Part 7. Tidal Interactions

Section A. Invited Reviews

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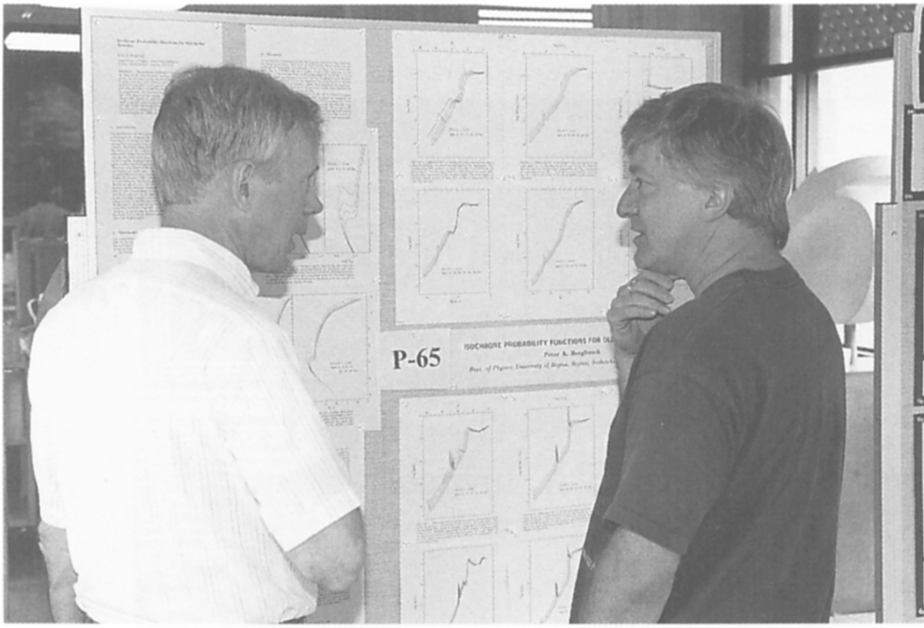

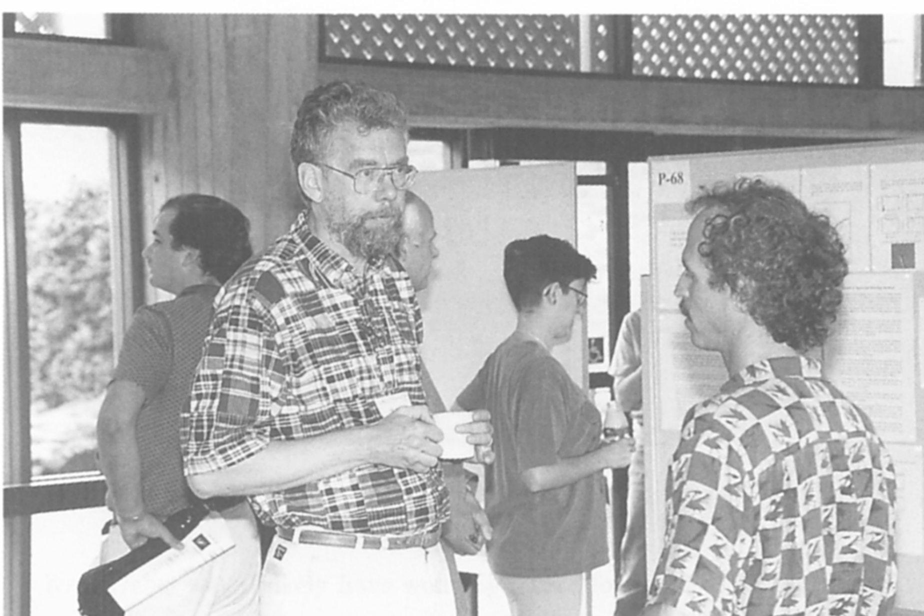

(Top) Allen Sweigart and Peter Bergbusch ponder the modelling of those pesky observations that (bottom) Bill Harris and Jon Holtzman make.

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Proper Motions of the Clouds

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Abstract. The proper motion of the LMC relative to three background QSOs has been determined. 125 CCD frames taken from 1989.0 to 1997.2 at the Cassegrain focus of the CTIO 1.5 m telescope were used. The method of observation and reduction is breafly presented. The results are compared with those obtained by other authors who use different methods and proper motion reference systems. We find a good agreement in $\mu_\alpha \cos\delta$, but a rather large discrepancy in μ_δ. Our LMC proper motion seems to indicate that the LMC is not leading the Magellanic Stream.

1. Introduction

Since Mathewson et al.'s (1974) discovery of the Magellanic Stream (MS), all models of the Magellanic System assume that the Large Magellanic Cloud (LMC) and the Small Magellanic Cloud (SMC) lead the MS in their orbital motions. Given that the MS forms a near great circle perpendicular to the Galactic plane, the Clouds have orbits which run over the Galactic poles. For the LMC, the models of Murai & Fujimoto (1980), Lin & Lynden Bell (1982), Shuter (1992), and Gardiner et al. (1994) predict a proper motion in the range of 1.5 to 2.0 mas yr^{-1} with a position angle $\theta \approx 90°$, measured in the celestial coordinate system in the sense NESW. In the case of the SMC, only Gardiner et al. (1994) predict its proper motion. In their numerical simulations, they compute the LMC and SMC current space velocities and proper motions that give the best reproduction of observational features of the Magellanic System. One of the results they obtain is $\mu = 1.6$ mas yr^{-1} with $\theta = 150°$ for the SMC proper motion.

Three quasars behind the LMC have been reported: Q0557−6713 (Blanco & Heathcote 1986), Q0558−6707, and Q0615−6615 (Maza 1989), at $3\overset{\circ}{.}9$, $4\overset{\circ}{.}1$, and $5\overset{\circ}{.}9$ from the center of the LMC. These quasars provide an excellent reference system for us to measure the proper motion of the LMC. From our experience with the parallax programs at CTIO, we have been able to measure the centroid of a point-like object with a precision of 3 mas (s.d.) and the mean position with a standard error of 1–2 mas. We have therefore decided to measure the proper motion of the LMC, in order to compare with the aforementioned predictions.

2. Observations and Results

The QSOs used as inertial fiducial points to measure the absolute proper motion of the LMC were observed with the CTIO 1.5 m telescope, using CCDs attached

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to the f/13.5 cassegrain focus. Observations were carried out in the course of the Universidad de Chile parallax program at CTIO, over an eight year period, using a Johnson R bandpass to reduce the effect of refraction.

During the first part of the program (1989 and 1990), we used an RCA (312 × 508) chip that gives a scale of 0″.3 pixel^{-1} and a field of view of 1′.6 × 2′.5; for the remainder of the program, two TEK (1024 × 1024) chips, giving a scale of 0″.24 pixel^{-1} and a 4′.1 × 4′.1 field of view, were used. Nevertheless, for the last epoch of Q0557−6713 and Q0558−6707 observations, we had to used a TEK (2048 × 2048) that gives the same scale as the smaller TEK chips. All the chips we used are thinned and back-side illuminated. Ideally this kind of program should use only one chip, but this is not possible because chips wear off and are replaced by improved chips on a rapid timescale.

The LMC stars defining the stellar reference frame of each QSO field were chosen according to the following criteria: they had to be on all frames taken with a seeing < 1″.7 and to have a magnitude near R = 2.5 mag, with the QSOs at the bright part of it. Only frames with a seeing less than 1″.7 were used. In order to use the frames of Q0557−6713 and Q0615−6615 taken at the beginning of the program, we limited the stellar reference frames of these QSO fields to LMC stars within the smaller field of view of the RCA CCD chip.

In order to select only LMC stars as members of the reference frame, B,V,R photometry was done for the three QSOs fields. Their color-magnitude diagrams show that the typical stellar population is that of the LMC with little contamination. These fields are almost completely dominated by LMC stars.

Coordinates (x, y) of the images centroids were calculated using DAOPHOT (Stetson 1987). On each frame, barycenter coordinates $(x_{(b)} = x - \overline{x}, y_{(b)} = y - \overline{y})$ of the reference stars and of the QSO were computed. For each QSO, the average of three frames taken in succession on a night of good seeing and with good orientation of the CCD relative to the cardinals points was chosen as the standard frame; the coordinates of the reference stars were then used to make linear transformations such that all frames have the same orientation and scale as the standard frame.

All the observations of a QSO were combined in the standard frame by

$$x_{(b,t_i)} = x_{(b,t_o)} + \mu\ x_{(b)} \times (t_i - t_o),$$

where $x_{(b,t_i)}$ is the barycenter coordinate of an object at epoch t_i, $\mu\ x_{(b)}$ is the proper motion in the coordinate x of the object relative to the barycenter of the stellar reference system, and t_o is the beginning of the year when the observations started. A similar equation is used to combine $y_{(b,t_i)}$. Before solving this set of equations, we applied corrections for color refraction which were determined empirically by taking frames at different hour angles, from three hours east to three hours west. Nevertheless, only frames taken with hour angle less than one hour were used to determine the proper motions of the objects.

To compute the proper motions of the QSOs and of LMC stars belonging to the stellar reference frame, we use the method called ordinary least-squares (OLS) regression by Isobe et al. (1990). Table 1 is a summary of the project; it gives (1) the name of the quasar; (2) and (3) the right ascension and declination components of the LMC proper motion, which are the “reflex” motion of the QSOs relative the LMC stars of the area, and their standard deviations; (4) the number of frames; (5) the number of epochs and (6) the observation period.

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Table 1. Proper Motion of the LMC

relative to	LMC $\mu_\alpha \cos(\delta)$ (mas yr^{-1})	μ_δ	Number of: frames	epochs	observation period
Q0557−6713	+1.4 ± 0.3	+3.1 ± 0.2	61	12	1989.02−1996.86
Q0558−6707	+1.3 ± 0.4	+3.4 ± 0.6	32	7	1992.81−1996.86
Q0615−6615	+1.7 ± 0.2	+2.8 ± 0.3	32	8	1989.90−1997.17
The three QSOs (weighted mean)	+1.6 ± 0.2	+3.0 ± 0.2			

3. Comparison with Previous Measurements

In the upper part of Table 2, we give the results of all measurements known of the LMC proper motion with precisions less than 1 mas yr^{-1} in both μ components, and the reference system used in the project. In the case of Jones et al. (1994) and Anguita et al. (1999), the proper motion components are given for the field where the observations were done, and for the center of rotation of the Cloud. The last values include corrections for rotation of the LMC plane and for solar motion. Similar information is given for the SMC in the lower part of Table 2.

Kroupa & Bastian (1997) calculate the weighted mean of the three independent LMC proper motion measurements known at the moment, and obtained $\mu_\alpha \cos(\delta) = 1.61 \pm 0.19$ mas yr^{-1} and $\mu_\delta =$ -0.06 ± 0.21 mas yr^{-1}, which correspond to $\mu = 1.61 \pm 0.28$ mas yr^{-1} with $\theta = 92°$, in agreement with model predictions. Comparing those values with our measurements we find that the R.A. components are quite similar, but that there is a large discrepancy between the two values of the declination components. The LMC proper motion we calculate is $\mu = 3.3 \pm 0.2$ mas yr^{-1} with $\theta = 31°$. The direction of our proper motion vector seems to indicate that the LMC is not leading the Magellanic Stream. In relation to this point, it is interesting to note that the LMC proper motion ($\mu = 1.7$ mas yr^{-1}, $\theta = 50°$) measured by Kroupa et al. (1994), using stars of the PPM Catalogue, is another vector that does not have the direction predicted by theoreticians.

What makes these results indeed interesting is that our value of the LMC proper motion is larger by a considerable amount than any prediction from models considering the Clouds gravitationally bound or unbound to the Galaxy, yet the fact that the same telescope was used during a relative short span between initial and final epochs (eight years) and that a QSO is used as reference should make the outcome highly reliable.

CCD relative astrometry of ten QSOs behind the SMC given by Tinney et al. (1997) is needed to address the discrepancy found in this project and to increase our knowledge of the kinematic properties of the Clouds. Unfortunately, the SMC proper motion, $\mu = 1.73 \pm 0.80$ mas yr^{-1} (Kroupa & Bastian 1997) calculated with 11 stars from data obtained with the Hipparcos satellite, has an uncertainty too large to give valuable information that could be used to analyze

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Table 2. Proper Motion of the Magellanic Clouds

Source	LMC	$\mu_\alpha \cos(\delta)$ (mas yr^{-1})	μ_δ	Reference System
Kroupa, et al. (1994)		+1.3 ± 0.6	+1.1 ± 0.7	PPM
Jones, et al. (1994)	field	+1.20 ± 0.28	+0.26 ± 0.27	Galaxies
	(LMC center)	+1.37 ± 0.28	−0.18 ± 0.27	
Kroupa & Bastian (1997)		+1.94 ± 0.29	−0.14± 0.36	Hipparcos
Anguita, et al. (1998)	field	+1.6 ± 0.2	+3.0 ± 0.2	Quasars
	(LMC center)	+1.7 ± 0.2	+2.8 ± 0.2	
Source	**SMC**	**$\mu_\alpha \cos(\delta)$ (mas yr^{-1})**	**μ_δ**	**Reference System**
Kroupa, et al. (1994)		+0.5 ± 1.0	−2.0 ± 1.4	PPM
Kroupa & Bastian (1997)		+1.23 ± 0.84	−1.21± 0.75	Hipparcos

the results obtained with Hipparcos and future ground-based CCD observations of SMC regions.

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Discussion

Steven Majewski: How do you account for color terms in your astrometric solution? Because the mean color and shape of the spectral energy distribution is very different between your QSOs and the Magellanic stars at the same magnitude (i.e. red giants) this is a critical correction. Have you checked your solution against the reference frame provided by redder, compact galaxies that you should have in your frames (which go to $V = 22$)?

Anguita: For several years I have been measuring CCD trigonometric parallaxes with the same telescope, so I know quite well how to determine and apply a correction we know as Differential Colour Refraction.

No, I have not checked our solution against the reference frame you mentioned. It could be an interesting test to do it.

William Kunkel: What assumptions did you employ about the rotation of the LMC?

Anguita: I measured the proper motions of three different LMC fields. To obtain the corresponding values of the LMC center of rotaton, I used the assumptions employed by Lin in 1994. In any case, the corrections were, at most, 0.0002 mas yr^{-1}.

Lance Gardiner: Are you aware that Mike Irwin has recently measured the proper motion of the SMC using CTIO 4m plates and found that the SMC is leading the Magellanic Stream?

Anguita: I am sorry, but I have no information about the SMC proper motion which, as you say, has been recently measured.