The Extended Gaia–PS1–SDSS (GPS1+) Proper Motion Catalog

Hai-Jun Tian1,2, Yang Xu3, Chao Liu1, Hans-Walter Rix2, Branimir Sesar2, and Bertrand Goldman2,4
1 Center for Astronomy and Space Sciences, China Three Gorges University, Yichang 443002, People’s Republic of China; hjtian@lamost.org
2 Max Planck Institute for Astronomy, Königstuhl 17, D-69117 Heidelberg, Germany
3 Key Lab for Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 10012, People’s Republic of China
4 Observatoire astronomique de Strasbourg, Université de Strasbourg, CNRS, UMR 7550, 11 rue de l’Université, F-67000 Strasbourg, France

Received 2020 February 20; revised 2020 April 24; accepted 2020 April 25; published 2020 June 10

Abstract

The Gaia + PanSTARRS1 (PS1) + Sloan Digital Sky Survey (SDSS) + Two Micron All-Sky Survey (2MASS) (GPS1) catalog was released in 2017. It delivered precise proper motions for around 350 million sources down to a magnitude of \( r \sim 20 \) mag. In this study, we present GPS1+, the extension GPS1 catalog down to \( r \sim 22.5 \) mag, based on Gaia data release 2 (DR2), PS1, SDSS, and 2MASS astrometry. GPS1+ totally provides proper motions for \( \sim 400 \) million sources with a characteristic systematic error of less than 0.1 mas yr\(^{-1}\). This catalog is divided into two subsamples, i.e., the primary and secondary parts. The primary \( \sim 264 \) million sources have either or both Gaia and SDSS astrometry, with a typical precision of 2.0–5.0 mas yr\(^{-1}\). In this part, \( \sim 160 \) million sources have Gaia proper motions, and we provide another new proper motion for each of them by building a Bayesian model. Relative to Gaia’s values, the precision is improved by \( \sim 0.1 \) dex on average; \( \sim 50 \) million sources are the objects whose proper motions are missing in Gaia DR2, and we provide their proper motions with a precision of \( \sim 4.5 \) mas yr\(^{-1}\). The remaining \( \sim 54 \) million faint sources are beyond Gaia detecting capability, and we provide their proper motions for the first time with a precision of 7.0 mas yr\(^{-1}\). However, the secondary \( \sim 136 \) million sources only have PS1 astrometry, where the average precision is worse than 15.0 mas yr\(^{-1}\). The large uncertainty probably limits it to qualitative applications. All the proper motions have been validated using QSOs and the existing Gaia proper motions. The catalog will be available via the TAP Service in the German Astrophysical Virtual Observatory.

Unified Astronomy Thesaurus concepts: Galaxy kinematics (602); Astrometry (80); Catalogs (205); Galaxy dynamics (591); Proper motions (1295)

1. Introduction

Gaia, a cornerstone mission of the European Space Agency (ESA), is ambitious in charting a three-dimensional map of our Galaxy with unprecedented precision. After 22 months of observations, Gaia delivered its second release (Gaia DR2) on 2018 April 25 (Gaia Collaboration et al. 2018). This catalog contains the positions of nearly 1.7 billion objects with a G-band magnitude brighter than \( \sim 20.7 \). Among these sources, more than 1.3 billion stars in the Milky Way have precise positions, proper motions, parallaxes, and colors. The average uncertainties in the respective proper motion components are up to 0.06 mas yr\(^{-1}\) (for \( G < 15 \) mag), 0.2 mas yr\(^{-1}\) (for \( G = 17 \) mag), and 1.2 mas yr\(^{-1}\) (for \( G = 20 \) mag). The Gaia DR2 parallaxes and proper motions are based only on Gaia data.

The Gaia DR2 supersedes the most majority of current existing proper motion catalogs. The previous proper motion catalogs, such as Proper Motions eXtended cataLogue (Roesser et al. 2010), Hot Stuff for One Year (HSOY; Altmann et al. 2017), the USNO CCD Astrograph Catalog (UCAC) series (Zacharias et al. 2004, 2010, 2017), Absolute Proper Motions Outside the Plane (Qi et al. 2015), and GPS1 (Tian et al. 2017a, hereafter, T17), are not comparable with Gaia DR2 in quality, even though HSOY, UCAC5, and GPS1 were built combining the precise Gaia DR1 astrometry (Gaia Collaboration et al. 2016).

Unfortunately, some limitations still exist in Gaia DR2: (1) more than 361 million sources only have positions (precision \( \sim 2 \) mas) at J2015.5 and the mean G magnitude, missing proper motions, and parallaxes, etc.; (2) the average precision of proper motions is hard to reach at a level of sub-mas yr\(^{-1}\) for faint sources, in particular for those close to the Gaia limiting magnitude; (3) Gaia DR2 is complete in \( 12 < G < 17 \) mag but is incomplete at an ill-defined faint magnitude limit; and (4) there are no sources with \( G > 20.7 \) mag.

In this study, we would like to extend the GPS1 and release a GPS1+ proper motion catalog to make up the limitations of Gaia DR2. Therefore, the GPS1+ will mainly focus on: (1) the sources (\( 19 < G < 20.7 \) mag), using the Gaia DR2 proper motions as priors to improve the proper motions combining PanSTARRS1 (PS1) and the Sloan Digital Sky Survey (SDSS) if their proper motions were measured in Gaia DR2; (2) the part of missing sources (>361 million) in Gaia DR2 where their proper motions are calculated with the same procedure as GPS1; and (3) the faint sources (\( 20.7 < G < 22.5 \) mag), using the same procedure as GPS1.

With the above motivations, we arrange the remainder of this paper as follows. In Section 2, we describe how to construct the GPS1+ catalog. In this section, we first briefly summarize the four data sets and describe a Bayesian model to calculate proper motions for the sources that have Gaia proper motions. Section 3 then presents the results of GPS1+ proper motions and demonstrates their performance in accuracy and precision. In Section 4, we briefly discuss the limitations of GPS1+ and summarize in Section 5.

Throughout the paper, we adopt the Solar motion as \( (U_\odot, V_\odot, W_\odot) = (9.58, 10.52, 7.01) \) km s\(^{-1}\) (Tian et al. 2015) and the International Astronomical Union circular speed of the local standard of rest (LSR) as \( V_\odot = 220 \) km s\(^{-1}\). Also, \( \alpha^* \) is used to denote the R.A. in the gnomonic projection coordinate.
2. The Construction of GPS1+

2.1. Data Set

We still use the four basic imaging surveys, i.e., Gaia, PS1, SDSS, and 2MASS, to build the GPS1+ catalog. Unlike GPS1, GPS1+ will be based on the Gaia DR2, but the other three astrometric data sets remain the same as those used in GPS1, i.e., the same data version and treatment.

Gaia DR2 consists of around 1.69 billion astrometric sources (Gaia Collaboration et al. 2018). All the sources have positions, and they are calibrated to the International Celestial Reference System (ICRF) at epoch J2015.5. The typical uncertainties in positions are of the order of 0.7 mas for sources at the faint end (i.e., \( G = 20 \) mag), as shown in the top panel of Figure 1. Therefore, Gaia DR2 is able to provide one precise observational position at epoch J2015.5. The epoch is different from J2015.0 in Gaia DR1.

About 1.33 billion sources have proper motions, but more than 361 million sources have no proper motions in Gaia DR2. The sources missing proper motions are mainly located at the faint region in Gaia DR2, as shown in the top panel of Figure 2 by comparing the histograms between the entire sources (blue) and those without proper motions (green) in Gaia DR2. The bottom panel of Figure 2 displays the scatter distribution of the uncertainties of Gaia DR2 proper motions at the faint region \((r > 19 \) mag). The red points are the median uncertainties of proper motions in different magnitude bins. The median uncertainty is larger than 2.0 mas yr\(^{-1}\) (marked with the black dashed line) for the sources close to the limiting magnitude. The proper motion precision of these sources will be significantly improved by combining the astrometry of PS1, SDSS, and Gaia. This point will be demonstrated in Section 2.2.

PanSTARRS1 (PS1; Chambers 2011) is a wide-field optical/near-infrared (IR) survey telescope system, which has been conducting multi-epoch and multi-color observations over the entire sky visible from Hawaii (decl. \( \gtrsim -30^\circ \)) for many years. Its Processing Version 3 catalog (PV3; Chambers & Magnier et al. 2016) contained around 65 detections for each source over a sky area of \(~30,000 \) deg\(^2\) with epochs throughout the 5.5 yr from 2010 to 2014.

As done in GPS1, we determine a robust average position and its uncertainties for each faint object within a season.
(hereafter, SeasonAVG, \( m_{PS1} > 19.0 \) mag) in PS1. Each source is detected more than 10 times in an observing season. The typical single-epoch positional precision of faint sources is \( \sim 50 \) mas, as illustrated in the second panel of Figure 1. Furthermore, we apply the selection cuts used in GPS1 on the individual detections and the individual faint sources to remove the PS1 astrometry outliers. Finally, we obtain around 400 million faint objects with billions of detections.

The Sloan Digital Sky Survey (SDSS) began its regular operations in 2000 April (York & Adelman et al. 2000). Its ninth data release (DR9) almost contains all its photometric data (Ahn et al. 2012), which were imaged in the early epochs, e.g., 10–20 yr ago. The long epoch baseline makes this data very valuable. The typical astrometric uncertainties for faint stars (\( r > 19.0 \) mag) are around 80 mas per coordinate (Stoughton et al. 2002), as shown in the third panel of Figure 1.

The Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) All-Sky Data Release identifies around 471 million point sources and 1.6 million extended sources, covering virtually the entire celestial sphere between 1997 June and 2001 February. Faint source extractions have the astrometric accuracy of the order 100 mas, as shown in the bottom panel of Figure 1. Because of large positional uncertainties, 2MASS positions provide only a weak constraint for proper motion measurements.

We crossmatched the PS1 objects with Gaia, 2MASS, and SDSS using a 1.5° search radius. Therefore, the internal ID from PS1 is the key identifier to connect the four catalogs.

The black histogram in Figure 2 indicates that there are more than 60% PS1 sources beyond Gaia’s limiting magnitude. These sources (\( \geq 70\% \)) without Gaia (including Gaia missing) proper motions will be our main interest in this study.

### 2.2. Derivation of Proper Motions

Proper motions in GPS1+ are determined basically with the same procedure used in GPS1. The key difference just takes place on the sources that have Gaia proper motions. For these sources, we calculate two kinds of proper motions for each source: one is with the method of GPS1, i.e., by performing a linear least-squares fit; the other is fitted through a Bayesian model that uses Gaia proper motions as priors and combines the astrometry of Gaia, PS1, SDSS, and 2MASS. It is worth mentioning that both of the two fit methods do not involve Gaia parallaxes, so the derived proper motions will be away from the impact of parallaxes, unlike Gaia’s proper motions that are correlated with the parallax.

With the procedure of GPS1 construction, we build a reference catalog by averaging repeatedly observed positions of PS1 galaxies in each tile (i.e., a sky area of a constant size of \( 10^5 \) by \( 10^5 \)) and calibrate the cataloged positions for each object in five (or six) PS1 epochs, one Gaia epoch, possibly one SDSS epoch, and one 2MASS epoch onto the same reference frame. All the steps have been minutely summarized in Section 3 of T17. For each source, we calculate its proper motion by performing a linear least-squares fit based on a simple \( \chi^2 \), which is described in Equation (2) of T17. But for a source that has a Gaia proper motion, we re-measure another new proper motion by building a Bayesian model. We start with a likelihood:

\[
L = p((t_i, \gamma_i) | \mu, b) = \prod_i^{N} \left[ \frac{1}{\sqrt{\epsilon_i^2}} \exp \left( -\frac{1}{2} \left( \frac{\gamma_i - \gamma_i^{\text{model}}(t_i)}{\epsilon_i} \right)^2 \right) \right],
\]

where \( \gamma_i^{\text{obs}} \) is the observed position of a star with a positional uncertainty, \( \epsilon_i \), at epoch \( i \). The positional uncertainty \( \epsilon_i \) consists
of two parts: one part is the individual position precision, as illustrated in Figure 1; and the other part is the uncertainty from the offset calibration discussed in Section 3.2 of T17. $y_{\text{model}}(t_i)$ is the predicted position by a linear model at the given time $t_i$, i.e., $y_{\text{model}}(t_i) = \mu t_i + b$, where $N$ is the number of epochs in different surveys. The position $\hat{y}_i^\alpha$ has been calibrated by

$$\hat{y}_i^\alpha = y_i^\alpha - \Delta_i(\alpha, \delta) - \Delta_i(\delta, m),$$

where $y_i^\alpha$ is the original cataloged position of a star at epoch $i$, $\Delta_i(\alpha, \delta)$ is the direction dependent offset described in Section 3.2.1 of T17, and $\Delta_i(\delta, m)$ is the magnitude and decl. dependent offset described in Section 3.2.2 of T17.

According to Bayes theorem, the posterior probability can be easily expressed as

$$p(\{\mu, b|t_i, y_i^\alpha\}) = p(\{t_i, y_i^\alpha|\mu, b\})p(\mu, b),$$

so we assume the prior probability of $\mu$ obeys a Gaussian distribution with $\mu = \mu_{\text{Gaia}}$ and $\sigma = \epsilon_{\text{Gaia}}$, where $\mu_{\text{Gaia}}$ and $\epsilon_{\text{Gaia}}$ are the proper motion and uncertainty values of a source provided by Gaia DR2. We assume a flat prior probability of $b$, i.e., $p(b) = 1$.

We use emcee (Foreman-Mackey et al. 2013) to sample the posterior distribution (Equation (3)) and estimate proper motions in the two directions, i.e., $\mu_{\text{Gaia}}$ and $\mu_{\text{PS1}}$, respectively. In practice, we could use the joint posterior probability to

### Table 1

The Columns of GPS1+ Catalog

| Column | Unit  | Description |
|--------|-------|-------------|
| 1      | obj_id* | The unique but internal object_id in PS1 |
| 2      | R.A.   | degree      | R.A. at J2015.0 from Gaia DR2 |
| 3      | Decl.  | degree      | Decl. at J2015.0 from Gaia DR2 |
| 4      | e_ra   | mas         | Positional uncertainty in R.A. at J2015.0 from Gaia DR2 |
| 5      | e_dec  | mas         | Positional uncertainty in decl. at J2015.0 from Gaia DR2 |
| 6      | ra_ps1 | degree      | Average R.A. at PS1 from PS1 PV3 |
| 7      | dec_ps1| degree      | Average decl. at PS1 from PS1 PV3 |
| 8      | pmra   | mas yr$^{-1}$ | Proper motion with a robust fit in $\alpha \cos \delta$ |
| 9      | pmde   | mas yr$^{-1}$ | Proper motion with a robust fit in $\delta$ |
| 10     | e_pmra | mas yr$^{-1}$ | Error of the proper motion with a robust fit in $\alpha \cos \delta$ |
| 11     | e_pmde | mas yr$^{-1}$ | Error of the proper motion with a robust fit in $\delta$ |
| 12     | chi2pmra | ... | $\chi^2$ from the robust proper motion fit in $\alpha \cos \delta$ |
| 13     | chi2pmde | ... | $\chi^2$ from the robust proper motion fit in $\delta$ |
| 14     | pmra_x | mas yr$^{-1}$ | Proper motion with cross-validated fit in $\alpha \cos \delta$ |
| 15     | pmde_x | mas yr$^{-1}$ | Proper motion with cross-validated fit in $\delta$ |
| 16     | e_pmra_x | mas yr$^{-1}$ | Error of the proper motion with a cross-validated fit in $\alpha \cos \delta$ |
| 17     | e_pmde_x | mas yr$^{-1}$ | Error of the proper motion with a cross-validated fit in $\delta$ |
| 18     | pmra_mcmc | mas yr$^{-1}$ | Proper motion with a MCMC sampling fit in $\alpha \cos \delta$ |
| 19     | pmde_mcmc | mas yr$^{-1}$ | Proper motion with a MCMC sampling fit in $\delta$ |
| 20     | e_pmra_mcmc | mas yr$^{-1}$ | Error of the proper motion with a MCMC sampling fit in $\alpha \cos \delta$ |
| 21     | e_pmde_mcmc | mas yr$^{-1}$ | Error of the proper motion with a MCMC sampling fit in $\delta$ |
| 22     | pmra_gaia | mas yr$^{-1}$ | Proper motion from Gaia DR2 in $\alpha \cos \delta$ |
| 23     | pmde_gaia | mas yr$^{-1}$ | Proper motion from Gaia DR2 in $\delta$ |
| 24     | e_pmra_gaia | mas yr$^{-1}$ | Error of the proper motion from Gaia DR2 in $\alpha \cos \delta$ |
| 25     | e_pmde_gaia | mas yr$^{-1}$ | Error of the proper motion from Gaia DR2 in $\delta$ |
| 26     | n_obsps1 | ... | The number of SeasonAVG observations used in the proper motion fit |
| 27     | n_obs   | ... | The number of all the observations used in the robust proper motion fit |
| 28     | flag$^b$ | ... | An integer number used to flag the different data combination in the proper motion fit |
| 29     | magg   | mag        | The $g$-band magnitude from PS1 |
| 30     | magr   | mag        | The $r$-band magnitude from PS1 |
| 31     | magi   | mag        | The $i$-band magnitude from PS1 |
| 32     | magz   | mag        | The $z$-band magnitude from PS1 |
| 33     | nn     | mag        | The $y$-band magnitude from PS1 |
| 34     | e_magg | mag        | Error in the $g$-band magnitude from PS1 |
| 35     | e_magr | mag        | Error in the $r$-band magnitude from PS1 |
| 36     | e_magi | mag        | Error in the $i$-band magnitude from PS1 |
| 37     | e_magz | mag        | Error in the $z$-band magnitude from PS1 |
| 38     | e_magy | mag        | Error in the $y$-band magnitude from PS1 |
| 39     | maggaia | mag        | The $G$-band magnitude from Gaia |
| 40     | e_maggaia | mag    | Error in the $G$-band magnitude from Gaia |

Notes.

* Here obj_id is an internal PS1 ID, which is different from the public ID released in the PS1 catalog.

$^b$ In order to label the different survey combinations for proper motion, we assign PS1, 2MASS, SDSS, and Gaia with different integer identifiers, i.e., 0, 5, 10, and 20, respectively, and define a flag with the sum of identifiers of surveys combined.
constrain $\mu_*, \mu_0$, and $\mu_\delta$, simultaneously. The intercept $b$ is also a free parameter in the Monte Carlo Markov Chain (MCMC) sampling, but its value is not important for this study. Figure 3 illustrates two examples of proper motion contours and marginalized probability distributions of two sources with different magnitudes. The Gaia detector takes on different performances for sources with distinct brightnesses. For instance, Gaia is able to measure a good position for a source with $r = 19.6$ mag. Thus, the combination of the multi-surveys cannot significantly improve the precision of the Gaia proper motion (only by $\Delta \epsilon_\mu \sim 0.2$ mas yr$^{-1}$, see the left panel of Figure 3). However, for a source with $r = 20.9$ mag, which is close to the Gaia limiting magnitude, the combination of PS1, SDSS, and Gaia can improve the precision of the Gaia proper motion by $\Delta \epsilon_\mu \sim 1.0$ mas yr$^{-1}$ (see the right panel of Figure 3).

3. Results and Performance

Using the approach described in Section 2.2 and the method used in GPS1 (see Section 3 of T17), we determine proper motions for around 400 million sources, down to a magnitude of $\sim 22.5$ in the $r$ band. Among these sources, about 40% of sources are re-measured new proper motions with the Bayesian method described in Section 2.2. The proper motions of the remaining objects are obtained with the previous method used in GPS1. The catalog draws on PS1 SeasonAVG and Gaia DR2.
as the primary data, together with the best available combinations of other surveys. The final catalog uses the robust fit (where all the data points are fitted regardless of outliers), cross-validation fit (where outliers are removed while fitting), and MCMC fit (with which proper motions from Gaia DR2 are used as priors while sampling if the proper motions exist in Gaia DR2). For reference, we also include the proper motions of Gaia DR2 if they exist. Table 1 lists the main columns contained in the catalog. In the following subsections, we discuss the precision and accuracy of proper motions in the different cases.

### 3.1. Proper Motion Uncertainties in the Different Data Set Combinations

The footprint overlap among Gaia, PS1, SDSS, and 2MASS surveys introduces some complexity; 14.5% stars are covered by Gaia, PS1, and SDSS; 43.6% by PS1 and Gaia, but not SDSS; 33.9% stars are only observed by PS1; and the remaining 8% by PS1 and SDSS, but not Gaia. Therefore, it is necessary to investigate how the final proper motions are affected by combining the different data sets.

Like GPS1, we investigate how the uncertainties in proper motion differ among the following four combinations of data sets: Gaia + PS1 + SDSS + 2MASS (GPS), Gaia + PS1 + 2MASS (GP), PS1 + SDSS + 2MASS (PD), and only PS1 (PS1). For the catalog table, different surveys are assigned different integer identifiers: 0, 5, 10, and 20 for PS1, 2MASS, SDSS, and Gaia, respectively. This defines a flag for different survey combinations entering a fit, represented as the sum of the individual survey identifiers. The primary observations are those from PS1, so the positions for each star must include the PS1 detections when fitting for the proper motion.

Figure 4 summarizes the distribution of proper motion uncertainties for the four different combinations. The figure is drawn with one million sources randomly selected from the GPS1+ catalog. In the four panels, the blue points correspond to the stars in different combinations and the red curves are the median uncertainties in proper motions within different magnitude bins. The average uncertainties in magnitude bins are listed in Table 2, with the mean (19 < m_r < 22.5) marked by black lines. In the GPS mode, the average uncertainties are \( \epsilon_{\mu_{\alpha}} \sim 2.24 \text{ mas yr}^{-1} \) and \( \epsilon_{\mu_{\delta}} \sim 2.10 \text{ mas yr}^{-1} \). This is better than the GP mode (\( \mu_{\alpha_{\ast}} \sim 3.98 \text{ mas yr}^{-1} \) and \( \mu_{\delta} \sim 3.19 \text{ mas yr}^{-1} \)). SDSS positions improve the precision by \( \sim 1.5 \text{ mas yr}^{-1} \) for both \( \epsilon_{\mu_{\alpha}} \) and \( \epsilon_{\mu_{\delta}} \). Without Gaia positions (the PD mode), the typical uncertainties become \( \epsilon_{\mu_{\alpha}} \sim 7.45 \text{ mas yr}^{-1} \) and \( \epsilon_{\mu_{\delta}} \sim 7.05 \text{ mas yr}^{-1} \). Gaia positions improve the precision by \( \sim 4.3 \text{ mas yr}^{-1} \) for both \( \epsilon_{\mu_{\alpha}} \) and \( \epsilon_{\mu_{\delta}} \). For PS1 data alone, the mean uncertainties become \( \epsilon_{\mu_{\alpha}} \sim 21.03 \text{ mas yr}^{-1} \) and \( \epsilon_{\mu_{\delta}} \sim 17.75 \text{ mas yr}^{-1} \). The precision improvement is dominated by Gaia and SDSS.

Figure 5 illustrates the distribution of uncertainties of these stars as Mollweide projection maps of the entire 3\( \pi \) sky region. The pink solid (\( b = 0^\circ \)) and two dotted lines (\( b = \pm 20^\circ \)) mark the location of the Galactic plane in the equatorial coordinate system, where sources are crowded and the effects of dust extinction manifest (Tian et al. 2014). To highlight the structures in the maps, the color bar is scaled in \( \pm 3\sigma \) around the entire median value for each map.

![Figure 5](image-url)
According to the performance, around 66% of sources in the GPS, GP, and PD modes are defined as the primary sources, which have a good precision with an average value of 2.0–5.0 mas yr\(^{-1}\); while the remaining ~34% of sources only have PS1 astrometry, which are defined as the secondary sources with an average precision of worse than 15.0 mas yr\(^{-1}\). The bad precision means the secondary sources probably have no good applications.

### 3.2. Proper Motion Validation with QSOs

To validate the derived proper motions, we crossmatch the GPS1\(+\) catalog with the quasi-stellar object (QSO) candidates from Hermlscheck et al. (2016) and randomly select 58,000 QSOs with high probabilities in the entire PS1 3\(\pi\) sky region.

Figure 6 displays the histograms of the \(\bar{\mu}_{a,*}\) (the top panel) and \(\bar{\mu}_{\delta}\) (the bottom panel) for the QSOs. The median values of the \(\bar{\mu}_{a,*}\) and \(\bar{\mu}_{\delta}\) are \(-0.13\) mas yr\(^{-1}\) and \(-0.17\) mas yr\(^{-1}\), and the dispersions are \(4.57\) mas yr\(^{-1}\) and \(5.05\) mas yr\(^{-1}\), respectively. The median values suggest that the accuracies of GPS1\(+\) proper motions are better than 0.2 mas yr\(^{-1}\) on average for both \(\bar{\mu}_{a,*}\) and \(\bar{\mu}_{\delta}\). The dispersion values roughly reflect the root mean square (rms) of GPS1\(+\) proper motions. Note that the apparent proper motions of QSOs suffer from the impact of differential chromatic refraction (DCR), especially in \(\delta\). At high declinations, the \(\delta\) proper motions are biased by up to 2 mas yr\(^{-1}\). At low declinations, the \(\delta\) proper motions are underestimated by \(\sim 2.0\) mas yr\(^{-1}\). This definitely makes the dispersion values of the QSO proper motions become larger than the true values.

### 3.3. Comparison with Gaia Proper Motions

Gaia DR2 provides us enough proper motions with good measurements for stars in the entire sky. In GPS1\(+\), we re-calculate the proper motions for the sources with Gaia DR2 proper motions with two methods: (1) the GPS1 method, in which proper motions are obtained by combining the astrometry of Gaia, PS1, SDSS, and 2MASS, regardless of Gaia DR2 proper motions; (2) the MCMC method, in which proper motions are obtained by combining the astrometry of Gaia, PS1, SDSS, and 2MASS, and using Gaia DR2 proper motions as priors during MCMC sampling. For the comparison, we randomly select about half a million of stars that have three kinds of proper motions, simultaneously.

Figure 7 illustrates the comparison of proper motions between our GPS1\(+\) and Gaia DR2 for \(\bar{\mu}_{a,*}\) (the top sub-panel) and \(\bar{\mu}_{\delta}\) (the bottom sub-panel). Two typical proper motions are presented: the GP proper motions (the left panel), and the GPS proper motions (the right panel). The median of the differences of proper motions \((\Delta \mu = \mu_{\text{GPS1}+} - \mu_{\text{Gaia}})\) lies within \(\pm 0.05\) mas yr\(^{-1}\) of zero, implying that the accuracy of the GPS1\(+\) proper motion is better than 0.05 mas yr\(^{-1}\) for both \(\mu_{a,*}\) and \(\mu_{\delta}\). The red bars indicate the average rms of the GPS1\(+\) proper motion is better than 5.0 mas yr\(^{-1}\) in the GP mode and 3.0 mas yr\(^{-1}\) in the GPS mode, respectively. Here, we assume that the proper motions are measured well enough in Gaia DR2.

Figure 8 represents the comparison of proper motions between our GPS1\(+\)(MCMC) case and Gaia DR2 for \(\mu_{a,*}\) (the left panel) and \(\mu_{\delta}\) (the right panel). The insets are the histograms of the error-weighted difference between the two, e.g., \(\tilde{\Delta} \mu = (\mu_{\text{ours}} - \mu_{\text{Gaia}})/\sqrt{\epsilon^2_{\mu,\text{ours}} + \epsilon^2_{\mu,\text{Gaia}}},\) where the two

![Figure 6](image-url) Validation of GPS1\(+\) proper motions with QSOs. The light dashed lines denote 0 mas yr\(^{-1}\).
are the errors of our and Gaia’s proper motions. The median of the error-weighted differences (marked by the white dashed lines) for the $\mu_\alpha$ and $\mu_\delta$ are $-0.02 \pm 0.46$ and $0.01 \pm 0.52$, respectively. The plot indicates that our proper motions are consistent with Gaia at a high level.

3.4. Proper Motions beyond Gaia

In this section, we explicitly summarize what unique data GPS1+ can offer beyond Gaia DR2. Overall, more than 60\% of sources in GPS1+ are beyond the Gaia limiting magnitude. It means that Gaia cannot reach this part of objects, even in Gaia’s next data release. The average precision of proper motions for this part of sources is $\sim 7.0$ mas yr$^{-1}$ if they are measured by SDSS (around one third of them have the astrometry of SDSS). Meanwhile, around 40\% of sources are measured new proper motions with the Bayesian technique with the goal of improving the precisions of Gaia DR2 proper motions at the end faint. Moreover, it is worth mentioning that around 13\% of sources are the objects whose proper motions are missing in Gaia DR2. We provide the proper motions for these sources in GPS1+ with an average precision of $\sim 4.5$ mas yr$^{-1}$.

Figure 9 displays the situations of the proper motions beyond Gaia in the different magnitudes. The top panel illustrates the cumulative histograms of the GPS1+ sources ($N_{\text{GPS1+}}$, the black curve), and the sources for which GPS1+ provides proper motions—but Gaia DR2 does not ($N_{\text{Gaia,missing}}$, the blue curve)—across the $3\pi$ sky over the magnitude at the faint
Figure 9. Top: the cumulative histograms of the GPS1+ sources ($N_{\text{GPS1+}}$, the black curve), and the sources for which GPS1+ provides proper motions—but Gaia DR2 does not ($N_{\text{Gaia,missing}}$, the blue curve)—across the 3π sky over the magnitude at the faint region ($r > 19$ mag). Middle: the number ratio vs. magnitude. The black and blue curves represent the ratios of $N_{\text{Gaia},\mu}/N_{\text{GPS1+}}$ and $N_{\text{Gaia,missing}}/N_{\text{Gaia}}$ in the different magnitude bins, where $N_{\text{Gaia},\mu}$ and $N_{\text{Gaia}}$ are the number of sources for which Gaia DR2 provides proper motions and all the sources for which Gaia DR2 provides positions in a magnitude bin, respectively. Bottom: the precision improvement factor ($\log(\epsilon_{\mu,\text{Gaia}}/\epsilon_{\mu,\text{MCMC}})$) of the Gaia DR2 proper motion at the faint region by the Bayesian technique, where $\epsilon_{\mu,\text{Gaia}}$ and $\epsilon_{\mu,\text{MCMC}}$ denote the precisions of total proper motions measured in Gaia DR2 and with the Bayesian technique in GPS1+, respectively. At $r < 20.5$ mag, the precisions of Gaia DR2 proper motions are finely improved, only by around 0.05 dex. At $r > 20.5$ mag, the precisions are improved by about 0.1 dex on average. Note that this scatter plot is obtained from a sample of one million sources randomly selected from the whole GPS1+ catalog.

For the most part, GPS1+ constitutes a catalog that extends the depth of GPS1 from $r < 20$ mag down to 22.5 mag. It not only fills up some proper motions missed in Gaia DR2 but also improves the proper motion precision of faint sources in Gaia DR2. The most important point is that GPS1+ provide new proper motions for a large number of faint sources beyond Gaia and other existing catalogs. GPS1+ has important values for the studies involved with faint sources, such as the precise age of field stars from white dwarf companions (Fouesneau et al. 2019; D. Qiu et al. 2020, in preparation), brown (Cook et al. 2017; Luhman et al. 2018), or ultracool (Scholz 2020) dwarfs; white dwarf binaries (Parsons et al. 2017; Wang 2018; Gentile Fusillo et al. 2019; Brown et al. 2020; Tian et al. 2020; Wang & Liu 2020); and the sdA problem (Pelisoli et al. 2018a, 2018b, 2019). Moreover, GPS1+ has some potential values for studies, such as the stellar kinematics (Tian et al. 2017b; Farihi et al. 2018; Wang et al. 2018; Tian et al. 2019), stellar stream (Fu et al. 2018), hypervelocity stars (Li et al. 2018; Brown et al. 2018), and so on.

In addition, it is worth summarizing the limitations of GPS1+ and where it should be used with caution. (1) Some sources may have erroneous proper motions in crowded regions, e.g., nearby globular clusters, partly because blended sources are easily classified erroneously as extended sources during the reference frame is built and partly because source crowding may lead to systematic errors in source centering. (2) Some regions are blank in the Galactic plane, particularly in the direction of Galactic center (see Figure 5). So many sources are included in these regions that it is hard for our pipeline to process these sources. (3) Some sources, e.g., QSOs, are significantly affected by the effect of DCR. Gaia is a space-based telescope, and its observations are not affected by DCR; meanwhile, PS1 and SDSS are ground-based telescopes and located in different places, so the two surveys suffer from DCR to a different extent. The combination of different surveys in the proper motion fit may lead to complex DCR effects. (4) Around one third of sources in GPS1+, i.e., the so-called secondary subsample, have an average precision of worse than 15.0 mas yr$^{-1}$ for their proper motions, because most of them are so faint that they are beyond the capability of Gaia’s detector and only have PS1 astrometry. They may have no good applications due to the bad precision.

5. Conclusions

Gaia DR2 released proper motions for more than 1.3 billion stars with unprecedented precision in the entire sky region. However, there are some spaces left for the successor of the GPS1 proper motion catalog. First, the uncertainties of Gaia proper motions increase with magnitudes as a function of a power law at the faint region ($r > 19.0$ mag), and the average uncertainty of Gaia proper motions becomes larger than 2 mas yr$^{-1}$ for the sources close to the Gaia limiting magnitude. Second, more than 361 million stars have no proper motions but have positions in Gaia DR2. Third, about 85% of PS1 sources have no Gaia proper motions in $21 < r < 22.5$ mag, which is beyond the Gaia limiting magnitude. In light of these points, we extend the GPS1 catalog.
With the same procedure as GPS1, we calculated the proper motions for all the PS1 sources fainter than 19 mag in the r band. For the sources with Gaia proper motions, we build a Bayesian model by taking Gaia proper motions as priors to calculate another new proper motion for each source by combining all the available astrometry from Gaia DR2, PS1, SDSS, and 2MASS. Finally, we release the GPS1+ proper motion catalog, which contains about 400 million point sources down to 22.5 mag in the r band, across three quarters of the sky. The systematic error (i.e., accuracy) is $<0.1$ mas yr$^{-1}$, but the typical uncertainty (i.e., precision) in the proper motion of a single source is mode-dependent: $\sim14.5\%$ of sources in the GPS1+ catalog are measured proper motions in the GPS mode and the average precision is $\sim2.0$ mas yr$^{-1}$; $\sim43.6\%$ and 8% of sources are measured in the GP and PD modes, and the precision is $\sim5$ mas yr$^{-1}$ on average, but $\sim33.9\%$ of sources are only observed by PS1, and the typical precision is worse than 15 mas yr$^{-1}$. Note that $\sim13\%$ of sources are the objects whose proper motions are missing in Gaia DR2, and GPS1+ provides their proper motion with a precision of $\sim4.5$ mas yr$^{-1}$, and $\sim40\%$ of sources have Gaia proper motions, so we recalculate their proper motions by building a Bayesian model. The final precision of proper motions can be improved up to $\sim1.0$ mas yr$^{-1}$ relative to Gaia’s values at the faint end.

According to the performance, we divide the GPS1+ catalog into two subsamples, i.e., the primary sources with a typical precision of 2.0–5.0 mas yr$^{-1}$, which have either or both of Gaia and SDSS astrometry; and the secondary sources with an average precision of worse than 15.0 mas yr$^{-1}$, which only have PS1 astrometry. The bad precision means that the secondary sources probably have no good applications.

The GPS1+ proper motions are validated with QSOs, and the performance is illustrated by comparing with proper motions of Gaia DR2.

H.-J.T. acknowledges the National Natural Science Foundation of China (NSFC) under grants 11873034. H.-W.R. acknowledges funding from the European Research Council under the European Unions Seventh Framework Programme (FP 7) ERC Grant Agreement No. 321035. The PanSTARRS1 Survey (PS1) has been made possible through contributions of the Institute for Astronomy at the University of Hawaii, PanSTARRS Project Office, Max-Planck Society, and its participating institutes, specifically the Max Planck Institute for Astronomy, Heidelberg, and the Max Planck Institute for Extraterrestrial Physics, Garching; Johns Hopkins University; Durham University; University of Edinburgh; Queen’s University Belfast; Harvard-Smithsonian Center for Astrophysics; Las Cumbres Observatory Global Telescope Network Incorporated; National Central University of Taiwan; Space Telescope Science Institute; National Aeronautics and Space Administration under grant No. NNX08AR22G issued through the Planetary Science Division of the NASA Science Mission Directorate; the National Science Foundation under grant No. AST-1238877; University of Maryland; Eotvos Lorand University; and Los Alamos National Laboratory. This work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement.

ORCID iDs

Hai-Jun Tian https://orcid.org/0000-0001-9289-0589
Chao Liu https://orcid.org/0000-0002-1802-6917
Hans-Walter Rix https://orcid.org/0000-0003-4996-9069

References

Ahn, C. P., Alexandroff, R., Allende Prieto, C., et al. 2012, ApJS, 203, 21
Altman, M., Roeser, S., Demleitner, M., Bastian, U., & Schilbach, E. 2017, A&A, 600, 4
Brown, W. R., Klicic, M., Kosakowski, A., et al. 2020, ApJ, 889, 49
Brown, W. R., Lattanzi, M. G., Kenyon, S. J., & Keller, M. J. 2018, ApJ, 866, 39
Chambers, K. 2011, AAS Meeting, 218, 113.01
Chambers, K. C., Magner, E. A., Metcalfe, N., et al. 2016, arXiv:1612.05560
Cook, N. J., Scholz, A., & Jayawardhana, R. 2017, AJ, 154, 256
Farihi, J., Arendt, A. R., Machado, H. S., & Whitehouse, L. J. 2018, MNRAS, 477, 3801
Foreman-Mackey, D., Hogg, D. W., Lang, D., & Goodman, J. 2013, PASP, 125, 306
Fouesneau, M., Rix, H.-W., von Hippel, T., Hogg, D. W., & Tian, H. 2019, ApJ, 870, 9
Fu, S. W., Simon, J. D., Shetrone, M., et al. 2018, ApJ, 866, 42
Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2016, A&A, 595, A2
Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2018, A&A, 616, A1
Gentile Fusillo, N. P., Tremblay, P.-E., & Gürsicke, B. T. 2019, MNRAS, 482, 4570
Hernitschek, N., Schlafly, E. F., Sesar, B., et al. 2016, ApJ, 817, 73H
Li, Y.-B., Luo, A.-L., & Zhao, G. 2018, AJ, 156, 87
Luhman, K. L., Herrmann, K. A., Mamajek, E. E., Espin, T. L., & Pecaut, M. J. 2018, AJ, 156, 76
Parsons, S. G., Hermes, J. J., Marsh, T. R., et al. 2017, MNRAS, 471, 976
Pelisoli, I., Bell, K. J., Kepler, S. O., & Koester, D. 2019, MNRAS, 482, 3831
Pelisoli, I., Kepler, S. O., & Koester, D. 2018a, MNRAS, 475, 2480
Pelisoli, I., Kepler, S. O., Koester, D., et al. 2018b, MNRAS, 478, 867
Qi, Z., Yu, Y., Bucciarelli, B., et al. 2015, AJ, 150, 137
Roeser, S., Demleitner, M., & Schilbach, E. 2010, ApJ, 139, 2440
Scholz, R.-D. 2020, A&A, 637, A45
Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, AJ, 131, 1163
Stoughton, C., Lupton, R. H., Bernardi, M., et al. 2002, AJ, 123, 485
Tian, H., Liu, C., Xu, Y., & Xue, X. 2019, ApJ, 871, 184
Tian, H.-J., El-Badry, K., Rix, H.-W., & Gould, A. 2020, ApJS, 246, 4
Tian, H. J., Gupta, P., Sesar, B., et al. 2017a, ApJS, 232, 4
Tian, H. J., Liu, C., Carlin, J. L., et al. 2015, ApJ, 809, 145
Tian, H. J., Liu, C., Hu, J. Y., et al. 2014, A&A, 569, L2
Tian, H.-J., Liu, C., & Wan, J.-C. 2017b, RAA, 17, 114
Wang, B. 2018, RAA, 18, 349
Wang, B., & Liu, D. 2020, arXiv:2005.01880
Wang, H., López-Corredoira, M., Carlin, J. L., & Deng, L. 2018, MNRAS, 477, 2858
York, D. G., Adelman, J., Anderson, J. E., Jr., et al. 2000, AJ, 120, 1579
Zacharias, N., Finch, C., & Frouard, J. 2017, AJ, 153, 166
Zacharias, N., Finch, C., Girard, T., et al. 2010, AJ, 139, 2184
Zacharias, N., Urban, E. S., Zacharias, M. L., et al. 2004, AJ, 127, 3043