The Astronomical Journal, 127:3034–3042, 2004 May

AN IMPROVED PROPER-MOTION CATALOG COMBINING USNO-B AND THE SLOAN DIGITAL SKY SURVEY

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Received 2003 November 3; accepted 2004 January 27

ABSTRACT

An improved proper-motion catalog is presented, combining the USNO-B and Sloan Digital Sky Survey (SDSS) catalogs in the area of sky covered by SDSS Data Release 1 (DR1; 2099 deg^2). USNO-B positions are recalibrated using SDSS galaxies, and proper motions are recomputed including both the USNO-B and SDSS positions. Statistical errors in the USNO-B proper motions are decreased by roughly 20%–30%, systematic errors are greatly reduced, and the proper motions are placed on an absolute reference frame. Requiring a match to an SDSS object removes the large number of false high proper motion objects in USNO-B. The resultant catalog is 90% complete to $g < 19.7$, with statistical errors in the component proper motions of roughly 3–3.5 mas yr^{-1}, substantially smaller systematic errors, and a contamination rate of less than 0.5%. A number of studies are currently underway using proper motions from this catalog. The catalog is available via ftp.

Key words: astrometry — catalogs

1. INTRODUCTION

The Sloan Digital Sky Survey (SDSS; Gunn et al. 1998; York et al. 2000; Lupton et al. 2001; Stoughton et al. 2002) is imaging roughly one-quarter of the sky in five broad optical bands (*u*, *g*, *r*, *i*, and *z*; Fukugita et al. 1996; Hogg et al. 2001; Smith et al. 2002), with 95% completeness limits for point sources of 22.0, 22.2, 22.2, 21.3, and 20.5, respectively. The SDSS Data Release 1 (DR1; Abazajian et al. 2003) made publicly available 2099 deg^2 of imaging data, photometrically calibrated to 2% rms. While primarily designed for the study of galaxies and QSOs, the imaging data represent an unprecedented database of stellar photometry for the study of stellar populations and Galactic structure, and indeed much work as been done in these areas to date (e.g., Harris et al. 2003; Yanny et al. 2003; Hawley et al. 2002; Margon et al. 2002; Newberg et al. 2002; Rockosi et al. 2002; Ivezić et al. 2000).

Most of the SDSS survey area is imaged only once in the course of the survey, so proper motions cannot be derived for stars from SDSS imaging alone. Even for those areas imaged more than once by SDSS, more precise proper motions can be obtained by matching SDSS to catalogs derived from Schmidt photographic plate surveys taken decades ago, such as the Palomar Observatory Sky Surveys (POSS-I and POSS-II) in the northern sky; the larger positional errors on the plates are more than compensated for by the much larger epoch difference (approximately 50 yr when matching SDSS to POSS-I, e.g., as opposed to a current maximum of 4 yr when matching multiple SDSS scans). DR1 presents proper motions based on matches of SDSS to USNO-A2.0 (Monet et al. 1998), an all-sky single-epoch astrometric catalog based on POSS-I plates in the area of sky covered by DR1. These proper motions have a limitation that originates from the technical requirements imposed by the SDSS target selection process, during which the match to USNO-A2.0 is performed; each SDSS object is processed independently of other SDSS objects and thus is simply matched to the closest USNO-A2.0 object within a 30″ radius. There is no opportunity for a more sophisticated matching algorithm, or to remove systematics between the SDSS and USNO-A2.0 astrometry (and photometry), both of which would require examining more than one matched pair at a time.

This limitation leads to two problems with the DR1 proper motions. First, systematic errors in both the USNO-A2.0 (primarily) and SDSS positions lead to systematic errors in the proper motions, typically comparable to the size of the statistical errors ($\sim$4 mas yr^{-1}); these errors are evident when plotting the proper motions of spectroscopically confirmed QSOs. Second, mismatches occur both for stars with large proper motions and for the small fraction of stars missing from USNO-A2.0 and result in spurious large motions. While the percentage of mismatches is expected to be essentially 0% for SDSS/USNO-A2.0 pairs separated by less than 1″, for separations of order 5″ (corresponding to a proper motion of 100 mas yr^{-1} for an epoch difference between SDSS and POSS-I of 50 yr), the percentage of expected mismatches is roughly 40%. Thus, any survey of high proper motion stars using the DR1 proper motions must accept a high contamination rate.

USNO-A2.0 has now been superseded by USNO-B1.0 (Monet et al. 2003, hereafter USNO-B), which adds plates from more recent Schmidt photographic surveys, such as POSS-II, to the earlier epoch data on which USNO-A2.0 was based and includes proper motions based on detections from as many as five plates. USNO-B is all-sky, complete to $V \sim 21$, with positions accurate to 200 mas at J2000.0, proper motions with random errors of roughly 4–7 mas yr^{-1} and comparable systematic errors, and O, E, J, F, and N magnitudes accurate to 0.3 mag. It is an unparalleled database for proper-motion studies, but it too suffers from some limitations. First, there is considerable contamination among the high proper motion objects due to mismatches and false detections (e.g., due to diffraction spikes or dust), complicating the extraction of well-defined samples of high proper motion stars. This large contamination is partly by design, erring on the conservative side to include all detections, real or otherwise, as opposed to excluding some real detections with the rejected false detections. Second, as emphasized in Monet et al. (2003), USNO-B presents relative, not absolute, proper motions, with zero proper motion corresponding to the mean motion of the calibrating stars, dominated by stars with yellow magnitudes of 17–18. Third, there are known but not understood systematic errors in the positions as much as 250 mas. All of these will be addressed to some extent by the next version of USNO-B, which will be based on a recalibration using the Two Micron All Sky Survey (Skrutskie et al. 1997). Finally, the photometry in USNO-B is, of course, based on photographic plates, and many plates lack direct photometric calibrators. Analysis of the proper motions presented in USNO-B would benefit greatly from improved photometry, which can be provided by matching to SDSS.

This paper presents an improved proper-motion catalog for SDSS DR1, based on a match between SDSS and USNO-B. The object positions on the USNO-B plates are recalibrated using SDSS astrometry of galaxies, and proper motions are then recalculated using both the USNO-B and SDSS positions, greatly reducing the systematic errors, decreasing the statistical errors by roughly 20%–30%, and yielding absolute proper motions. Further, requiring that a USNO-B object match an SDSS object eliminates most of the false detections. The combination of improved USNO-B proper motions with SDSS photometry provides a powerful database for stellar population and Galactic structure studies.

2. ALGORITHMS

2.1. *Astrometry*

SDSS images the sky in drift-scan mode. The camera contains six columns of CCDs, with each column containing five CCDs, one for each filter bandpass (*u*, *g*, *r*, *i*, and *z*). The sky drifts down the columns, thus each drift-scan images six strips on the sky with five filter photometry, each strip approximately 0°.225 wide. Data are processed in units of these strips. See Stoughton et al. (2002) for a detailed description of the survey and its data processing.

All SDSS objects within a strip are matched to USNO-B, using a 1″ matching radius, after first applying the USNO-B proper motions to convert the USNO-B positions to the epoch of the SDSS observations. Objects in USNO-B that were detected on only two plates are not matched. Only matches where exactly one SDSS object matched exactly one USNO-B object are retained.

For each USNO-B object, the mean offsets in right ascension and declination between the SDSS position and the USNO-B position for the nearest 100 galaxies (nearest in coordinate parallel to the scan direction—the coordinate perpendicular to the scan direction is ignored, as the length of the binning window is always larger than the width of a scan) are calculated and added to the USNO-B position. This is done separately for each of the five plate positions in USNO-B. The SDSS morphological classification is used to determine which objects are galaxies. A "clean" sample of galaxies is used, where "clean" requires that (1) the galaxy be detected on all five plates in USNO-B; (2) it pass the set of criteria suggested on the SDSS DR1 Web site for defining a clean sample of galaxies,[1] rejecting objects affected by problems with deblending, pixel interpolation, etc.; and (3) its USNO-B magnitude (after recalibration onto the SDSS system—see § 2.2) on that plate be in the range 17–19.5 (to avoid large galaxies with poorly defined centroids). This recalibrates the positions at each epoch in USNO-B to the reference frame defined by the SDSS galaxies.

There are two major types of systematic errors in SDSS astrometry. First, atmospheric effects and random errors in the primary reference catalogs used introduce systematic errors of typically 45 mas (for those areas of sky reduced using the US Naval Observatory CCD Astrograph Catalog [UCAC; Zacharias et al. 2000]—this includes most of DR1) to 75 mas (for those areas of sky reduced against Tycho-2 [Høg et al. 2000]) on scales of roughly a tenth of a degree. Second, systematic errors in the UCAC (for data reduced against UCAC), and charge transfer effects in the SDSS astrometric CCDs (for data reduced against Tycho-2), contribute another 20–30 mas of systematic error. (See Pier et al. 2003 for a detailed discussion of SDSS astrometry.) The systematic errors in USNO-B are harder to characterize but can be as great as 250 mas. By recalibrating USNO-B using SDSS astrometry, many of the systematic errors in USNO-B are replaced with the smaller systematic errors in SDSS. To the extent that the two catalogs now share the same systematic errors, those errors are eliminated in the calculation of proper motions when combining the catalogs. By using galaxies as the calibrators, the new proper motions will be absolute rather than relative.

New proper motions are then calculated using a linear fit to both the recalibrated USNO-B positions at each epoch and the SDSS positions. The individual positions are weighted by their inverse variance, with SDSS and USNO-B positions assigned errors of 45 and 120 mas, respectively. While the catalog includes all objects, some have poor fits (most likely due to mismatched detections in USNO-B). A convenient filter is to consider as real only those objects that are considered "clean" according to the DR1 prescription, match exactly one object in USNO-B, and have rms residuals for the (new) fit in both right ascension and declination less than 350 mas. All analyses given below will use this sample.

[1] See http://www.sdss.org/dr1/products/catalogs/flags.html.

2.2. *Photometry*

Sesar et al. (2004) discuss the photometric recalibration of various Schmidt photographic plate–based catalogs (including USNO-A, USNO-B, and Guide Star Catalog II) using SDSS photometry as a dense set of photometric calibrators. The catalog presented here includes recalibrated USNO-B photometry. The algorithms, while differing in some details, are very similar to those discussed by Sesar et al. The photometric calibration will thus be discussed only briefly in this paper; the reader is referred to Sesar et al. for a more detailed discussion of the algorithms, results, and scientific applications.

The stellar photometry on each plate is recalibrated separately onto the closest matching SDSS filter (g for O and J plates, r for E and F plates, and i for N plates). Again, calibrations for each plate are applied separately for each single SDSS strip. The same clean sample of one-to-one matched pairs used for the astrometric calibration are used for the photometric calibration, although now stars (as determined using the SDSS morphological classification) rather than galaxies are used. First, a zero-point offset and color term of the form

$$m'_{\rm USNO} = m_{\rm USNO} + a + bc_{\rm SDSS} \quad (1)$$

is fitted, where $m_{\rm USNO}$ is the USNO-B catalog magnitude, $c_{\rm SDSS}$ is the SDSS color ($g-r$ for O, E, J, and F plates, $r-i$ for N plates), a is the zero-point offset for that plate, b is the color term, and $m'_{\rm USNO}$ is the recalibrated USNO-B magnitude on the SDSS system. An unweighted linear least-squares fit is used, so as to minimize the differences between the recalibrated USNO-B magnitudes and the SDSS magnitudes; all matched pairs on the plate in the SDSS magnitude range 15–18 are used. Next, magnitude terms are fitted by applying a running mean correction, adding the mean difference between the SDSS magnitude and the corrected USNO-B magnitude for the 25 nearest matched pairs sorted by magnitude. Finally, spatial variations across the plate are corrected by applying another running mean, adding the mean residual for the 25 nearest matched pairs sorted by coordinate parallel to the scan direction. Outliers whose magnitude difference exceeds 2 mag are rejected from all of the fits.

3. RESULTS

3.1. *Astrometry*

The simplest test of the quality of the recalibrated proper motions is to examine the measured proper motions of spectroscopically confirmed QSOs, which are morphologically stellar but should have no measurable proper motion. Figure 1 displays histograms of the component proper motions in right ascension and declination for all bright ($r < 18$) spectroscopically confirmed QSOs in the DR1 imaging area. Only bright QSOs are plotted to emphasize systematic errors arising from the calibrations rather than statistical errors due to increased centroiding errors for fainter objects. The solid histograms are for the recalibrated proper motions presented in this paper, while the dotted histograms are for the USNO-B catalog proper motions. The rms proper motion in right ascension (declination) is 3.60 (2.81) mas yr^{-1} for the recalibrated proper motions versus 5.30 (3.45) mas yr^{-1} for USNO-B, a roughly 30% (20%) improvement. The quality of both the USNO-B and recalibrated proper motions varies across the sky. For DR1 data near the celestial equator (SDSS stripes 9–12 and stripes 76–86), the rms proper motion in right ascension (declination) improves from 6.18 (3.65) to 4.07 (2.88) mas yr^{-1}, a 35% (20%) improvement. By contrast, at high declination (stripes 34–43), the USNO-B proper motions were significantly better, and thus the improvement is smaller, from 3.80 (3.17) to 2.86 (2.65) mas yr^{-1}.

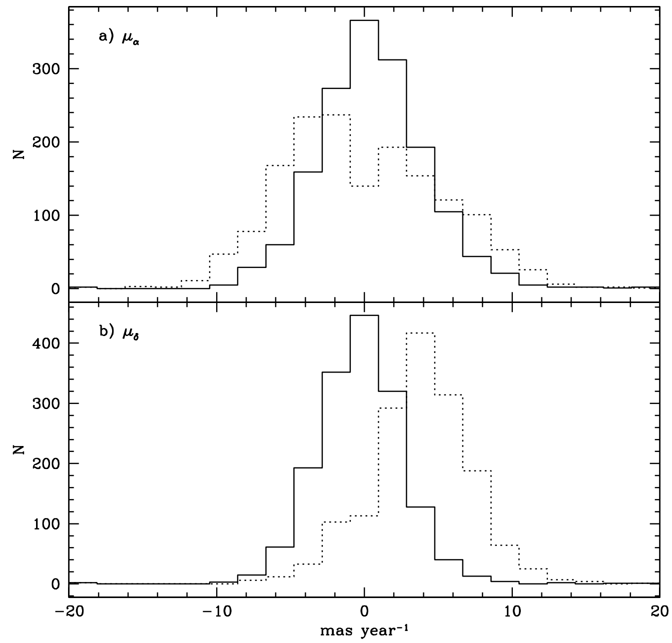

Fig. 1.—Histograms of component proper motions in (a) right ascension and (b) declination for all spectroscopically confirmed QSOs with $r < 18$. The solid histograms are for the recalibrated proper motions from this paper, while the dotted histograms are for proper motions from the USNO-B catalog.

The improvements in the rms errors are due not so much to the recalibration as to the addition of the considerably more accurate SDSS positions, tying down the later epoch, as well as the somewhat longer time baseline. More significant is the reduction in the overall systematic errors, particularly in declination, with the mean proper motion in declination for the bright QSOs dropping from 3.77 to −0.24 mas yr^{-1}; the improvements are primarily due to the recalibration of the USNO-B positions onto the SDSS reference frame. It is not clear why the systematic errors are larger in declination than right ascension; one possible cause is differential chromatic refraction, which is poorly behaved for QSOs with their strong emission lines and which for both surveys tends to have the strongest impact in declination. Magnitude-dependent errors, which are often important in Schmidt plate–based catalogs, are not expected to be significant for the current catalog (although if present may compromise some of the findings of this study); it spans the rough magnitude range 14–20, fainter than the limit for serious saturation effects on the Schmidt plates, and all stars are measured with respect to a local reference frame of faint, unsaturated galaxies. No significant magnitude terms are evident in the corrected centroids of the QSOs over the magnitude range of the catalog.

Figure 2 displays histograms of the total proper motions for the same QSO sample. For these bright QSOs, 68% have total recalibrated proper motions less than 4.7 mas yr^{-1}, and 95% have total recalibrated proper motions less than 8.4 mas yr^{-1}. This is roughly a 30% improvement over USNO-B, for which 68% have $\mu < 8.0$ mas yr^{-1} and 95% have $\mu < 12.2$ mas yr^{-1}. Figures 3 and 4 repeat Figures 1 and 2 for QSOs with $r < 20$, which is near the limit of the catalog, to give an indication of the errors achieved for fainter objects. The rms

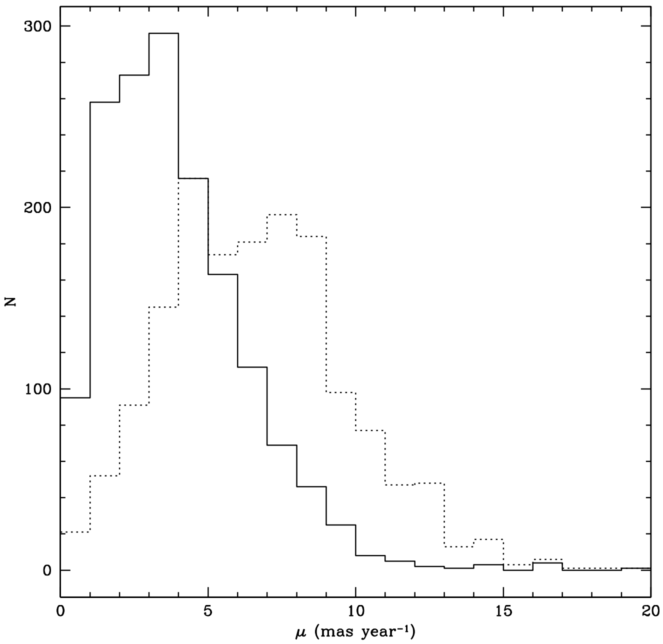

FIG. 2.—Histograms of total proper motions for all spectroscopically confirmed QSOs with $r < 18$. The solid histogram is for the recalibrated proper motions from this paper, while the dotted histogram is for proper motions from the USNO-B catalog.

recalibrated proper motion in right ascension (declination) increases to 4.23 (3.68) mas yr^{-1} when fainter QSOs are included; 68% have total recalibrated proper motions less than 5.6 mas yr^{-1}, and 95% have total recalibrated proper motions less than 10.6 mas yr^{-1}.

3.2. *Photometry*

Figure 5 plots the differences between the recalibrated USNO-B magnitudes and their associated SDSS magnitudes (g for O and J, r for E and F, and i for N), for all matched stars in DR1 brighter than 18th mag in the associated SDSS filter. The rms differences are roughly 0.14 mag in O, E, F, and N,

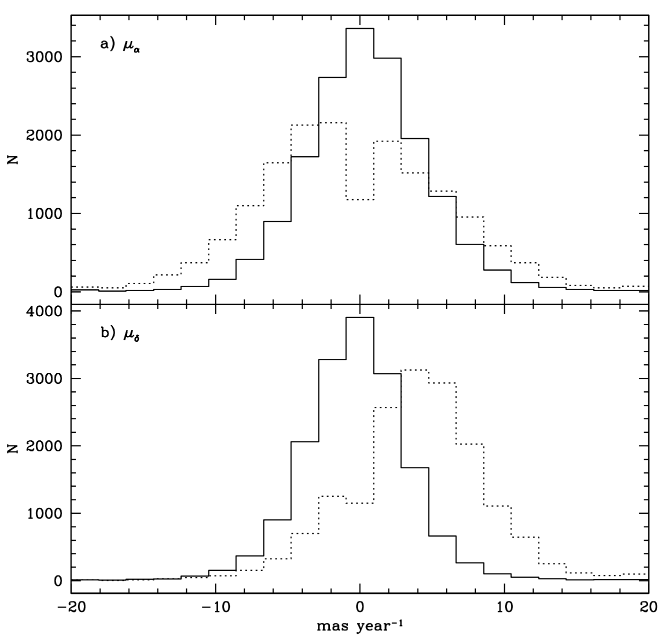

FIG. 3.—Same as Fig. 1, but for $r < 20$

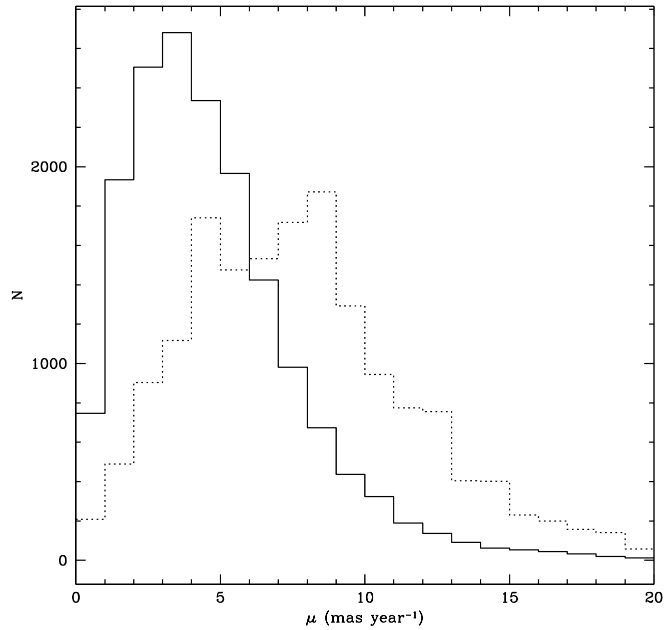

FIG. 4.—Same as Fig. 2, but for $r < 20$

and 0.18 mag in J. As discussed above, the photometric recalibration of various Schmidt photographic plate surveys, including USNO-B, are discussed in detail by Sesar et al. (2004); the reader is referred to that paper for more details on the photometric recalibrations.

3.3. *Completeness and Contamination*

SDSS reaches roughly 2 mag fainter than USNO-B, thus the completeness of the current catalog is determined by the completeness of USNO-B. As presented in Monet et al. (2003), USNO-B is essentially 100% complete for unblended stars (as determined by SDSS) for $g < 19.5$, dropping to about 97% when blended stars are included. However, the completeness is a function of color. Objects detected on fewer than four plates in USNO-B suffer from a large contamination by false matches. Thus, care must be taken to account for the completeness limits on each plate, as well as for mismatches. Figure 6 displays histograms of completeness versus magnitude in different SDSS filters for the new catalog presented here (hereafter referred to as SDSS+USNO-B). The catalog is 90% complete to $g = 19.7$, $r = 19.0$, $i = 18.2$, and $z = 17.5$; completeness in a given filter of course varies somewhat from plate to plate. (All analyses in this section compare the total sample of stars, limited to the "clean" sample as prescribed in the DR1 documentation, to the sample with reliable proper motions, limited to the subset of the "clean" sample that was a one-to-one match to USNO-B, and whose rms [new] fit residual was less than 350 mas in both coordinates. The completeness given here is somewhat lower than that presented in Monet et al. 2003 because of the more conservative definition of a "reliable" proper motion used in this paper.)

While proper motions are recalculated using the additional SDSS positions, there is no attempt to rematch individual plate detections within USNO-B, and so the sample of stars in this catalog with detected proper motions will be essentially the same sample as in USNO-B, although cleansed of most of the false matches and with improved proper motions. Thus, the SDSS+USNO-B catalog completeness as a function of proper motion is determined by the completeness of USNO-B.

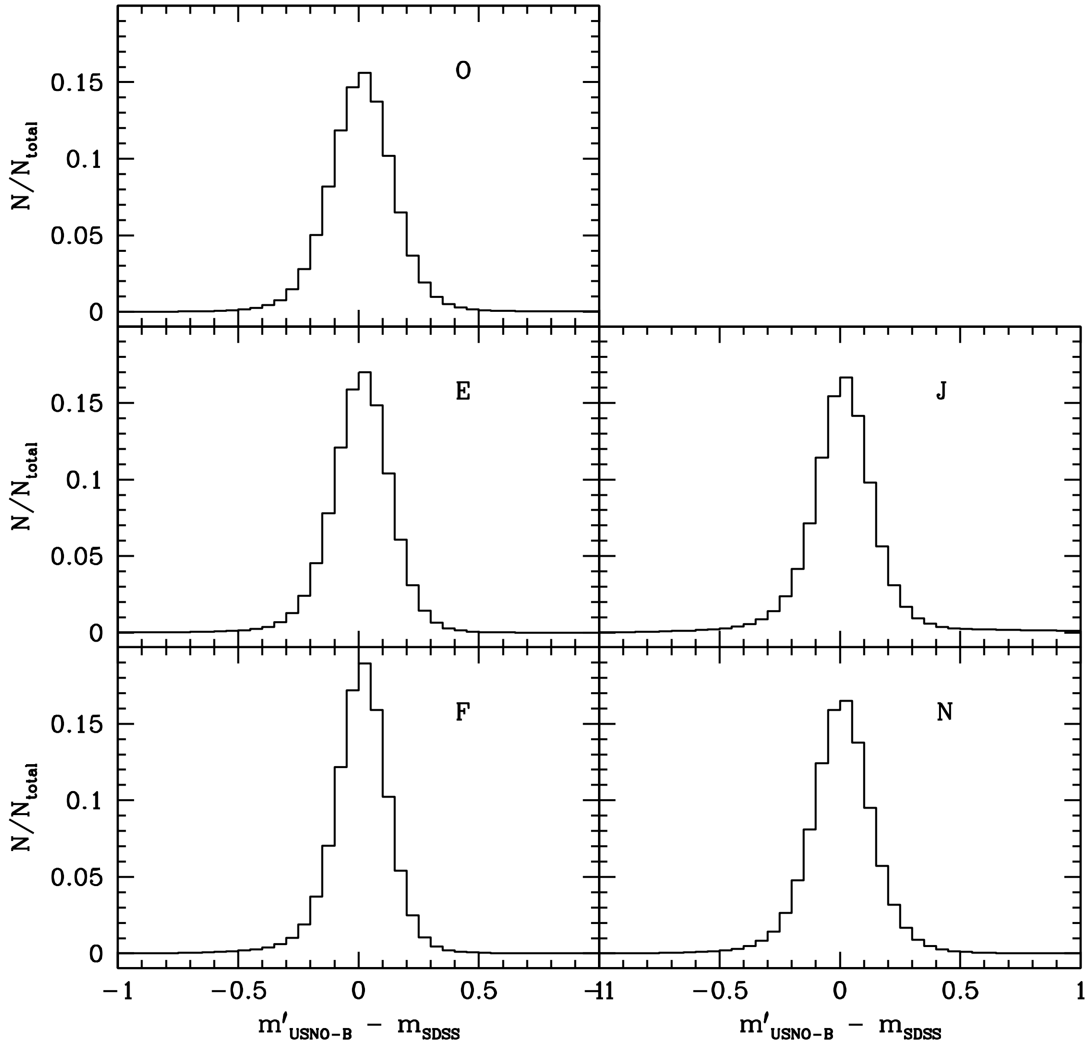

FIG. 5.—Differences between the recalibrated USNO-B magnitudes and their associated SDSS magnitudes for all matched stars in DR1 brighter than 18th mag in the associated SDSS filter.

Gould (2003) assessed the completeness of USNO-B for high proper motion objects by comparing it with the revised New Luyten Two-Tenths catalog (rNLTT; Gould & Salim 2003; Salim & Gould 2003). He finds an incompleteness for USNO-B of roughly 9% in the magnitude range $14 < V < 18.5$ outside the Galactic plane for $\mu > 180$ mas yr^{-1}, rising to 30% at $\mu = 1''$ yr^{-1}. This result is expected to characterize the completeness of the SDSS+USNO-B catalog. As a consistency check, and to better characterize the completeness as a function of the number of plates a star is detected on in USNO-B, part of that analysis is repeated here. Stars in the rNLTT catalog in the magnitude range $16 < V < 20$ were matched against the SDSS+USNO-B catalog. There are 908 such rNLTT stars located within the DR1 area, of which 799 match an entry in the SDSS+USNO-B catalog, yielding an incompleteness of 12%, in rough agreement with Gould (2003). Figure 7 presents the fraction of matches as a function of proper motion. Completeness drops by a few percent if matches are limited to stars detected on at least four USNO-B plates. For proper motions greater than 500 mas yr^{-1}, there are 24 rNLTT stars in the given magnitude range within the DR1 area, of which 20 match (17 if limited to stars detected on at least four plates).

Figure 8 plots the differences between the SDSS+USNO-B and rNLTT proper motions, versus the rNLTT proper motions, for the 799 matches. Most agree very well; 18 (2.3%) have proper motions differing by more than 50 mas yr^{-1} between the two catalogs. The USNO-B plate images for each epoch were examined by eye for these 18 stars with discrepant proper motions; the SDSS+USNO-B proper motions were correct for 16 of the stars, the rNLTT proper motion was correct for one star, and for the remaining star it was not obvious which catalog was correct.

During the fall observing seasons, SDSS is repeatedly scanning a strip of sky $2\overset{\circ}{.}5$ wide along the celestial equator, over the right ascension range $20^{\rm h}44^{\rm m}$ to $3^{\rm h}56^{\rm m}$. These repeat scans can be used to detect stars with large proper motions, with little confusion due to mismatches as even stars with proper motions as great as $1''$ yr^{-1} will only move $4''$ over the maximum epoch difference of 4 yr. Two sets of SDSS scans, separated by 4.06 yr (scans 3394 and 94) and 2.08 yr (scans 3434 and 1755) have been matched, creating a proper-motion catalog that is considerably fainter than USNO-B over a total of 166 deg^2. The astrometry of one scan in each pair has been recalibrated to that of the other scan in a similar matter as described above to improve the accuracy of the proper

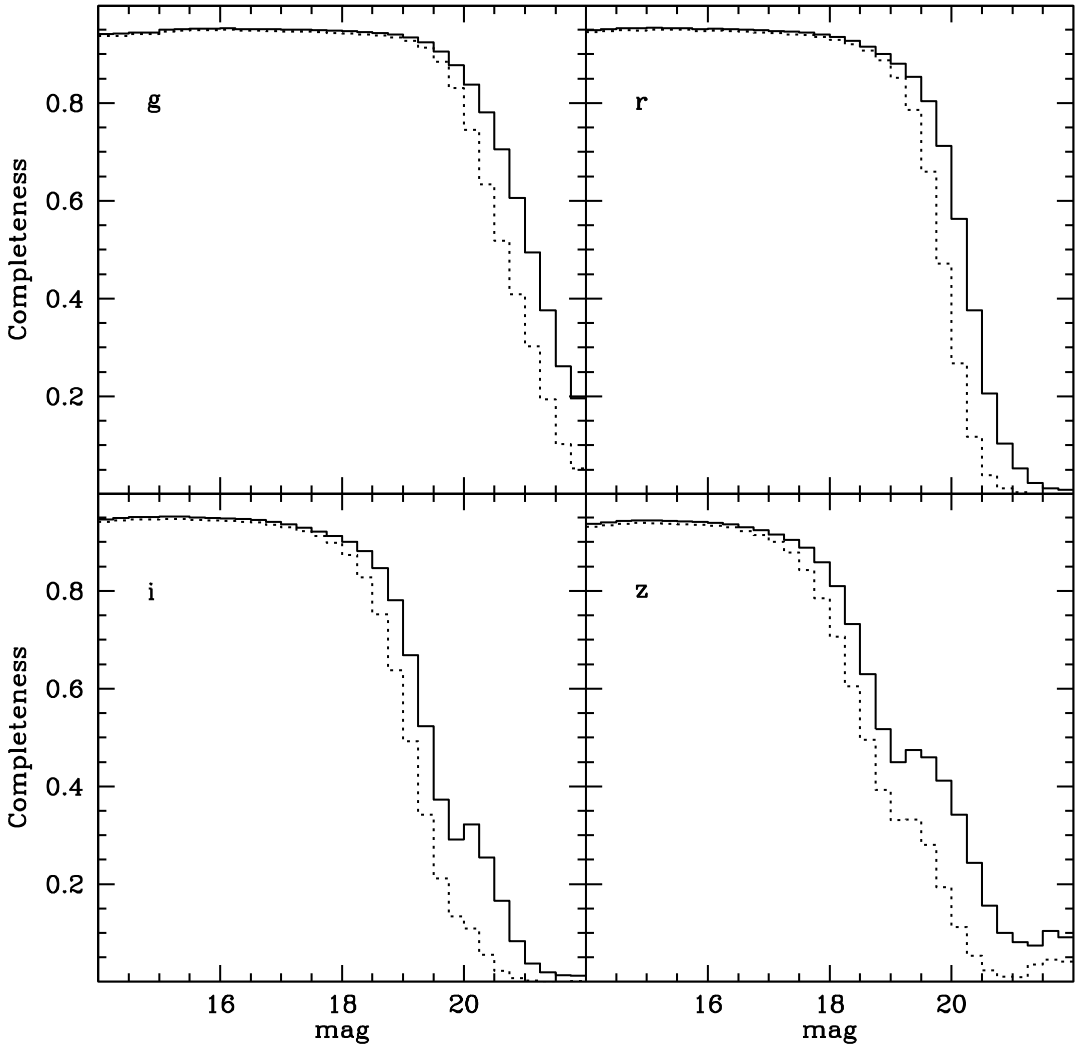

Fig. 6.—Completeness of the SDSS+USNO-B catalog as a function of magnitude in the SDSS filters g, r, i, and z. The solid histogram is for all stars, while the dotted histogram is for stars detected on at least four plates in USNO-B.

motions. Matching the SDSS+USNO-B catalog versus this SDSS+SDSS catalog gives a measure of both the completeness and contamination of the SDSS+USNO-B catalog. Figure 9 presents the completeness as a function of proper motion, for stars in the magnitude range $16 < g < 19.5$. Incompleteness increases from 6% at low proper motion to approximately 15% at high proper motion, in rough agreement with the rNLTT results. Less than 0.5% of the SDSS+USNO-B catalog stars lack a matching object in the other SDSS run, with no proper-motion dependency; thus, the contamination rate is less than 0.5% (perhaps much less, as some differences between the two SDSS runs can be expected due, e.g., to different deblending under different seeing), which is a major improvement on USNO-B (as will be described below). Figure 10 plots the differences between the SDSS+USNO-B and SDSS+SDSS proper motions for the 167,669 stars in common in the two catalogs (677 of which were detected on only three plates in USNO-B). A few tens have discordant proper motions, giving a false detection rate well under 0.1%.

3.4. *USNO-B Contamination by False Detections*

The contamination rate of false detections in USNO-B can be examined by comparing the number of objects in USNO-B that match an SDSS object, which has been shown to be very nearly the complete sample of real objects in USNO-B with very little contamination, with the total number of objects in USNO-B. The contamination rate in USNO-B is high by design; the intention was to err on the side of including all detections, real or not, so as not to exclude real objects that may have been excluded by any winnowing procedure. Users may then apply appropriate filters to extract the catalog of objects best suited for their application. Figure 11 displays histograms of counts versus proper motion for all objects in USNO-B within the DR1 area (*solid lines*), those whose rms residual around the fit is 300 mas or less in both coordinates (*dotted line*), and those that match an SDSS object with a reliably measured proper motion (*dashed line*, where "reliably measured" is defined in § 3.3), separately for objects detected on at least four plates (*top*) and those detected on only three plates (*bottom*). For objects detected on at least four plates, the contamination rate (as determined by comparing the solid line representing all objects in USNO-B with the dotted line representing those which matched an SDSS object, and which therefore presumably are real) is seen to be very small for objects with no detectable proper motion, increasing to roughly a factor of 10 false identifications for every real identification for high proper motion stars. Requiring that a real object have a rms residual around the fit of 300 mas or less helps greatly,

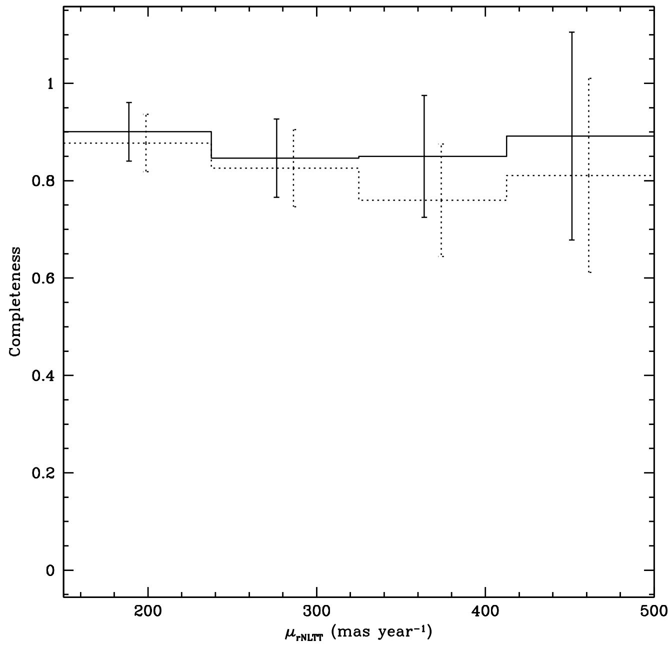

FIG. 7.—Fraction of rNLTT stars in the DR1 area with $16 < V < 20$ that are found in the SDSS+USNO-B catalog, as a function of proper motion. The solid histogram is for all stars, while the dotted histogram is for stars detected on at least four plates in USNO-B.

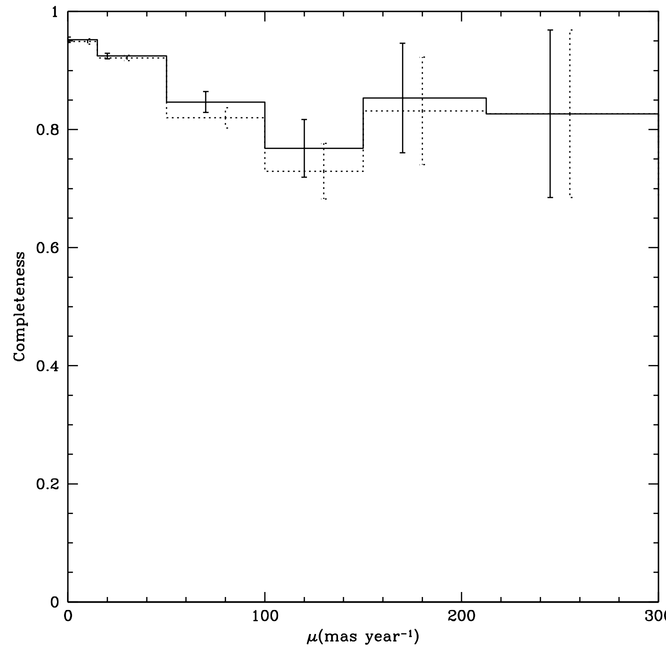

FIG. 9.—Fraction of stars in the SDSS+SDSS catalog with $16 < g < 19.5$ that are found in the SDSS+USNO-B catalog, as a function of proper motion. The solid histogram is for all stars, while the dotted histogram is for stars detected on at least four plates in USNO-B.

but still gives two to three false high proper motion stars for every real object. The contamination rate is considerably higher for stars detected on only three plates in USNO-B, and the rms residual filter is less effective at removing the contaminants. Contamination in USNO-B is discussed in considerably more detail by Levine et al. (2004).

4. THE CATALOG

The SDSS+USNO-B catalog is available via anonymous ftp at ftp.nofs.navy.mil, in the directory pub/outgoing/sdss-usnob. It is available as single binary FITS tables per strip (per "segment" in SDSS parlance). Refer to the README file for instructions on downloading the files and a full description of the catalog. In brief, the files contain all stars with a g point-spread function (PSF) magnitude brighter than 23. They contain copies of many of the survey outputs relevant to stars, including identifying information, processing flags, PSF magnitudes and their errors, extinction values, coordinates, spectroscopic targeting information, observation epoch, and seeing during the observation. In addition to the normal survey attributes, the following attributes are listed that contain the proper-motion information derived in this paper: (1) the number of objects in USNO-B that match this SDSS object within a 1″ radius (negative if the matching USNO-B object itself was matched by more than one SDSS object); (2) the distance to the nearest matching object (after converting USNO-B coordinates to the epoch of the SDSS observations), in arcseconds; (3) the proper motion in right ascension and

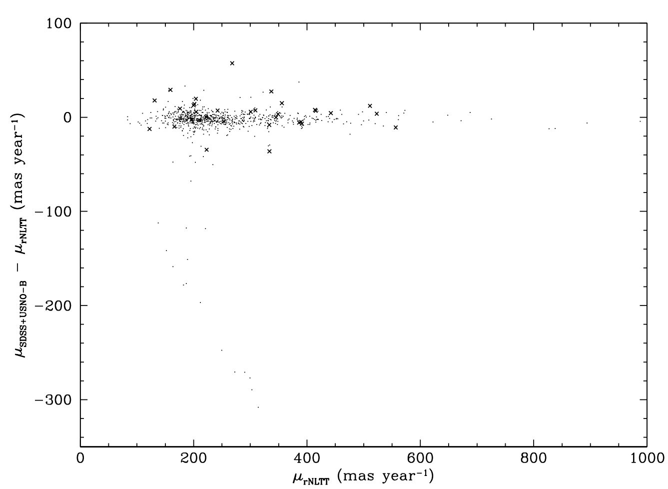

FIG. 8.—Difference between the SDSS+USNO-B and rNLTT proper motions vs. the rNLTT proper motion for all stars in common between the two catalogs with $16 < V < 20$. Points represent stars detected on at least four plates in USNO-B, while crosses represent stars detected on only three plates in USNO-B.

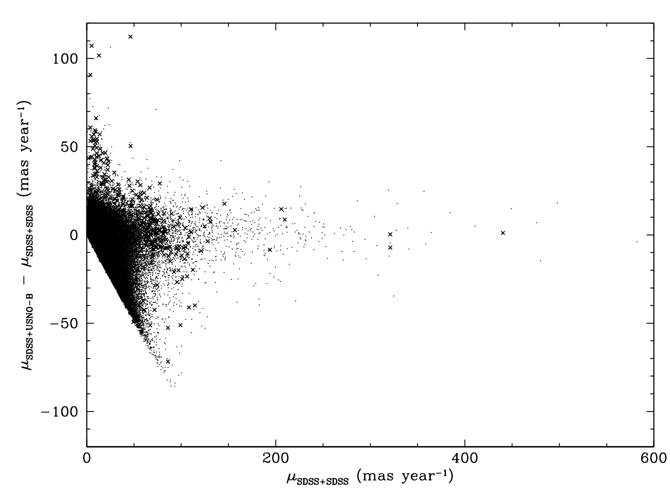

FIG. 10.—Difference between the SDSS+USNO-B and SDSS+SDSS proper motions vs. the SDSS+SDSS proper motion for all stars in common between the two catalogs with $16 < V < 19.5$. Points represent stars detected on at least four plates in USNO-B, while crosses represent stars detected on only three plates in USNO-B.

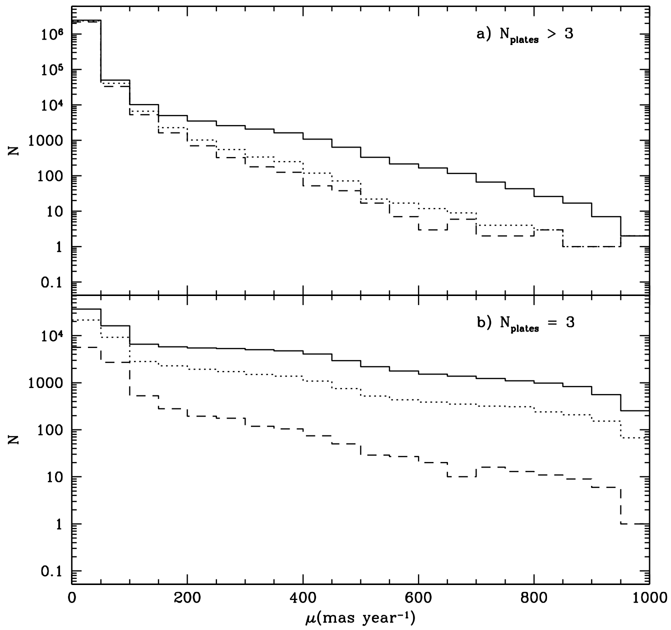

Fig. 11.—Histograms of counts vs. proper motion for all objects in USNO-B within the DR1 area (*solid lines*), those whose rms residual of the plate positions around the fitted proper motion is less than or equal to 300 mas (*dotted line*), and those that match an SDSS object (*dashed line*). (*a*) Histograms for objects detected on at least four plates. (*b*) Histograms for objects detected on only three plates.

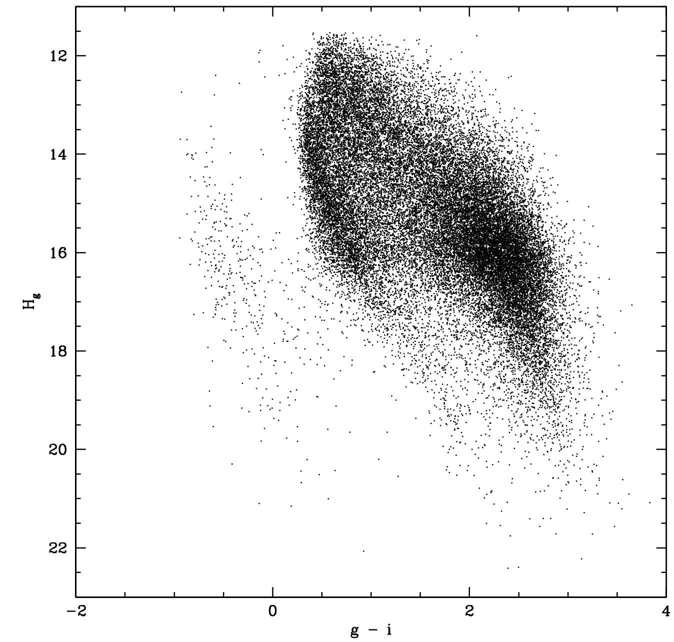

Fig. 12.—Reduced proper-motion diagram for stars in stripe 35 with reliably measured proper motions greater than 20 mas yr^{-1} and $16 < g < 19.5$.

declination, as well as in Galactic longitude and latitude, in milliarcseconds per year; (4) the rms residual for the proper-motion fit in right ascension and declination, in milliarcseconds; (5) the number of detections used in the fit, including the SDSS detection (thus, the number of plates the object was detected on in USNO-B plus one); and (6) the recalibrated O, E, J, F, and N USNO-B magnitudes.

The suggested method for creating a sample of stars with reliable proper motions is to select stars matching the "clean" criteria as described in the DR1 documentation, to require a one-to-one match to USNO-B (that is, the recorded number of matches be set to 1), and to require that the rms fit residual be less than 350 mas in both coordinates. A conservative cut would be to require further that the number of epochs fit be five or greater (that is, that it be detected on at least four plates in USNO-B). The contamination rate is greater for stars detected on only three plates, but there are many real matches among such stars. Clearly, the filter to apply depends on the application; however, this catalog is an attempt to assemble a clean sample of detections from USNO-B, and one cannot recover those objects in USNO-B that did not match an SDSS object.

5. DISCUSSION

This paper presents an improved proper-motion catalog for SDSS DR1, based on SDSS and USNO-B astrometry. To summarize, the SDSS+USNO-B catalog is 90% complete to $g < 19.7$, giving absolute proper motions with statistical errors of approximately 3–3.5 mas yr^{-1}, substantially smaller systematic errors, and a contamination rate of less than 0.5%. Completeness is a function of proper motion, dropping from around 94% for proper motions less than 20 mas yr^{-1} to around 85% for proper motions of 100–300 mas yr^{-1} to 70% for proper motions of 1″ yr^{-1}. A number of studies are currently underway that use these proper motions; these will be presented in subsequent papers. However, it is of interest to highlight a few applications of such a data set.

Figure 12 presents a reduced proper-motion diagram for a portion of DR1 (stripe 35, covering 293 deg^2, or 14% of DR1) for a "clean" sample of stars with reliably measured proper motions greater than 20 mas yr^{-1} and $16 < g < 19.5$. The reduced proper motion has the usual definition:

$$H_g = g + 5\log\left(\frac{\mu}{\text{arcsec yr}^{-1}}\right) + 5. \qquad (2)$$

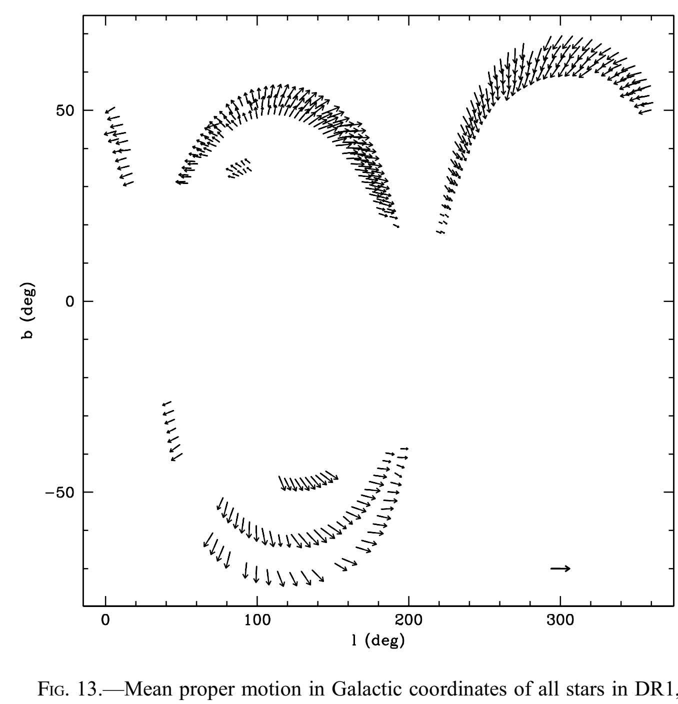

Fig. 13.—Mean proper motion in Galactic coordinates of all stars in DR1, as a function of Galactic coordinates. Each vector represents the mean motion for all stars in a 2°.5 long piece of a stripe, with the length scaled linearly to the total motion. The bold vector in the bottom right corner of the plot is for scale, representing a mean motion of 10 mas yr^{-1}.

The combination of accurate SDSS photometry and SDSS+ USNO-B astrometry gives a clean separation between the main-sequence stars, subdwarfs, and white dwarfs.

Reduced proper motions are a particularly effective way to find cool white dwarfs, whose colors redden as they cool and become indistinguishable from main-sequence stars. A number of spectroscopic follow-up programs are currently underway to confirm the coolest white dwarf candidates selected from this catalog and thus better constrain the faint end of the white dwarf luminosity function. Kleinman et al. (2004) display a similar diagram, based on proper motions from this catalog, for all spectroscopically confirmed white dwarfs in DR1. Digby et al. (2003) used reduced proper-motion diagrams, produced with photometry from the SDSS Early Data Release (Stoughton et al. 2002) and proper motions based on matches between the SDSS Early Data Release and scans of POSS-I E plates in the SuperCOSMOS Sky Survey, to study the subdwarf luminosity function.

A proper-motion error of 3 mas yr^{-1} corresponds to a tangential velocity error of 28 km s^{-1} at a distance of 2 kpc. Combined with photometric parallaxes from SDSS photometry, and radial velocities from SDSS spectroscopy in selected fields, this enables kinematical studies well out into the thick disk. A number of such studies are currently in progress. As a simple example, Figure 13 plots the mean proper motion for all stars in DR1 (each vector represents the mean motion for all stars in a $2\overset{\circ}{.}5$ long piece of a stripe), as a function of Galactic coordinates. The patterns imposed by Galactic rotation and solar motion are evident. While a quantitative analysis of such a diagram is beyond the scope of this paper, it gives some indication of the leverage obtained by the combination of SDSS and USNO-B for the study of the structure of the Milky Way.

The catalog presented in this paper, with its small systematic errors, is especially useful for classifying objects with small proper motions. For example, Kleinman et al. (2004) use the small but nonzero motions of faint DC white dwarfs to distinguish them from BL Lac objects. Similarly, Margon et al. (2002) and Downes et al. (2004) use the small motions of dwarf carbon stars to distinguish them from giant carbon stars at much larger distances.

Funding for the creation and distribution of the SDSS Archive has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Aeronautics and Space Administration, the National Science Foundation, the Department of Energy, the Japanese Monbukagakusho, and the Max Planck Society. The SDSS Web site is http://www.sdss.org. The SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions. The Participating Institutions are the University of Chicago, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, Los Alamos National Laboratory, the Max-Planck-Institut für Astronomie, the Max-Planck-Institut für Astrophysik, New Mexico State University, University of Pittsburgh, Princeton University, the US Naval Observatory, and the University of Washington.

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Note added in proof.—A similar paper by A. Gould and J. Kollmeier, deriving proper motions by combining SDSS, USNO-A2.0, and USNO-B1.0, appeared on astro-ph on the day this paper was submitted to the Astronomical Journal and is now in press in the Astrophysical Journal Supplement Series. It differs significantly in the techniques used for deriving recalibrated proper motions. The reader is referred to that paper for a different approach to the problem (A. Gould & J. Kollmeier, ApJS, preprint [doi: 10.1086/382529]).

The Astronomical Journal, 136:895, 2008 August
doi:10.1088/0004-6256/136/2/895

ERRATUM: "AN IMPROVED PROPER-MOTION CATALOG COMBINING USNO-B AND THE SLOAN DIGITAL SKY SURVEY" (2004, AJ, 127, 3034)

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The authors have discovered an error in the calculation of the proper motions in right ascension (the proper motions in declination were not affected by the error, and are thus correct). The error involves the use of an incorrect sign when interpreting the residuals in right ascension in the USNO-B catalog. The results of the error are as follows.

1. The proper motions in right ascension suffer from smoothly varying systematic errors of as much as 3 mas year^{-1}, though more typically 1–2 mas year^{-1}.
2. For objects which had a non-zero proper motion in right ascension in USNO-B, the differences between the proper motions in right ascension when correctly and incorrectly determined, after removing the systematic error, have a dispersion of approximately 1 mas year^{-1}. This additional error is insignificant in comparison with the known statistical errors in the proper motions of roughly 3.5 mas year^{-1} per coordinate.
3. In USNO-B, objects which had a proper motion consistent with zero to within a few sigma were set to have a proper motion of exactly zero. For these objects, the dispersion between the correctly and incorrectly determined proper motions in right ascension, after removing the systematic errors, is approximately 5 mas year^{-1}. These motions are simply wrong, though still consistent with zero proper motion to within the errors.

For users working with samples of stars chosen to have significantly detected proper motions, the impact of the error should be small. However, for users working closer to the statistical error limit, or averaging over many stars to determine small mean motions, the additional errors are clearly significant.

A corrected version of the catalog has been generated. The corrected motions will be available in Data Release 7 of the Sloan Digital Sky Survey Catalog Archive Server, due out in October 2008. Until then, corrected motions may be obtained by contacting the first author.