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PROPER MOTION OF THE MAGELLANIC CLOUDS USING SPM

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RESUMEN

Se han determinado los movimientos propios absolutos para estrellas y galaxias hasta $V = 17.5$ sobre un área de 450 grados cuadrados que incluye a las Nubes de Magallanes, usando observaciones fotográficas y CCD del programa Yale/San Juan Southern Proper Motion. Múltiples mediciones locales de movimientos propios fueron combinadas en una solución de traslapo usando estrellas fotométricamente seleccionadas del disco galáctico como sistema de referencia relativo, que luego fue transformado a uno absoluto usando galaxias externas y al ICRS usando estrellas Hipparcos. El catálogo resultante se usa para obtener el movimiento propio de las Nubes de Magallanes: $(\mu_\alpha \cos\delta, \mu_\delta)_{\rm LMC} = (+1.88, +0.37) \pm (0.27, 0.27)$ masa año^{-1} y $(\mu_\alpha \cos\delta, \mu_\delta)_{\rm SMC} = (+1.05, -1.03) \pm (0.30, 0.29)$ masa año^{-1}, basado en dos muestras de 3800 y 769 estrellas gigantes rojas de la LMC y SMC respectivamente. Una porción dominante de los errores se debe a la incertidumbre estimada del sistema inercial del Catálogo *Hipparcos*. Se logró sin embargo una determinación mucho más precisa del movimiento propio de la SMC respecto a la LMC: $(\mu_{\alpha \cos\delta}, \mu_\delta)_{\rm SMC-LMC} = (-0.91, -1.49) \pm (0.16, 0.15)$ masa año^{-1}. Este valor diferencial se usa para estimar la velocidad relativa de una nube respecto a la otra con una incertidumbre de ± 54 kms^{-1}. Nuestros resultados son consistentes con una órbita de la Nubes marginalmente ligada a la Vía Láctea, aunque siguiendo una órbita elongada.

ABSTRACT

Absolute proper motions are determined for stars and galaxies to $V = 17.5$ over a 450 square-degree area that includes the Magellanic Clouds, using photographic and CCD observations of the Yale/San Juan Southern Proper Motion program. Multiple, local relative proper motion measures were combined in an overlap solution using photometrically selected galactic disk stars to define a global relative system that is then transformed to absolute using external galaxies and Hipparcos stars to tie into the ICRS. The resulting catalog is used to derive the mean absolute proper motions of the Magellanic Clouds: $(\mu_\alpha \cos\delta, \mu_\delta)_{\rm LMC} = (+1.88, +0.37) \pm (0.27, 0.27)$ mas yr^{-1} and $(\mu_\alpha \cos\delta, \mu_\delta)_{\rm SMC} = (+1.05, -1.03) \pm (0.30, 0.29)$ mas yr^{-1}, based on best-measured samples of 3822 LMC stars and 964 SMC stars. A dominant portion of the formal errors is due to the estimated uncertainty in the inertial system of the *Hipparcos* Catalog. A more precise determination was made for the proper motion of the SMC *relative* to the LMC; $(\mu_{\alpha \cos\delta}, \mu_\delta)_{\rm SMC-LMC} = (-0.91, -1.49) \pm (0.16, 0.15)$ mas yr^{-1}. This differential value is used to estimate of the total velocity difference of the two clouds to within ± 54 km s^{-1}. The absolute proper motion results are consistent with the Clouds' orbits being marginally bound to the Milky Way, albeit on an elongated orbit.

Key Words: astrometry — Magellanic Clouds — proper motions

1. INTRODUCTION

It is widely accepted that the complexity and intricacies of the Magellanic Clouds' external and internal features have been largely determined by the orbit they have followed in the past few Gigayears. Due to their large distance, about 50 and 60 kpc to the LMC and the SMC, respectively, only radial velocities were precise enough to provide some assessment of their spatial velocity. Line-of-sight measurements of the Clouds began about a hundred years ago, while proper motion measurements of useful accuracy were possible only in the 1990's.

The first proper motion results (Jones et al. 1989; Tucholke & Hiesgen 1991; Bastian et al. 1993; Lin 1993; Kroupa et al. 1994; Jones et al. 1994; Irwin et al. 1996; Kroupa & Bastian 1997a,b,c; Anguita 1999) based on plate and/or CCD data, were

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compatible with a picture in which the Magellanic Clouds were bound to each other and to the Milky Way. Such scenario relied heavily on the fact that the Galactic gravitational potential used (isothermal sphere) yields such results by default, and proper motion errors were not small enough to refine the tangential velocities.

In the past ten years though, investigations yielded quite a variety of results (Anguita et al. 2000; Drake et al. 2001; Pedreros et al. 2002; Momany & Zaggia 2005; Kallivayalil et al. 2006b; Méndez et al. 2006; Kallivayalil et al. 2006a; Piatek et al. 2008; Costa et al. 2009). HST-based results coupled to cosmologically inspired dark matter Halo models, suggest that the Clouds are not bound to the Galaxy, opposite to the long-held paradigm.

In this investigation, the Yale-San Juan Southern Proper Motion (SPM) program, for the first time, completes a wide-field astrometric proper motion survey of the Magellanic System. The SPM program is a joint venture of Yale University and Universidad Nacional de San Juan in Argentina, initiated in the early 1960s by D. Brower and J. Schilt. The goal of the SPM program is to provide absolute proper motions, positions, and BV photometry for the Southern sky to a limiting magnitude of $V \sim 18$.

2. THE SPM PROGRAM

The SPM program (Girard et al. 2010) makes use of the Yale Southern Observatory's double astrograph at Cesco Observatory in the foothills of the Andes mountains in El Leoncito, Argentina. This telescope consists of two 51-cm refractors, designed for photography in the blue and yellow bands, respectively. The first-epoch survey, taken between 1965 and 1974 was made on glass photographic plates, exposed simultaneously in blue-yellow pairs and always centered on the meridian. The plates' field of view (FOV) extends over an area of $6.3° \times 6.3°$. The sky south of $\delta = -17°$ was observed in the first-epoch period. Second-epoch SPM plate observations were begun in 1988. By the mid 1990's, only a third of the second-epoch survey was completed. In 2000 a CCD camera system was installed on the double astrograph to replace the photographic plate holders. Since 2004, regular CCD observations have been carried out to finish the second-epoch survey of the SPM program. By December 2008, the survey was effectively completed for the sky south of $\delta = -20°$. An objective wire grating was always used in order to produce measurable grating images for the brighter stars. In this manner, the effective dynamic range of the plates was greatly increased, allowing bright Hipparcos-magnitude stars to be linked to external galaxies on the same plate or CCD frame.

All SPM plates were scanned with the Precision Measuring Machine (PMM) at the US Naval Observatory's Flagstaff Station. A more thorough description of the plate material and the various image systems is given by (Girard et al. 2004). Areas where there were only 2nd-epoch plate positions were complemented with 2000.0 CCD-based positions from the UCAC2 catalogue. Data from all the CCD cameras went through the usual processing to calibrate the flux detected by the electronics, for the zero charge of the chip (bias), accumulated signal from the electronics dark current (dark) and different response to light from each pixel (flat).

3. ASTROMETRIC AND PHOTOMETRIC CALIBRATION

In general, similar techniques to those used in constructing previous versions of SPM catalogs were used to process this data. Stars for which both the central-order exposure and first-order grating-image pair were measurable were used to derive and correct each plate's magnitude equation individually. The corrected x, y plate positions were transformed into the system of Tycho-2, only for cross-identification purposes.

The CCD x, y positions were corrected for a fixed-pattern geometric distortion, believed to be linked to the filter, built up from residuals of hundreds of frames at different pointings reduced into UCAC2 coordinates. The corrected CCD x, y positions were then transformed onto the system of the UCAC2, again, for cross-identification purposes.

Areas of the sky with 2nd-epoch plate measures only were supplemented with 2000.0 UCAC2 CCD-based positions. These data only sample stars down to about $V = 16$ mag, while SPM plates and CCD frames can reach $V = 18$ mag. The obtained catalog's southern border runs at about $\delta = -78°$, while the northern border is approximately at $\delta = -66.5°$ (for $\alpha < 52°$) and at $\delta = -62°$ (for $\alpha > 52°$). Right ascension limits go from $-13.74° < \alpha < 118.20°$.

The V photometry is derived from the visual filtered CCD camera reduced in a standard fashion using aperture photometry with calibration into Tycho2 BV photometry (corrected to the Johnson system). When no CCD data were available, V plate photometry was used.

4. PROPER MOTIONS

Relative proper motions were measured on each CCD-size field, with respect to photometrically selected G-M dwarfs in the Galaxy disk. These stars have a mean absolute motion along the sky that can be parametrized as a smooth function of RA and Dec. Taking advantage of the substantial overlap ($\sim$50%) between fields, each frame's proper motions were solved into the average frame defined by all reference stars of the surrounding fields. This adjustment also helps to correct residual distortions, as they are statistically smoothed out in the average frame. To avoid frames drifting away from the global system as they are being aligned to one another, all reference stars in the field are explicitly assigned a relative proper motion of zero. Once the adjustments are applied, new averages can be computed, and the whole process is iterated until the adjustments converge to zero. As a result, a very precise relative global reference frame is built.

Confirmed extragalactic objects were later used to fit a smooth function, a quadratic polynomial in (α, δ), that describes the mean motion of the global relative reference frame, that was later used to convert the relative proper motion into absolute ones. An additional zero-point correction was needed to put our proper motions into the ICRS, although theoretically, the external galaxies define an external absolute inertial system. The measured proper motions of bright Hipparcos stars showed that a residual magnitude equation remained in the derived proper motions. Such difference is consequence of a known problem in the SPM photographic plates, a magnitude equation, whose effect seems to be different for extended objects (galaxies) than for stars, the latter being used to characterize and correct for this systematic problem of the plates. It was decided to calculate a final correction to the absolute proper motion, using the mean offset between our proper motions and those measured by Hipparcos for the Hipparcos stars.

Each star has as many measurements of proper motions as pairs of 1st-2nd epoch fields exist for it. A final proper motion for a star is computed from the formal error weighted average of the all available proper motion measurements, after 3σ iterative clippling (the most deviant measurement is rejected each time). Uncertainties in the proper motions were derived from the weighted scatter of the multiple measurements per star available. The proper motion uncertainties are about 2.3 mas yr^{-1}, for stars brighter than $V = 10$, about 3.8 mas yr^{-1} for stars around $V = 16.4$ and 11 mas yr^{-1} or more for fainter objects.

5. LMC AND SMC SAMPLES

Bona fide red giants in the LMC and SMC were chosen to measure the mean absolute proper motion of each Cloud. 3800 LMC and 769 SMC stars were selected, which overlap sufficiently in magnitude with the reference stars, minimizing any magnitude-related systematic offset in their proper motions. Only stars with 2nd-epoch CCD data were selected, as those based on 2nd-epoch plate data only showed a significanly higher dispersion and some visible systematics.

Differing from previous works, which sampled a few very small scattered fields over each cloud, our samples cover the LMC and SMC homogeneously and extensively, making any perspective or rotation correction unnecessary. Our results are

$$(\mu_\alpha \cos\delta, \mu_\delta)_{\rm LMC} = (+1.88, +0.37) \pm (0.27, 0.27),$$

$$(\mu_\alpha \cos\delta, \mu_\delta)_{\rm SMC} = (+1.05, -1.03) \pm (0.30, 0.29),$$

measured in mas yr^{-1}. The errors quoted include: the formal error of the mean value $(\sigma/\sqrt{N_{\rm stars}})$, the error of the quadratic polynomial at the LMC and SMC centers, transformation to Hipparcos errors and Hipparcos systematic error (0.25 mas yr^{-1}). Clearly, the error budget is dominated by Hipparcos systematics.

6. RELATIVE PROPER MOTION OF SMC WITH RESPECT TO LMC

We measured the mean motion of our reference stars precisely all over our field of view. Combined with the relative proper motion of LMC and SMC stars with respect to these reference stars, it is straightforward to obtain the proper motion of the SMC with respect to that of the LMC, at a higher precision not limited by the Hipparcos uncertainty. Such relative proper motion is:

$$\Delta\mu_{\alpha\cos\delta}(\mathrm{SMC} - \mathrm{LMC}) = -0.91 \pm 0.16\,\mathrm{mas\ yr}^{-1},$$
$$\Delta\mu_{\delta}(\mathrm{SMC} - \mathrm{LMC}) = -1.49 \pm 0.15\,\mathrm{mas\ yr}^{-1}.$$

These values cannot be transformed directly into a measurement of the relative velocity between the Clouds, because their different locations in the sky makes their planes of tangential velocities different as well. The necessary rotation and projections to measure the SMC velocity on the LMC reference frame does not allow us to obtain such relative velocity as a function of the above numbers.

Instead, we used these values to obtain new independent measurements of the SMC's absolute proper motion, based on existing measurements of the LMC's absolute proper motion plus our precise relative proper motion from above. Moreover, since all authors that directly measured the proper motion of the SMC had previously measured the LMC's proper motion as well, we verified if their original SMC results are consistent with our relative measure.

7. CONCLUSIONS

After a comparison in an absolute and relative sense with previous proper motion results, we conclude that our proper motions are compatible with the LMC and SMC being born and formed as separate entities, which later joined in a temporary binary state for the past few Gigayears, being recently disrupted by the Milky Way in their most recent perigalaticon passage about 200 Myr ago. The Clouds orbits are *marginally* bound to the Milky Way, possibly following a very elongated but still periodic orbit around the Galaxy.

The search for a realistic orbit of the Magellanic Clouds is far from over. Having (formally) very accurate and precise space-based proper motions for the Clouds, has not facilitated our understanding of their dynamics but has, instead, opened new questions and has placed all dynamic scenarios of the Magellanic System in doubt. As of today, it is still unclear if the Magellanic Stream and the Leading Arm are caused mostly by a tidal interaction or are the result of the ram-pressure of the Galactic Halo on the gas of the Clouds.

Given the inherent difficulties in measuring an accurate proper motion for the Magellanic Clouds, the obvious dangers that systematic errors pose in those measurements and the fact that the dynamical models of the Magellanic System are extremely sensitive to small variations in the proper motions of the Clouds, we believe that we are not yet in the position of considering them known parameters in the orbital calculation. But we are getting closer.

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