic crosshairs could lead to systematic differences between our settings on the bright stars and on the faint unknowns. Such systematic differences need not show up either as increased random setting errors or in the test star discrepancies. The best test for the presence of such systematic errors is comparison of our positions for identification candidates with positions of comparable accuracy measured by others using different measuring engines and preferably different plate material.

Table I lists our positions for 33 radio-emitting quasars, together with accurate optical and radio positions for these objects taken from the literature. The list is not completely comprehensive; some published positions which disagree from the *mean* position for the object by several times their own quoted errors have been judiciously ignored. The left-hand plots in figures 3, 4 and 5 show the target diagrams of the discrepancies between our positions and the weighted means of the other optical, radio and mean

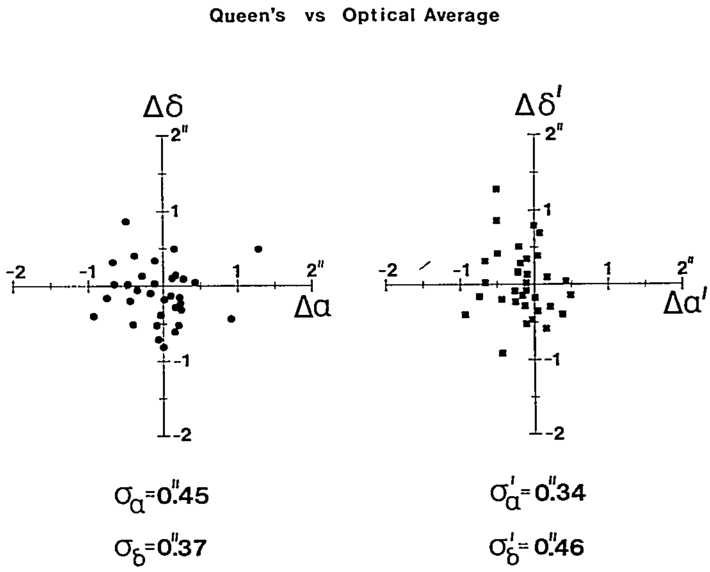

FIG. 3—Target diagrams of the discrepancies in arc-seconds (Queen's minus other optical) for the 33 quasars from Table 1. Left-hand plot: direct comparison. Right-hand plot: comparison taking account of print orientation during our measurements. The "other optical" positions are the weighted means of those listed in Table I.

TABLE I

1950.0 POSITIONS FOR 33 RADIO-EMITTING QUASARS

Name	Right Ascension	Declination	Reference	Optical or Radio
3CR 9	00^{h}17^m 49^{s}94 ±0^{s}02	+15°24′ 16$''$1 ±0$''$3	Bri77	O
	49.944±0.008	16.21±0.08	Mur69	O
	49.92 ±0.02	16.2 ±0.4	Hun71	O
	49.89 ±0.011	16.44±0.15	Arg72	O
3CR 48	01^{h}34^m 49^{s}83 ±0^{s}04	+32°54′ 19$''$7 ±0$''$3	Bri77	O
	49.817±0.04	20.22±0.5	Gri63	O
	49.836±0.013	20.26±0.11	Mur69	O
	49.830±0.010	20.15±0.15	Kri70	O
	49.819±0.012	20.40±0.12	Arg72	O
	49.780±0.010	19.96±0.13	Bar72	O
	49.826±0.002	20.52±0.03	Els76	R
	49.83 ±0.015	20.7 ±0.2	Fom76	R
3CR 93	03^{h}40^m 51^{s}56 ±0^{s}02	+04°48′ 21$''$2 ±0$''$5	Bri77	O
	51.562±0.011	21.76±0.11	Mur69	O
	51.54 ±0.02	22.1 ±0.3	Hun71	O
	51.541±0.010	21.70±0.20	Arg72	O
	51.55 ±0.03	22.3 ±0.5	Wil73	O
3CR 138	05^{h}18^m 16^{s}51 ±0^{s}02	+16°35′ 27$''$0 ±0$''$4	Bri77	O
	16.65 ±0.06	26.4 ±1.0	Vér68	O
	16.508±0.012	27.03±0.12	Mur69	O
	16.525±0.02	26.75±0.3	Kri70	O
	16.53 ±0.02	26.7 ±0.3	Hun71	O
	16.50 ±0.03	27.3 ±0.4	Wil73	O
	16.526±0.005	26.85±0.09	Els76	R
PK0735+17	07^{h}35^m 14^{s}09 ±0^{s}03	+17°49′ 08$''$9 ±0$''$3	Bri77	O
	14.12 ±0.03	09.0 ±0.5	Vér72	O
	14.14 ±0.03	08.8 ±0.4	Wil73	O
	14.11 ±0.03	08.9 ±0.5	Hos74	O
	14.11 ±0.03	09.4 ±0.3	Hos74	R
OI363	07^{h}38^m 00^{s}17 ±0^{s}04	+31°19′ 02$''$1 ±0$''$4	Bri77	O
	00.24 ±0.04	01.2 ±0.5	Vér72	O
	00.16 ±0.04	02.2 ±0.5	Wil76	O
	00.17 ±0.01	02.5 ±0.2	Bro70a	R
	00.176±0.002	02.02±0.02	Els76	R
3CR 186	07^{h}40^m 56^{s}78 ±0^{s}03	+38°00′ 31$''$1 ±0$''$3	Bri77	O
	56.742±0.014	31.08±0.10	Mur69	O
	56.752±0.013	31.07±0.12	Arg72	O
	56.77 ±0.06	30.9 ±0.6	Ril75	O
	56.75 ±0.05	31.3 ±0.6	Adg72	R
	56.72 ±0.08	31.3 ±0.8	Sha75	R

TABLE I (*continued*)

Name	Right Ascension	Declination	Reference	Optical or Radio
3CR 191	$08^{h}02^{m}$ $03^{s}.76 \pm 0^{s}.02$	$+10°23'$ $58''.0 \pm 0''.3$	Bri77	O
	03.78 ±0.06	58.1 ±1.0	San65	O
	03.76 ±0.02	57.6 ±0.3	Kri70	O
	03.78 ±0.03	57.7 ±0.3	Hun71	O
3CR 196	$08^{h}09^{m}$ $59^{s}.42 \pm 0^{s}.04$	$+48°22'$ $07''.4 \pm 0''.4$	Bri77	O
	59.39 ±0.04	08.03±0.5	Gri63	O
	59.386±0.018	07.71±0.12	Mur69	O
	59.400±0.015	07.57±0.12	Arg72	O
	59.46 ±0.05	07.5 ±0.5	Wil73	O
	59.42 ±0.04	07.2 ±0.4	Adg72	R
	59.37 ±0.07	06.8 ±0.5	Ghi73	R
3CR 204	$08^{h}33^{m}$ $18^{s}.05 \pm 0^{s}.11$	$+65°24'$ $04''.3 \pm 0''.4$	Bri77	O
	18.025±0.029	04.44±0.12	Mur69	O
	18.146±0.025	03.86±0.13	Arg72	O
3CR 205	$08^{h}35^{m}$ $10^{s}.04 \pm 0^{s}.04$	$+58°04'$ $51''.4 \pm 0''.3$	Bri77	O
	09.942±0.023	51.76±0.12	Mur69	O
	10.020±0.019	51.44±0.13	Arg72	O
	10.19 ±0.04	52.6 ±0.3	Bar72	O
3CR 216	$09^{h}06^{m}$ $17^{s}.28 \pm 0^{s}.03$	$+43°05'$ $58''.7 \pm 0''.3$	Bri77	O
	17.26 ±0.09	59.0 ±1.0	San65	O
	17.265±0.014	58.56±0.12	Arg72	O
	17.25 ±0.04	59.4 ±0.4	Adg72	R
	17.20 ±0.05	59.2 ±0.4	Ghi73	R
	17.32 ±0.08	58.6 ±0.7	Sha75	R
4C39.25	$09^{h}23^{m}$ $55^{s}.28 \pm 0^{s}.03$	$+39°15'$ $23''.9 \pm 0''.6$	Bri77	O
	55.41 ±0.04	23.4 ±0.5	Vér72	O
	55.310±0.015	22.94±0.14	Arg73	O
	55.33 ±0.04	23.9 ±0.5	Vér75	O
	55.296±0.004	23.73±0.04	Rog73	R
	55.297±0.004	23.73±0.03	Cla76	R
	55.314±0.003	23.58±0.04	Els76	R
4C55.17	$09^{h}54^{m}$ $14^{s}.39 \pm 0^{s}.08$	$+55°37'$ $16''.2 \pm 0''.4$	Bri77	O
	14.41 ±0.06	16.3 ±0.5	Vér72	O
	14.38 ±0.05	17.3 ±0.4	Adg72	R
	14.41 ±0.07	16.9 ±0.6	Ghi73	R
3CR 249.1	$11^{h}00^{m}$ $27^{s}.32 \pm 0^{s}.11$	$+77°15'$ $08''.4 \pm 0''.4$	Bri77	O
	27.316±0.042	08.62±0.09	Mur69	O
	27.316±0.046	08.41±0.17	Arg72	O
	27.58 ±0.12	08.10±0.4	Wil73	O
PK1116+12	$11^{h}16^{m}$ $20^{s}.78 \pm 0^{s}.04$	$+12°51'$ $06''.8 \pm 0''.6$	Bri77	O
	20.755±0.02	06.5 ±0.2	Kri70	O

TABLE I (*continued*)

Name	Right Ascension	Declination	Reference	Optical or Radio
	$20^{s}79 \pm 0^{s}02$	07″0 ±0″4	Hun71	O
	20.77 ±0.03	07.2 ±0.4	Wil73	O
	20.81 ±0.03	06.8 ±0.4	Adg72	R
	20.73 ±0.05	07.5 ±0.6	Ghi73	R
	20.79 ±0.015	06.9 ±0.2	Fom76	R
3CR 263	$11^{h}37^{m}$ $09^{s}32 \pm 0^{s}05$	+66°04′ 26″6 ±0″3	Bri77	O
	09.38 ±0.12	25.9 ±1.0	San65	O
	09.296±0.028	27.04±0.10	Mur69	O
	09.349±0.025	26.88±0.15	Arg72	O
PK1148–00	$11^{h}48^{m}$ $10^{s}11 \pm 0^{s}02$	−00°07′ 13″3 ±0″4	Bri77	O
	10.17 ±0.03	13.05±0.4	Kri70	O
	10.14 ±0.02	13.1 ±0.4	Hun71	O
	10.12 ±0.02	12.5 ±0.3	Bar72	O
	10.15 ±0.03	12.9 ±0.4	Adg72	R
	10.12 ±0.07	13.1 ±0.5	McE75	R
3CR 277.1	$12^{h}50^{m}$ $15^{s}17 \pm 0^{s}04$	+56°50′ 36″1 ±0″5	Bri77	O
	15.278±0.022	36.72±0.12	Mur69	O
	15.118±0.019	36.39±0.13	Arg72	O
	15.12 ±0.05	37.5 ±0.4	Wil73	O
	15.19 ±0.06	37.0 ±0.5	Adg72	R
	15.24 ±0.11	36.3 ±0.8	Ghi73	R
	15.19 ±0.01	36.5 ±0.1	Poo74	R
PK1318+11	$13^{h}18^{m}$ $49^{s}62 \pm 0^{s}02$	+11°22′ 31″3 ±0″3	Bri77	O
	49.61 ±0.03	30.8 ±0.5	Vér73	O
3CR 287	$13^{h}28^{m}$ $15^{s}92 \pm 0^{s}04$	+25°24′ 37″0 ±0″9	Bri77	O
	15.925±0.04	37.7 ±0.6	Kri70	O
	15.918±0.005	37.58±0.04	Els76	R
	15.92 ±0.015	37.60±0.2	Fom76	R
3CR 286	$13^{h}28^{m}$ $49^{s}66 \pm 0^{s}02$	+30°45′ 58″5 ±0″4	Bri77	O
	49.67 ±0.02	58.35±0.15	Kri70	O
	49.657±0.012	58.46±0.12	Arg72	O
	49.56 ±0.02	58.3 ±0.3	Bar72	O
	49.654±0.002	58.70±0.03	Els76	R
	49.67 ±0.015	58.7 ±0.2	Fom76	R
3CR 288.1	$13^{h}40^{m}$ $29^{s}88 \pm 0^{s}04$	+60°36′ 48″4 ±0″3	Bri77	O
	29.911±0.024	48.51±0.12	Mur69	O
	29.940±0.021	48.36±0.15	Arg72	O
	30.00 ±0.12	48.1 ±0.8	Ghi73	R
OQ 172	$14^{h}42^{m}$ $50^{s}41 \pm 0^{s}04$	+10°11′ 11″6 ±0″4	Bri77	O
	50.44 ±0.04	11.8 ±0.6	Bro73b	O
	50.476±0.010	11.89±0.18	Els76	R

TABLE I (*continued*)

Name	Right Ascension	Declination	Reference	Optical or Radio
3CR 309.1	14^h58^m $56^s.79 \pm 0^s.20$	$+71°52'$ $10''.9 \pm 0''.4$	Bri77	O
	56.476±0.036	11.42±0.10	Mur69	O
	56.70 ±0.06	10.8 ±0.25	Kri70	O
	56.648±0.03	11.33±0.16	Arg72	O
	56.64 ±0.08	11.2 ±0.4	Wil73	O
	56.67 ±0.21	10.8 ±1.0	Ghi73	R
	56.61 ±0.04	11.3 ±0.1	Bro73a	R
	56.644±0.005	11.15±0.02	Els76	R
DA 406	16^h11^m $47^s.90 \pm 0^s.02$	$+34°20'$ $19''.9 \pm 0''.5$	Bri77	O
	47.96 ±0.04	20.7 ±0.5	Vér73	O
	47.99 ±0.04	19.9 ±0.5	Wil73	O
	47.906±0.003	19.81±0.04	Els76	R
	47.92 ±0.015	19.7 ±0.2	Fom76	R
3CR 345	16^h41^m $17^s.61 \pm 0^s.03$	$+39°54'$ $10''.7 \pm 0''.3$	Bri77	O
	17.625±0.015	10.99±0.10	Mur69	O
	17.56 ±0.03	10.7 ±0.3	Kri70	O
	17.606±0.013	10.72±0.12	Arg72	O
	17.61 ±0.04	11.4 ±0.5	Wil73	O
	17.634±0.004	11.0 ±0.07	Rog73	R
	17.635±0.002	10.96±0.04	Cla76	R
	17.602±0.002	10.82±0.02	Els76	R
3CR 380	18^h28^m $13^s.52 \pm 0^s.03$	$+48°42'$ $40''.3 \pm 0''.3$	Bri77	O
	13.485±0.045	40.15±0.4	Kri70	O
	13.513±0.016	40.45±0.12	Arg72	O
	13.54 ±0.04	40.5 ±0.4	Adg72	R
	13.46 ±0.08	40.1 ±0.6	Ghi73	R
	13.53 ±0.07	40.6 ±0.7	Sha75	R
BL Lac	22^h00^m $39^s.34 \pm 0^s.03$	$+42°02'$ $08''.8 \pm 0''.3$	Bri77	O
	39.41 ±0.04	08.7 ±0.5	Vér72	O
	39.397±0.021	08.47±0.14	Arg73	O
	39.36 ±0.01	08.55±0.15	Coh72	R
	39.385±0.005	08.40±0.04	Cla76	R
	39.36 ±0.002	08.60±0.02	Els76	R
4C31.63	22^h01^m $01^s.45 \pm 0^s.02$	$+31°31'$ $05''.8 \pm 0''.3$	Bri77	O
	01.431±0.018	06.11±0.14	Arg73	O
	01.46 ±0.04	05.7 ±0.5	Vér75	O
	01.49 ±0.04	05.5 ±0.3	Arg73	R
	01.423±0.003	05.87±0.07	Els76	R
PK2247+14	22^h47^m $56^s.75 \pm 0^s.04$	$+14°03'$ $57''.3 \pm 0''.3$	Bri77	O
	56.75 ±0.03	58.1 ±0.5	Vér72	O

TABLE I (*concluded*)

Name	Right Ascension	Declination	Reference	Optical or Radio
3CR454	22h49m 07s.74 ±0s.02	+18°32′ 44″.2 ±0″.3	Bri77	O
	07.65 ±0.03	43.7 ±0.2	Kri70	O
	07.77 ±0.04	43.6 ±0.6	Adg72	R
3CR454.3	22h51m 29s.48 ±0s.03	+15°52′ 54″.3 ±0″.4	Bri77	O
	29.485±0.035	54.45±0.4	Kri70	O
	29.54 ±0.02	53.9 ±0.6	Hun71	O
	29.533±0.011	54.98±0.15	Arg72	O
	29.524±0.01	54.36±0.2	Coh72	R
	29.530±0.009	54.24±0.03	Rog73	R
	29.533±0.003	54.24±0.05	Cla76	R
	29.510±0.006	54.23±0.09	Els76	R

References for Table I

Adg72	Adgie *et al.* (1972)
Arg72	Argue and Kenworthy (1972)
Arg73	Argue *et al.* (1973)
Bar72	Barbieri *et al.* (1972)
Bri77	Bridle and Goodson (1977—this paper)
Bro73a	Brosche *et al.* (1973)
Bro73b	Browne *et al.* (1973)
Cla76	Clark *et al.* (1976)
Coh72	Cohen (1972)
Els76	Elsmore and Ryle (1976)
Fom76	Fomalont (1976)
Ghi73	Ghigo and Owen (1973)
Gri63	Griffin (1963)
Hos74	Hoskins *et al.* (1974)
Hun71	Hunstead (1971)
Kri70	Kristian and Sandage (1970)
McE75	McEwan *et al.* (1975)
Mur69	Murray *et al.* (1969)
Poo74	Pooley and Henbest (1974)
Ril75	Riley and Pooley (1975)
Rog73	Rogers *et al.* (1973)
San65	Sandage *et al.* (1965)
Sha75	Sharp and Bash (1975)
Vér68	Véron (1968)
Vér72	Véron (1972)
Vér73	Véron and Véron (1973)
Vér75	Véron and Véron (1975)
Wil73	Wills *et al.* (1973)
Wil76	Wills and Wills (1976)

(radio *and* optical) positions. The published positions were weighted inversely as the squares of their quoted errors in determining the mean positions. The scatter in these diagrams (Table II) is again consistent with a standard error of between 0″.3 and 0″.35 in our measurements. None of the mean discrepancies differs significantly from zero (at the one-percent level), so there is little evidence for an overall systematic bias in our measurements. This analysis could, however, mask systematic bias in our settings along one coordinate of the measuring engine, because the prints are measured in a variety of orientations (to reduce the necessary size of our holder). For example, a systematic offset in the X-coordinate between

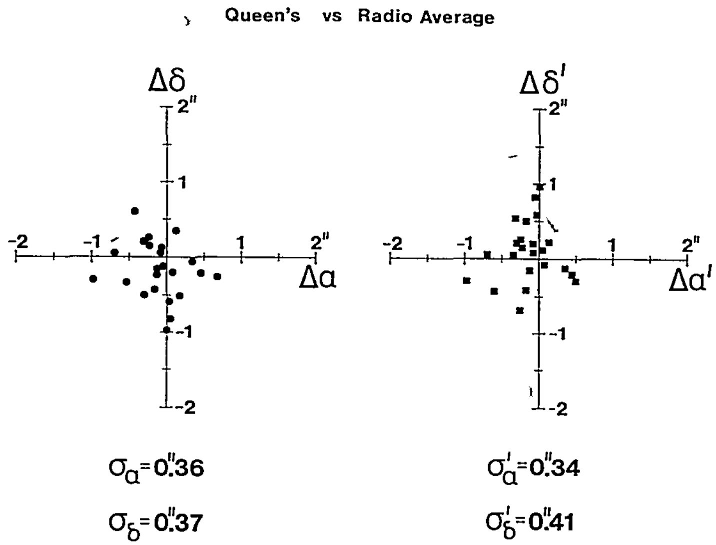

FIG. 4—As for figure 3, except that comparison is with average radio positions for 23 quasars not significantly resolved by the radio interferometers.

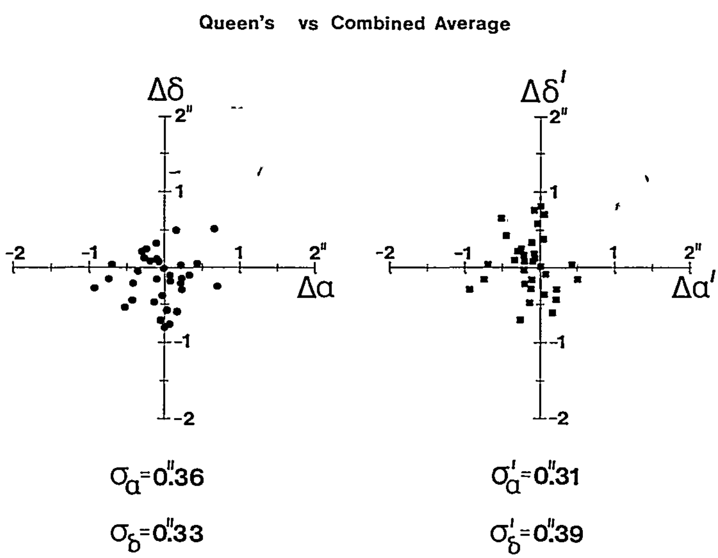

FIG. 5—As for figure 3, except that comparison is with other optical and radio positions combined for the 33 quasars.

TABLE II

COMPARISON OF QUEEN'S POSITIONS WITH OTHER ASTROMETRY

Comparison	Mean Discrepancy (Queen's Minus Other)	Standard Deviation
Average Optical (33 quasars)	$\overline{\Delta\alpha} = -0\overset{''}{.}055 \pm 0\overset{''}{.}078$ $\overline{\Delta\delta} = -0\overset{''}{.}095 \pm 0\overset{''}{.}065$	$\sigma_\alpha = 0\overset{''}{.}45$ $\sigma_\delta = 0\overset{''}{.}37$
Average Radio (23 quasars)*	$\overline{\Delta\alpha} = -0\overset{''}{.}103 \pm 0\overset{''}{.}075$ $\overline{\Delta\delta} = -0\overset{''}{.}166 \pm 0\overset{''}{.}078$	$\sigma_\alpha = 0\overset{''}{.}36$ $\sigma_\delta = 0\overset{''}{.}37$
Average Optical and Radio	$\overline{\Delta\alpha} = -0\overset{''}{.}052 \pm 0\overset{''}{.}063$ $\overline{\Delta\delta} = -0\overset{''}{.}140 \pm 0\overset{''}{.}058$	$\sigma_\alpha = 0\overset{''}{.}36$ $\sigma_\delta = 0\overset{''}{.}33$

*Only unresolved radio sources were used, eliminating ten systems for which accurate optical positions are available.

TABLE III

COMPARISON OF QUEEN'S POSITIONS WITH OTHER ASTROMETRY, ALLOWING FOR PRINT ORIENTATION DURING OUR MEASUREMENT

Comparison	Mean Discrepancy (Queen's Minus Other)	Standard Deviation
Average Optical	$\overline{\Delta\alpha'} = -0\overset{''}{.}160 \pm 0\overset{''}{.}059$ $\overline{\Delta\delta'} = -0\overset{''}{.}027 \pm 0\overset{''}{.}081$	$\sigma'_\alpha = 0\overset{''}{.}34$ $\sigma'_\delta = 0\overset{''}{.}46$
Average Radio	$\overline{\Delta\alpha'} = -0\overset{''}{.}134 \pm 0\overset{''}{.}071$ $\overline{\Delta\delta'} = 0\overset{''}{.}091 \pm 0\overset{''}{.}085$	$\sigma'_\alpha = 0\overset{''}{.}34$ $\sigma'_\delta = 0\overset{''}{.}41$
Average Optical and Radio	$\overline{\Delta\alpha'} = -0\overset{''}{.}134 \pm 0\overset{''}{.}053$ $\overline{\Delta\delta'} = 0\overset{''}{.}054 \pm 0\overset{''}{.}067$	$\sigma'_\alpha = 0\overset{''}{.}31$ $\sigma'_\delta = 0\overset{''}{.}39$

faint identification candidates and bright stars due to distortion of the microscope crosshair could appear as a right-ascension or declination offset of either sign in these diagrams. The right-hand plots in figures 3, 4 and 5 test for such effects; they are plotted taking into account the print orientations, so that $\Delta\alpha'$ increasing always corresponds to X increasing, $\Delta\delta'$ increasing corresponds to Y increasing, etc. The offsets in $\Delta\alpha'$ (Table III) are close to being significant at the one-percent level and would imply a systematic differential underestimate of our X coordinates of faint images by ~ two microns. We believe, however, that this effect is an artifact of the small sample size (33 objects); if the same comparison is made using only the best available optical positions (Argue and Kenworthy (1972) — estimated standard errors ~ $0\overset{''}{.}15$) the effect disappears (see figure 6 and Table

TABLE IV

COMPARISON OF QUEEN'S POSITIONS WITH ARGUE AND KENWORTHY (1972) FOR 16 QUASARS (FIGURE 6)

Comparison	Mean Discrepancy	Standard Deviation
Direct	$\overline{\Delta\alpha} = +0''.127 \pm 0''.086$ $\overline{\Delta\delta} = -0''.140 \pm 0''.070$	$\sigma_\alpha = 0''.34$ $\sigma_\delta = 0''.28$
Allowing for Print Orientation	$\overline{\Delta\alpha'} = -0''.049 \pm 0''.076$ $\overline{\Delta\delta'} = -0''.090 \pm 0''.091$	$\sigma'_\alpha = 0''.30$ $\sigma'_\delta = 0''.36$

IV). We therefore believe our systematic bias to be $\lesssim$ two microns in both measuring-engine coordinates, or $\lesssim 0''.15$ in sky coordinates.

Although the sample size is small (16 objects), the comparison with Argue and Kenworthy (1972) verifies our estimate of our own standard errors as $\sim 0''.3$ to $0''.35$. In all of the comparisons in which our print orientation is taken into account, there is evidence that the standard error along the *Y* (vertical) coordinate of our engine exceeds that along the *X* (horizontal) coordinate by $\sim$ 20 percent. This may be a result of the asymmetry of the two lead screws with respect to the carriage weight.

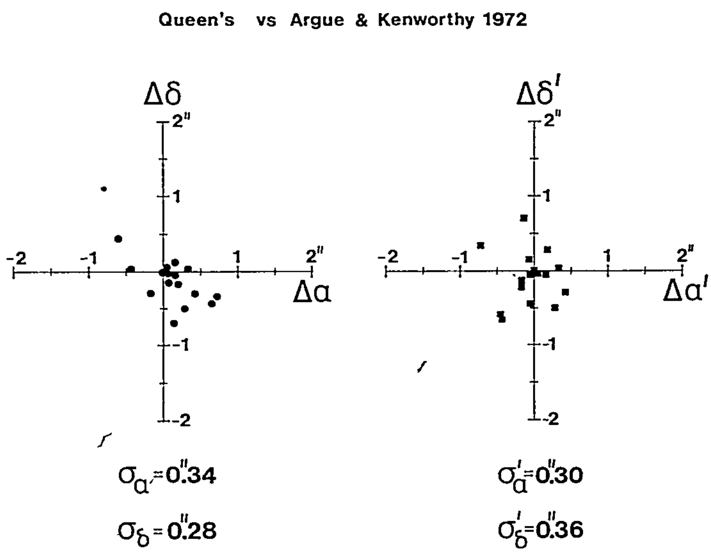

FIG. 6—As for figure 3, except that comparison is for the 16 quasars in common with the high-precision astrometry by Argue and Kenworthy (1972).

7. *Conclusion*. We have demonstrated that our measurements of faint quasar images from the *Palomar Sky Atlas* prints at Queen's University have standard errors of 0."3 to 0."35 and systematic errors $\lesssim$ 0."15. No unusual precautions have been taken with the storage of our prints, so it can be expected that other reasonably well-treated print copies could yield this accuracy. This conclusion is completely consistent with the pioneering study of astrometry from the *Sky Atlas* prints at Sydney University by Hunstead (1971, 1974).

Our equipment is now being used to obtain accurate positions for radio galaxies and for optical counterparts of radio sources in the λ21-cm BDFL catalogue (Bridle *et al*. 1972; Bridle and Fomalont 1974).

Acknowledgments. This research is supported primarily by a grant from the Advisory Research Committee of Queen's University, with additional support from the National Research Council of Canada. R.E.G. thanks the School of Graduate Studies at Queen's University for the award of a Carl Reinhardt Fellowship.

REFERENCES

Adgie, R. L., Crowther, J. H. and Gent, H. 1972, *Monthly Notices Roy. Astron. Soc.*, **159**, 233.

Argue, A. N. and Kenworthy, C. M. 1972, *ibid*., **160**, 197.

Argue, A. N., Kenworthy, C. M. and Stewart, P. M. 1973, *Astrophys. Letters*, **14**, 99.

Barbieri, C., Capaccioli, M., Ganz, R. and Pinto, G. 1972, *Astron. J.*, **77**, 444.

Bridle, A. H. and Fomalont, E. B. 1974, *ibid*., **79**, 1000.

Bridle, A. H., Davis, M. M., Fomalont, E. B. and Lequeux, J. 1972, *ibid*., **77**, 405.

Brosche, P., Wade, C. M. and Hjellming, R. M. 1973, *Astrophys. J.*, **183**, 805.

Browne, I. W. A., Crowther, J. H. and Adgie, R. L. 1973, *Nature*. **244**, 146.

Clark, T. A., Hutton, L. K., Marandino, G. E., Counselman, C. C., Robertson, D. S., Shapiro, I. I., Wittels, J. J., Hinteregger, H. F., Knight, C. A., Rogers, A. E. E., Whitney, A. R., Niell, A. E., Rönnäng, B. O. and Rydbeck, O. E. H. 1976, *Astron. J.*, **81**, 599.

Cohen, M. H. 1972, *Astrophys. Letters*, **12**, 81.

Counselman, C. C., III 1976, *Ann. Rev. Astron. Astrophys.*, **14**, 197.

Dieckvoss, W., Kox, H., Günther, A. and Brosterhus, E. 1975, *AGK3: Star Catalogue of Positions and Proper Motions North of −2.5° Declination*, Hamburger Sternwarte, Hamburg-Bergedorf.

Dixon, M. E. 1962, *Monthly Notes Astron. Soc. Southern Africa*, **21**, 180.

Elsmore, B. and Ryle, M. 1976, *Monthly Notices Roy. Astron. Soc.*, **174**, 411.

Field, G. B., Arp, H. and Bahcall, J. N. 1973, *The Redshift Controversy* (Frontiers in Physics Lecture Note Series), W. A. Benjamin, Inc., Reading, Mass.

Fomalont, E. B. 1976, private communication.

Gent, H., Crowther, J. H., Adgie, R. L., Hoskins, D. G., Murdoch, H. S., Hazard, C. and Jauncey, D. L. 1973, *Nature*, **241**, 261.

Ghigo, F. D. and Owen, F. N. 1973, *Astron. J.*, **78**, 848.
Griffin, R. F. 1963, *ibid.*, **68**, 421.
Guindon, B. 1976, Ph.D. thesis, Queen's University, Kingston, Ontario.
Hoskins, D. G., Murdoch, H. S., Adgie, R. L., Crowther, J. H. and Gent, H. 1974, *Monthly Notices Roy. Astron. Soc.*, **166**, 235.
Hunstead, R. W. 1971, *ibid.*, **152**, 277.
Hunstead, R. W. 1974, in *New Problems in Astrometry*, IAU Symp. No. 61, ed. Gliese, W., Murray, C. A. and Tucker, R. H., D. Riedel Publishing Co., Dordrecht, Holland, p. 175.
Kristian, J. and Sandage, A. 1970, *Astrophys. J.*, **162**, 391.
Lund, J. M. and Dixon, R. S. 1973, *Publ. Astron. Soc. Pacific*, **85**, 230.
McEwan, N. J., Browne, I. W. A. and Crowther, J. H. 1975, *Mem. Roy. Astron. Soc.*, **80**, 1.
Murray, C. A., Tucker, R. H. and Clements, E. D. 1969, *Nature*, **221**, 1229.
Pooley, G. G. and Henbest, S. N. 1974, *Monthly Notices Roy. Astron. Soc.* **169**, 477.
Riley, J. M. and Pooley, G. G. 1975, *Mem. Roy. Astron. Soc.*, **80**, 105.
Rogers, A. E. E., Counselman, C. C., III, Hinteregger, H. F., Knight, C. A., Robertson, D. S., Shapiro, I. I., Whitney, A. R. and Clark, T. A. 1973, *Astrophys. J.*, **186**, 801.
Rudnick, L. and Owen, F. N. 1976, *Astrophys. J. Letters*, **203**, L107.
Sandage, A., Véron, P. and Wyndham, J. D. 1965, *Astrophys. J.*, **142**, 1307.
Schlesinger, F. 1911, *ibid.*, **33**, 161.
Schlesinger, F. 1926, *Astron. J.*, **37**, 77.
Sharp, J. R. and Bash, F. N. 1975, *ibid.*, **80**, 335.
Smart, W. M. 1962, *Textbook on Spherical Astronomy* (Fifth Edition), Cambridge University Press, p. 404.
Véron, P. 1968, *Ann. Astrophys.*, **31**, 483.
Véron, M. P. 1972, *Astron. Astrophys.*, **20**, 471.
Véron, M. P. and Véron, P. 1973, *ibid.*, **28**, 319.
Véron, M. P. and Véron, P. 1975, *ibid.*, **42**, 1.
Wade, C. M. 1974, in *New Problems in Astrometry*, IAU Symp. No 61, ed. Gliese, W., Murray, C. A. and Tucker, R. H., D. Riedel Publishing Co., Dordrecht, Holland, p. 133.
Wills, B. J., Wills, D. and Douglas, J. N. 1973, *Astron. J.*, **78**, 521.
Wills, D. and Wills, B. J. 1976, *Astrophys. J. Suppl.*, **31**, 143.