Red Giants in the Small Magellanic Cloud. I. Disk and Tidal Stream Kinematics

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ABSTRACT

We present results from an extensive spectroscopic survey of field stars in the Small Magellanic Cloud (SMC). 3037 sources, predominantly first-ascent red giants, spread across roughly 37.5 deg2, are analysed. The line of sight velocity field is dominated by the projection of the orbital motion of the SMC around the LMC/Milky Way. The residuals are inconsistent with both a non-rotating spheroid and a nearly face on disk system. The current sample and previous stellar and HI kinematics can be reconciled by rotating disk models with line of nodes position angle Θ ≈ 120−130°, moderate inclination (25−70°), and rotation curves rising at 20−40 km s−1 kpc−1. The metal-poor stars exhibit a lower velocity gradient and higher velocity dispersion than the metal-rich stars. If our interpretation of the velocity patterns as bulk rotation is appropriate, then some revision to simulations of the SMC orbit is required since these are generally tuned to the SMC disk line-of-nodes lying in a NE-SW direction. Residuals show strong spatial structure indicative of non-circular motions that increase in importance with increasing distance from the SMC centre. Kinematic substructure in the north-west part of our survey area is associated with the tidal tail or Counter-Bridge predicted by simulations. Lower line-of-sight velocities towards the Wing and the larger velocities just beyond the SW end of the SMC Bar are probably associated with stellar components of the Magellanic Bridge and Counter-Bridge, respectively. Our results reinforce the notion that the intermediate-age stellar population of the SMC is subject to substantial stripping by external forces.

Key words: galaxies: evolution; galaxies: kinematics and dynamics; galaxies: individual: SMC; stars: kinematics and dynamics

1 INTRODUCTION

One of the principal goals of contemporary astrophysics is to develop a more complete understanding of galaxy formation and evolution. While the prevailing theoretical framework, Lambda-Cold Dark Matter (Λ-CDM, e.g. Peebles & Ratra 2003), is rather successful in replicating the large scale structures observed in the Universe (e.g. Springel et al. 2005; Cole et al. 2005), it suffers significant shortcomings at explaining smaller scale phenomena where density perturbations depart strongly from the linear regime and the role of baryon physics becomes substantial (e.g. Kroupa et al. 2010; Famaey & McGaugh 2013). In Λ-CDM cosmology, galaxy formation is a hierarchical process in which the larger structures grow through the aggregation of small dark matter haloes and baryons. As the dissipative gas cools, it collapses to densities sufficient for star formation to occur (Tegmark et al. 1997). The ongoing accretion of gas with higher specific angular momentum promotes an inside-out development of galactic disks and the gradual migration in time of star formation activity to larger galactocentric radii. This is in accord with observations of negative radial chemical abundance gradients in the disks of local spiral galaxies and the formation of stars with comparatively low metallicities in their outer disk regions in the present epoch (e.g. Wang et al. 2011).

However, the basic theoretical framework overpredicts the numbers of dwarf galaxies in the Local Volume, including the number that are satellites to the Milky Way (Klypin et al. 1999). While the mass function of galaxies might be expected to be similar in shape to that of the dark matter haloes, i.e. proportional to M−1.9, it is observed to be closer in form to M−1 in the low luminosity regime (Cole et al. 2001). In addition, observational studies of the rotation curves of dwarf galaxies show them to be slowly rising...
with increasing galacto-centric distance \cite{deBlokBosma2002}, indicative of a dark matter distribution that is significantly flatter than the centrally cusped form predicted by $\Lambda$-CDM. To account for these disparities, several mechanisms have been invoked that can both regulate the formation of stars in galaxies and smooth out the central cusp in their dark matter distributions. These include internal factors such as supernovae feedback \cite{Governato2010}, and external influences such as background UV radiation and tidal and/or ram-pressure stripping of potentially star forming gas from a system by galaxy-galaxy interactions \cite{Kazantzidis2010}. For example, observations of the Fornax galaxy cluster indicate that environmental factors regulate the levels of star formation activity in the dwarf members \cite{Drinkwater2001}. These regulating mechanisms have also been linked to the apparently discordant outside-in progression of star formation in many low luminosity dwarf irregular systems \cite[e.g.][]{Zhang2012}. Deep imaging studies reveal recent star formation to be concentrated within their central regions \cite[e.g. Phoenix, IC 1613 and NGC 6822][]{Hidalgo2009, Skillman2003, Wyder2001}, suggesting that accretion of high angular momentum gas is inhibited. The reduction in turbulent gas pressure in the denser inner parts of these galaxies following the supernovae blow out of disk material, is suspected to lead to the inward migration of enriched parts of these galaxies following the supernovae blow out of disk material, is suspected to lead to the inward migration of enriched gas and the contraction towards their centers of the star forming disk \cite[e.g.][]{Pilkington2012, Stinson2009}. Additionally, tidal interactions may incite bar like instabilities in these galaxies that can promote the inward flow of gas in their disks.

Despite being somewhat less common than predicted by theory, dwarfs still numerically dominate the galaxy population. As the antecedents of larger galaxies such as Messier 31 and the Milky Way, it is vital to understand their architectures and evolution, including the roles of disk rotation and pressure support, their dark matter distributions and the regulation of their star formation. The Small Magellanic Cloud (SMC) is the smaller of a pair of comparatively massive \((M > 10^9 M_\odot)\) dwarf galaxies close \((D < 60 kpc)\) to the Milky Way. As probable satellites of the Galaxy they are relatively unusual in that they are gas rich whereas the majority of dwarf galaxies within 270 kpc of the Milky Way and Messier 31 appear to be gas poor \cite[e.g.][]{Greevich2009}. However, there is substantial evidence that gas is being stripped from the Magellanic Clouds as a consequence of their interactions with the Galaxy and each other. For example, they are immersed within an extended body of diffuse HI gas that stretches out many tens of degrees across the sky, forming the Magellanic Stream and the Leading Arm \cite[e.g.][]{Putman2003}.

In HI observations the SMC displays a “frothy” appearance, attributed to a large number of recent supernova explosions, and a substantial velocity gradient along a position-angle \((PA) \approx 60^\circ\), which has been associated with the systemic rotation of a cold disk of gas \cite{Stanimirovic2004}. The young and the intermediate/old stellar populations of the Cloud display quite distinctive morphologies. The former have an irregular distribution and it has been inferred from observations of Cepheids that the main body of the SMC, where much of this stellar population resides, corresponds to a bar structure that is being viewed virtually end on \cite{Caldwell1985}. The south-west end of the main body is believed to be slightly more distant than the north-east although this latter region appears to consist of two distinct kinematic structures lying at different distances \cite{Hatzidimitriou1993}. The old/intermediate stellar population appears to be much more evenly distributed \cite{Zaritsky2000} and recent observations suggest it extends many degrees from the center of the Cloud \cite{Nidever2011}. Moreover, its kinematical properties appear to be consistent with those of a pressure supported spheroid \cite{Harris2006}. The contrast between the distributions of the young and the older populations have led to suggestions that the former is the outcome of a recent gas infall event \cite{Zaritsky2000, Zaritsky2004}, while \cite{Subramanian2012} have proposed that a dwarf-dwarf merger occurred between 2–5 Gyr ago.

Several key observational properties of the SMC are qualitatively reproduced by N-body and chemo-dynamical modelling in which it interacts with the Large Magellanic Cloud (LMC).
and the Galaxy, including the velocity field of the Magellanic Stream, the Magellanic Bridge structure towards the LMC, the kinematics and the distribution of the intermediate/old stellar population, the large line of sight depth of the Cloud and the age-metallicity relation (Murai & Fujimoto 1984; Gardiner & Noguchi 1996; Yoshizawa & Noguchi 2003; Bekki & Chiba 2009). Realistic simulations are particularly important for reconstructing the interaction history of the Magellanic Clouds that can lead to a deeper understanding of the impact of tidal and ram pressure forces on the structure and the evolution of the SMC and dwarf galaxies in general. In addition, these computations, through accurately reproducing the properties of the Magellanic Stream, can afford further insight on the distribution of the dark matter halo of the Galaxy (Haghi et al. 2006).

As the initial conditions of these simulations are typically determined by integrating the Clouds’ orbits backwards in time and through choosing galaxy structures and disk orientations that lead to agreement with our understanding of the SMC in the present epoch (e.g. Gardiner & Noguchi 1996), the limitations of current observations and in our knowledge of the orbits contribute to inaccuracies in the inferred evolutionary history. Fortunately much improved proper motion determinations are becoming available and are leading to a better definition of the orbits of both the SMC and the LMC (e.g. Kallivayalil et al. 2013). Considering this, it seems timely to re-examine our understanding of the structure and kinematics of the SMC as this could also help to further refine the simulations. In this vein we have recently performed the most extensive spectroscopic study of the SMC’s red-giant population to date. Here we present radial velocities for in excess of 3000 stars distributed across an area of roughly 37.5 deg$^2$ centered on the Cloud. In subsequent sections we outline our initial photometric selection of candidates and our acquisition, reduction and analysis of the spectroscopic follow-up data. We examine in detail the projected line-of-sight velocity field of the red-giant population to search for evidence of large scale trends. We compare our results to prior work on the intermediate/old and the young star populations of the SMC and consider them in the contexts of a disk model and a recent tidal interaction.

2 PHOTOMETRIC SELECTION OF CANDIDATE SMC RED GIANT STARS

An initial selection of candidate SMC red-giants was made from the near-IR photometry of the 2 micron All-Sky Survey (2MASS; Skrutskie et al. 2006) point source catalogue (PSC). A $J, J-K_S$ colour-magnitude diagram was constructed for stellar-like sources with photometric uncertainties of less than 0.5 mag. in both $J$ and $K_S$, within an approximately 37.5 deg$^2$ region centred on the Cloud (figure 1). Sources flagged as possible blends, as having photometry contaminated by image artifacts or nearby bright objects and/or as lying within the boundaries of catalogued extended sources were excluded. We selected all remaining objects to the red of the line defined by $J = 26.5 - 20 \times (J-K_S)$ and blueward of $J-K_S=2.0$ or $J-K_S=1.25$ for $12.0 \leq J < 13.9$ and $13.9 \leq J < 15.2$, respectively. These criteria, highlighted in figure 2, encompass the region of colour-magnitude space spanned by both the red-giant branch (RGB) and asymptotic-giant branch (AGB) of the SMC population and led to a preliminary catalogue of 92,893 sources.

3 OPTICAL SPECTROSCOPY

3.1 Observations and data reduction.

Follow-up optical spectroscopy for a subsample of these stars was acquired during the period 18-21 October 2011, with the 2dF/AAOmega instrument and the 3.9m Anglo-Australian Telescope (AAT) located at Siding Spring Observatory, Australia. AAOmega is a two arm fibre-fed multi-object optical-spectrograph capable of the simultaneous observation of 400 objects distributed over a two degree circular field-of-view (Saunders et al. 2004; Sharp et al. 2006).

During this observing campaign, the blue and red arms of the instrument were configured with the 1500 V (R=4000) and 1700 D (R=10000) gratings and tuned to central wavelengths of 5350Å and 8670Å, respectively. This provided coverage of the $\lambda$5167, 5172 and 5183Å Mg b and $\lambda$8498, 8542 and 8662Å CaII triplet lines. Fortunately, skies were largely clear for much of the run and seeing was generally close to the Siding Spring Observatory median value. Therefore, during the four nights approximately 7000 objects were targeted with 23 different field configurations. Details of the pointings, including dates, field centers and exposure times are reported in Table 1.

The AAOmega data were reduced using the Australian Astronomical Observatory’s 2dFDR pipeline which is described at length by Bailey et al. (1998) and Sharp & Birchall (2010). In brief, the data were first bias and dark subtracted using master frames created from exposures taken over the course of the four nights. Fibre-flat exposures of a quartz lamp, obtained immediately prior to the science observations of each target, were used to locate the spectra in each CCD frame. The fibre-flat field and science spectra were extracted and the latter divided by the former to reduce the impact of pixel-to-pixel response variations. Spectra of a CuAr+CuNe+FeAr arc lamp, that were also acquired adjacent in time to the science observations, were then used to wavelength calibrate each dataset. Finally, the multiple datasets obtained for the targets, typically three per plate configuration (see Table 1), were combined to form the final spectra.

3.2 Spectroscopic analysis.

The spectra from the red-arm of the instrument were first matched to multiplicative combinations of low-order polynomials and normalised synthetic spectra drawn from the library of Kirby (2011). As these models were calculated in local thermodynamic equilibrium (LTE) and do not accurately reproduce the form of the strong, empirical, CaII triplet absorption features, the synthetic Ca lines were augmented with Voigt profiles. An iterative approach to fitting was adopted in which a $\chi^2$ goodness-of-fit statistic was minimised weighting the spectral channels by their inverse variances as determined by the 2dFDR pipeline. Following this step, any points lying more than 3$\sigma$ above or below the model were rejected before the data were re-fitted. This procedure was repeated three times and afforded reasonable representations of the datasets of field dwarfs and RGB stars. A useful additional outcome of this process was a model based estimate for the radial velocity of each target. Subsequently, to achieve first order normalisation, each spectrum was divided by the low order polynomial component of its corresponding model. As the synthetic spectral library employed here is not optimised for C-stars, our model representations of the
Table 1. Details of the field configurations used for obtaining the spectroscopic follow-up observations of candidate SMC red-giant stars.

| Name     | RA (hh:mm:ss) | Dec (°′″) | $t_{\text{exp}}$ (s) | $n_{\text{exp}}$ | Obs. date | Plate ID | Seeing (arcsec) |
|----------|---------------|-----------|-----------------------|------------------|-----------|----------|-----------------|
| C1FA     | 00:48:14      | -71:47:59 | 1200                  | 3                | 2011/10/18 | 0        | 2               |
| C1FB     | 00:48:14      | -71:47:55 | 1200                  | 3                | 2011/10/20 | 1        | 2               |
| C2FA     | 01:04:47      | -71:54:19 | 1200                  | 3                | 2011/10/18 | 1        | 1.5             |
| C2FB     | 01:04:47      | -71:54:25 | 1200                  | 4                | 2011/10/20 | 0        | 2               |
| C3FA     | 00:46:59      | -73:20:44 | 1200                  | 3                | 2011/10/18 | 0        | 1               |
| C3FB     | 00:47:00      | -73:20:46 | 1200                  | 4                | 2011/10/20 | 1        | 1.5             |
| C3FC     | 00:46:59      | -73:20:44 | 1200                  | 3                | 2011/10/21 | 1        | 1.5             |
| C4FA     | 01:05:00      | -73:24:27 | 1200                  | 2                | 2011/10/18 | 1        | 1.5             |
| C4FB     | 01:04:59      | -73:24:32 | 1200                  | 3                | 2011/10/20 | 0        | 2               |
| 3D05FA   | 00:33:53      | -70:10:18 | 1200                  | 3                | 2011/10/21 | 0        | 1.5             |
| 3D06FA   | 00:49:58      | -70:16:05 | 1200                  | 4                | 2011/10/20 | 0        | 1.5             |
| 3D07FA   | 00:15:50      | -70:26:53 | 1200                  | 3                | 2011/10/19 | 1        | 1.5             |
| 3D08FA   | 00:22:40      | -70:40:10 | 1200                  | 3                | 2011/10/19 | 1        | 1.5             |
| 3D09FA   | 00:31:46      | -71:36:12 | 1200                  | 3                | 2011/10/19 | 0        | 2               |
| 3D10FA   | 01:22:57      | -71:59:36 | 1200                  | 3                | 2011/10/19 | 0        | 1.5             |
| 3D11FA   | 00:27:18      | -73:01:35 | 1200                  | 3                | 2011/10/19 | 0        | 2.5             |
| 3D12FA   | 01:23:15      | -73:15:34 | 1200                  | 3                | 2011/10/21 | 0        | 1.5             |
| 3D13FA   | 00:23:34      | -74:18:20 | 1200                  | 3                | 2011/10/19 | 0        | 2               |
| 3D14FA   | 00:43:22      | -74:41:34 | 1200                  | 3                | 2011/10/18 | 1        | 2               |
| 3D15FA   | 01:04:36      | -74:55:41 | 1200                  | 3                | 2011/10/21 | 1        | 1.5             |
| 3D16FA   | 01:24:45      | -75:55:33 | 1200                  | 3                | 2011/10/21 | 1        | 1.5             |
| 3D19     | 01:34:49      | -69:39:53 | 1200                  | 3                | 2011/10/21 | 0        | 1.5             |
| 3D22     | 00:45:35      | -75:27:40 | 1200                  | 3                | 2011/10/19 | 1        | 2               |

Table 2. Details of the ten RGB radial velocity template stars drawn from the clusters NGC 288, NGC 362 and Melotte 66.

| ID  | RA (hh:mm:ss.ss) | Dec (°′″/″) | $v_r$ (km/s) | References |
|-----|------------------|-------------|-------------|------------|
| 403 | 00:52:46.25      | -26:37:26.0 | -46.0       | 1, 2       |
| 338 | 00:52:52.80      | -26:34:38.8 | -49.2       | 1, 2       |
| 344 | 00:52:52.87      | -26:35:20.2 | -49.0       | 1, 2       |
| 274 | 00:53:01.13      | -26:36:07.1 | -40.5       | 1, 2       |
| 2127| 01:02:37.64      | -70:50:37.1 | +222.6      | 3, 2       |
| 1441| 01:03:21.73      | -70:48:40.4 | +222.3      | 3, 2       |
| 1423| 01:03:33.01      | -70:49:37.2 | +232.3      | 3, 2       |
| 4151| 07:26:12.07      | -47:43:24.7 | +23.0       | 4, 5       |
| 4266| 07:26:17.30      | -47:44:00.1 | +21.0       | 4, 5       |
| 3133| 07:26:30.53      | -47:41:43.9 | +18.0       | 4, 5       |

Table 3. Details of the six SMC C-star radial velocity templates.

| ID  | RA (hh:mm:ss.ss) | Dec (°′″/″) | $v_r$ (km/s) | Reference |
|-----|------------------|-------------|-------------|-----------|
| 3D05FA 4342 | 00:21:19.5       | -70:54:36   | +139.0      | 1         |
| 3D05FA 155  | 00:26:34.3       | -70:14:24   | +158.8      | 1         |
| 3D09FA 11102 | 00:29:04.4     | -72:13:17   | +183.6      | 1         |
| 3D05FA 3280 | 00:30:47.4       | -70:28:06   | +112.6      | 1         |
| 3D05FA 2366 | 00:31:25.3       | -70:23:46   | +132.8      | 1         |
| 3D14FA 348  | 01:40:27.0       | -75:41:54   | +163.7      | 1         |

1. Olszewski et al. (1984), 2. Shetrone & Keane (2000), 3. Harris (1982), 4. Hawarden (1976), 5. Friel et al. (2002)

spectra of objects of this nature were of lower quality but were sufficient for the purposes here.

Next, all the normalised red-arm spectra were cross-correlated with AAOmega data that we obtained for ten RGB objects in the clusters NGC 362, Melotte 66 and NGC 288. These stars were observed through a variety of AAOmega’s fibres and were adopted because reliable radial velocity estimates are available for them in the literature (Table 2). The cross-correlation procedure was undertaken with the IRAF FXCOR software routine running within a PyRAF environment. The quoted velocity for each star is a mean of these ten estimates, weighted by their individual errors as reported by FXCOR. Their associated uncertainties have been determined from the mean of the absolute deviation of these measurements. As our spectroscopic sample also includes C-stars, this whole process was repeated with our AAOmega observations of six C-rich giants taken from the study of Kunkel et al. (1997), details of which are reported in Table 3.

3.3 Radial velocity measurements.

For the vast majority of stars, the radial velocities obtained with FXCOR were found to be in excellent agreement with the values output by the $\chi^2$ model fitting procedure, above. The small number of exceptions can be attributed to spectra that are of very low signal-to-noise, datasets that are severely affected by fibre fringing or spectra of C-rich stars, which we discuss later on. Nonetheless, to thoroughly assess the internal precision and external accuracy of these measurements, several further checks have been performed.

Firstly, a small fraction of the spectroscopically observed sam-
Field pointings were observed twice during the course of the four nights run. The different velocity estimates for these objects have been compared to each other. Excepting the handful of stars where the discrepancy appears to be much larger than typical (i.e. of the order ~10 km s\(^{-1}\)), a very close correspondence is observed between the two sets of measurements, with the magnitude of the velocity difference for 68% of objects being \( \Delta v < 1.9 \text{ km s}^{-1} \). This scatter is comparable in size to the uncertainty estimated above.

Secondly, 17 RGB stars in the calibration cluster Melotte 66, have been observed several times previously with AAOmega by other independent teams of investigators, using different fibre configurations. These sets of measurements have been compared to each other and after excluding a probable radial velocity variable star, discussed further below, any systematic offsets between the various pairings of measurements were determined to be very small, \( \Delta v_{\text{sys}} < 1 \text{ km s}^{-1} \). Additionally, the scatters in the velocity differences between our observations and those acquired on 08 December 2009, 24 December 2009 and 22 April 2011, are only 1.8, 1.7 and 1.9 km s\(^{-1}\), respectively, consistent with very low fibre-to-fibre velocity differences.

Thirdly, our AAOmega radial velocities for several Melotte 66 stars have been compared to recent measurements made with the European Southern Observatory’s Very Large Telescope (VLT) and Ultraviolet-visible echelle spectrograph (UVES), that are reported to be repeatable at the 0.5 km s\(^{-1}\) level (Sestito et al. 2008). While there are five objects in common with the AAOmega sample, star 1346 is one of our radial velocity templates (4266) and star 1614 is flagged as a fast rotator by Sestito et al. (2008). Together, the measurements of star 1614 suggest it is also a radial velocity variable (+17.3 ± 2.3, +17.8 ± 2.3, +25.6 ± 2.3 and +57.8 ± 2.3 km s\(^{-1}\) on 08 December 2009 and 24 December 2009, 22 April 2011 and 21 October 2011, respectively). For the three remaining stars the differences between the UVES and the AAOmega velocities (i.e. \( v_{\text{AAOmega}} - v_{\text{UVES}} \)) are only -0.42 ± 0.2 km s\(^{-1}\) for 1493, -0.30 ± 0.2 km s\(^{-1}\) for 1785 and -0.50 ± 0.2 km s\(^{-1}\) for 2218.

Lastly, we compared the velocity determinations for 151 SMC RGB stars common to our sample and that of Harris & Zaritsky (2006). The latter measurements are based on observations obtained with the Magellan telescope and the multi-slit Inamori Magellan Areal Camera (IMACS). The scatter between the sets of measurements is determined to be approximately 13.5 km s\(^{-1}\), which is similar in magnitude to the typical uncertainties quoted by Harris & Zaritsky (2006). However, a small systematic offset of +4.5 km s\(^{-1}\) (\( v_{\text{AAOmega}} - v_{\text{IMACS}} \)) is apparent between the results of these two studies. At face value, this seems significant but in practice it is probably not. The IMACS velocity measurements suffered from systematic errors of the order 10 km s\(^{-1}\), although substantial efforts were made to mitigate these (Harris & Zaritsky 2006).

Taking stock of the results from these comparisons, we conclude that we have met our initial goal of obtaining radial velocity measurements that are repeatable to better than 5 km s\(^{-1}\) for the vast majority of the red-giants in our sample.
distinctive Swan band feature at 5165 Å, so this wavelength range is useful for the discrimination of these objects too.

A set of orthogonal basis vectors was constructed to represent all the blue-arm dataset sub-sections. The principal eigenvector formed in this process (which accounts for approximately 40% of the variance) can be attributed to the spectral shape induced by the strong molecular C absorption in the atmospheres of some stars. Comparing the locations of all the spectroscopic targets and the 185 objects previously identified as C-star members of the SMC and re-observed here (Morgan & Hatzidimitriou 1995), in the 2d-space defined by this new co-ordinate and radial velocity, the C-rich stars are observed to lie well below the locus of points de-linedated by the bulk of the sample (see figure 3). A by-eye inspection of the red-arm data sets for a random selection of these objects, not previously catalogued as C-rich, affirms the presence of strong molecular C absorption. A 5σ clip has been applied to the main locus of points shown in figure 3 and the 449 objects below have been flagged as probable C-stars.

Subsequently, the C-stars were removed from the sample and the set of basis vectors for the remaining blue-arm data was reconstructed. The principal eigenvector (corresponding to approximately 10% of the variance) can now be ascribed to the spectral shape induced by the strong molecular C absorption in the atmospheres of some stars. Comparing the locations of all the spectroscopic targets and the 185 objects previously identified as C-star members of the SMC and re-observed here (Morgan & Hatzidimitriou 1995), in the 2d-space defined by this new co-ordinate and radial velocity, the C-rich stars are observed to lie well below the locus of points de-linedated by the bulk of the sample (see figure 3). A by-eye inspection of the red-arm data sets for a random selection of these objects, not previously catalogued as C-rich, affirms the presence of strong molecular C absorption. A 5σ clip has been applied to the main locus of points shown in figure 3 and the 449 objects below have been flagged as probable C-stars.

Table 4. Details of the 4172 red-giants identified in our spectroscopic follow-up of sources towards the SMC. The full table is available in the electronic version of the article.

| RA          | Dec          | 2MASS J | J     | δJ    | Ks    | δKs   | Helio. corr. | vmodel | vhelio | δV     |
|-------------|--------------|---------|-------|-------|-------|-------|-------------|--------|--------|--------|
| hh:mm:ss.ss | °:′:″        |         | /mag. | /mag. | /mag. | /mag. | /kms⁻¹      | /kms⁻¹ | /kms⁻¹ | /kms⁻¹ |
| 00:00:28.28 | -75:33:04.4  | 00002828-7533044 | 14.68 | 0.04  | 13.72 | 0.05  | 13.6 | 189.6 | 188.7 | 2.4     |
| 00:01:43.01 | -75:35:11.9  | 00014300-7535119 | 13.94 | 0.02  | 12.94 | 0.03  | 13.6 | 156.9 | 156.2 | 2.4     |
| 00:02:26.40 | -75:01:30.2  | 00022640-7501302 | 13.23 | 0.03  | 12.30 | 0.03  | 13.7 | 147.0 | 146.9 | 2.3     |
| 00:02:31.86 | -75:12:37.1  | 00023186-7512371 | 14.26 | 0.03  | 13.43 | 0.03  | 13.6 | 152.3 | 153.0 | 2.1     |
| 00:02:57.95 | -75:36:52.9  | 00025794-7536529 | 13.31 | 0.03  | 12.56 | 0.02  | 13.5 | 72.9  | 72.2  | 2.3     |

Figure 5. The histogram of the radial velocity estimates for our entire sample of SMC RGB stars (grey).

Table 5. Details of the 352 carbon rich giants that were included in our spectroscopic survey of the SMC. The full table is available in the electronic version of the article.

| RA          | Dec          | 2MASS J | J     | δJ    | Ks    | δKs   | Helio. corr. | vmodel | vhelio | δV     |
|-------------|--------------|---------|-------|-------|-------|-------|-------------|--------|--------|--------|
| hh:mm:ss.ss | °:′:″        |         | /mag. | /mag. | /mag. | /mag. | /kms⁻¹      | /kms⁻¹ | /kms⁻¹ | /kms⁻¹ |
| 00:04:57.49 | -76:25:07.7  | 00045748-7625076 | 13.33 | 0.02  | 12.36 | 0.03  | 13.5 | 154.3 | 149.7 | 5.9     |
| 00:06:12.83 | -75:16:21.1  | 00061283-7516211 | 13.71 | 0.02  | 12.36 | 0.03  | 13.5 | 154.3 | 149.7 | 5.9     |
| 00:08:09.42 | -75:19:06.1  | 00080942-7519060 | 13.56 | 0.02  | 12.32 | 0.02  | 13.5 | 145.5 | 139.9 | 5.5     |
| 00:11:31.72 | -73:59:54.0  | 00113171-7359539 | 13.99 | 0.03  | 13.07 | 0.03  | 13.6 | 149.5 | 144.8 | 8.9     |
| 00:14:58.50 | -75:07:29.4  | 00145849-7507294 | 12.90 | 0.02  | 11.39 | 0.02  | 13.3 | 167.9 | 162.5 | 5.9     |

4 RADIAL VELOCITIES OF THE SMC GIANTS

4.1 The sample dominated by RGB stars

Cioni et al. (2000) determine the tip of the RGB in the SMC to lie at $J \approx 13.7$ so by conservatively selecting the stars with $J \geq 14$, which weren’t flagged as C-rich in Section 3.4, we form a sample that is dominated by objects on the RGB and appropriate for a metallicity study. With radial velocities for 3037 unique RGB sources we are also in a strong position to explore the kinematics of the intermediate stellar population across a large swathe of the Cloud. Indeed, the Besancon model of the Galaxy (Robin et al. 2003) reveals that only 65 contaminating Galactic giants (just 2% of the sample) meet our SMC RGB star colour and radial velocity selection criteria. Since a histogram of their radial velocities (figure 7) shows these to be relatively evenly spread across our parameter space, we conclude that they are unlikely to have any significant bearing on our subsequent analysis and conclusions.
Table 6. A table summarising the results from fitting Gaussians to the radial velocity histograms for our spatial sub-samples of RGB stars.

| Field | $N_{\text{tot}}$ | $v_r$ /kms$^{-1}$ | $\sigma_{v_r}$ /kms$^{-1}$ | $\Delta v_r$ /kms$^{-1}$ |
|-------|----------------|------------------|----------------|------------------|
| C1    | 321            | +135.6±1.3       | 22.8±0.9        | -5.4±1.3         |
| C2    | 390            | +143.2±1.2       | 23.2±0.8        | -0.5±1.1         |
| C3    | 586            | +148.6±1.0       | 25.1±0.8        | -0.6±1.1         |
| C4    | 333            | +158.9±1.4       | 24.6±1.0        | +6.8±1.3         |
| 3D05  | 57             | +142.2±3.4       | 25.5±2.4        | +16.0±3.4        |
| 3D06  | 99             | +136.0±2.7       | 26.8±1.9        | +6.0±2.8         |
| 3D07  | 112            | +134.9±2.3       | 24.0±1.7        | -0.7±2.2         |
| 3D08  | 115            | +135.5±2.1       | 22.4±1.5        | -6.0±2.1         |
| 3D09  | 145            | +133.8±2.2       | 25.9±1.6        | -1.9±2.2         |
| 3D10  | 120            | +147.9±2.3       | 24.7±1.7        | -2.4±2.2         |
| 3D11  | 121            | +145.4±2.2       | 24.5±1.6        | -0.1±2.2         |
| 3D12  | 124            | +162.0±2.3       | 25.3±1.7        | +3.4±2.4         |
| 3D13  | 108            | +149.5±2.4       | 25.0±1.7        | -3.1±2.4         |
| 3D14  | 142            | +157.3±1.8       | 21.7±1.3        | -0.0±1.8         |
| 3D15  | 170            | +163.8±1.9       | 24.9±1.4        | +2.1±1.9         |
| 3D16  | 92             | +162.6±3.1       | 29.2±2.2        | -4.8±3.1         |
| 3D19  | 29             | +136.3±4.4       | 23.4±3.2        | -2.3±4.5         |
| 3D22  | 29             | +156.1±5.7       | 30.3±4.1        | -0.4±5.6         |

The typical precision of our radial velocity measurements has been discussed in Section 3.3. A histogram of them is shown in figure [5]. We have calculated both the skew ($\gamma_1=0.057\pm0.044$) and the kurtosis ($\gamma_2=-0.084\pm0.088$) of the overall radial velocity distribution and have found both to be consistent with normality. The results of a Kolmogorov-Smirnov test for normality ($P=0.12$) are also compatible with this conclusion. We have determined the mean and dispersion of the radial velocities to be $v_{\text{los}}\approx+147.8\pm0.5\text{km s}^{-1}$ and $\sigma_{v_{\text{los}}}\approx26.4\pm0.4\text{km s}^{-1}$, respectively, with the maximum likelihood estimator.
4.2 Carbon stars

We also obtained spectroscopic data for several hundred candidate C-rich SMC giants (see Section 3.4). These objects, details of which are listed in Table 7, span the full magnitude range of our study from \(J=12.0\)–15.2 but we have restricted our kinematic analysis to the 352 stars with \(J<14.0\) that are located in the canonical red AGB wing of the SMC colour-magnitude diagram (figure 2). Theoretical models suggest that the lowest luminosity C-rich giants may be formed in close binary systems (e.g. Marigo et al. 1999). Additionally, the objects in this sub-sample were assigned uniformly higher priorities for spectroscopic follow-up than the stars with \(J>14.0\).

As discussed briefly in Section 3.4, the radial velocities of the objects flagged as C-rich were determined by cross-correlating their spectra against those of six C-rich SMC giants previously investigated by Kunkel et al. (1997). These authors noted their radial velocities to be systematically shifted to the blue by about 6 \(\text{km s}^{-1}\) with respect to the measurements of Hardy et al. (1989). We observe an offset of similar magnitude and direction between the velocities we obtained from cross-correlation and the estimates output by our model fitting procedure. While we caution that the synthetic spectra used here were hardly ideal for matching to C-stars, we have applied an offset of +5 \(\text{km s}^{-1}\) to our measurements to bring them into closer agreement with both the system of Hardy et al. (1989) and our model based estimates. Following the approach taken with the RGB stars we have examined both the skew \((\gamma_1=0.109\pm0.131)\) and the kurtosis \((\gamma_2=-0.109\pm0.261)\) of the C-star radial velocity distribution. We have found both of these parameters, together with the results of a Kolmogorov-Smirnov test \((P=0.833)\), to be in accord with normality (figure 6). We have used the the maximum likelihood estimator above to determine the mean and dispersion of this distribution to be \(v_{\text{los}}\approx149.6\pm1.4\text{ km s}^{-1}\) and \(\sigma_{v_{\text{los}}}\approx26.1\pm1.0\text{ km s}^{-1}\), which are in accord with the parameters of the RGB star ensemble.

4.3 Space motion of the SMC centre of mass.

To search the RGB radial velocities for evidence of systematic variation with position on sky, we have initially split the measurements up into 18 sub-samples, each corresponding to a distinct 2dF field pointing. Basic parameters (e.g. the mean and the dispersion) for the radial velocity distributions of these fields have been obtained by applying the above likelihood statistic, under the assumption they too, are gaussian. The results from this procedure are shown graphically in figure 8 and are listed in Table 5. These reveal an overall radial velocity gradient across the sample of about +7 \(\text{km s}^{-1}\) deg\(^{-1}\), in an approximately NW-SE direction. Our much smaller sample of C-stars also reflects this trend (see figure 12 and Table 7).

As discussed by previous investigators (e.g. van der Marel et al. 2002), a substantial contribution to our observed radial velocity gradient may stem from the expected variation in the line-of-sight velocity component of the Cloud’s space velocity across our extensive survey area. A number of estimates of the proper motion of the SMC centre-of-mass have been published since the RGB star study of Harris & Zaritsky (2006) and these have substantially reduced uncertainties compared to similar earlier work. The most recent is based on three epochs of Hubble Space Telescope imaging and has measured \(\mu_\alpha \cos\delta=0.772\pm0.063\text{ mas yr}^{-1}\) and \(\mu_\delta=-1.117\pm0.061\text{ mas yr}^{-1}\) (Kallivayalil et al. 2013). We have used this information in con-
junction with a kinematical model for solid body rotation (e.g. van der Marel et al. 2002) to assess the impact of the Cloud’s tangential motion on our measured values. We have neglected for now any contribution to the velocities from a putative disk structure, and, for consistency with the work of Kallivayalil et al. (2013), we have assumed initially that the SMC center of mass is coincident with the HI kinematic center (Stanimirovic et al. 2004). This model was matched to the measured radial velocities of the individual RGB stars by locating the global minimum of a $\chi^2$ goodness-of-fit statistic. We allowed the model parameters $v_{sys}$, $v_t$, and $\Theta_t$ (in the notation of van der Marel et al. (2002), respectively the systemic velocity, the tangential velocity and the position-angle of the tangential velocity, east from north) to vary freely in this process. We assumed for now an intrinsic velocity dispersion of $\sigma_{v_{los}}=25$ kms$^{-1}$, which is compatible with both the typical values we measure for the sub-samples across the cluster and the results of earlier studies of the intermediate age stellar population of the Cloud.

We find this basic model can provide a reasonable match to the data with a reduced-$\chi^2 \approx 1$ for parameter values of $v_{sys}=147.5\pm0.5$ kms$^{-1}$, $v_t=416.8\pm23.0$ kms$^{-1}$ and $\Theta_t=152.1\pm2.9^\circ$. The errors quoted here were obtained via a bootstrap with random replacement approach. The broad agreement between these parameters and the values inferred from the most recent estimate of the SMC centre of mass proper motion, $v_t=386\pm21$ kms$^{-1}$ and $\Theta_t=145.4\pm2.6^\circ$ (assuming a distance modulus of $(m-M)_0=18.90$) and our determination of the radial velocity, $v_{sys}=147.7\pm0.5$ kms$^{-1}$, argues that any manifestation of systemic rotational motion in the RGB star kinematics has an amplitude well below the velocity dispersion of this population.

4.4 Main trends in the velocity field of the red-giant sample

To reveal any more subtle velocity structures within our dataset, the predictions of our basic kinematical model have been subtracted from our measurements. Subsequently, we constructed a surface of the velocities in the rest frame of the SMC galaxy (GRF) for our survey area by estimating this parameter at a series of regularly spaced grid points in RA and declination (every 10 arcmin), using a bi-variate gaussian smoothing kernel, with an adaptive width corresponding to one third the distance to the 200th closest star, to weight the individual measurements (e.g. Walker et al. 2006).
contour plot of this surface is displayed in figure [9] and a map of the width of the smoothing kernel is shown in figure [10]. No gradient in the red-giant velocity field is obvious along the major axis of the SMC Bar. This is consistent with the results of most previous kinematical studies of the intermediate and old populations of the SMC. For example, Dopita et al. (1989) reported a lack of organised structure in the velocities of 44 planetary nebulae located largely along the Bar, while both Hatzidimitriou et al. (1997) and Hardy et al. (1989) found no evidence of systemic rotation in their radial velocities of modest sized samples of C-stars.

Nonetheless, figure [9] reveals a rather striking dipole-like velocity pattern within roughly the central 10 deg$^2$ that has a major axis almost perpendicular to the SMC Bar. To the NW side of the Bar, negative GRF velocities at $v_r$<−5kms$^{-1}$ predominate, while immediately to the SE, positive velocities extend to $v_r$>10kms$^{-1}$. An analysis of several thousand simulated velocity datasets, which were generated by randomly re-assigning the GRF velocities to the positions of our sample stars, indicates that this signal is statistically significant (figure [13]). The implied velocity gradient here is similar in magnitude and direction to that induced by the transverse motion of the Cloud center-of-mass as estimated recently from proper motion measurements of the inner regions of the SMC. This gradient could be largely accounted for if these astrometric measurements were systematically underestimated by at least 50% in both RA and declination. However, while the most recent determination of the transverse motion of the Cloud is smaller than most previous estimates, the reduction does not amount to 50%, so it seems unlikely that the observed effect is due to grossly inaccurate astrometry.

Hardy et al. (1989) measured a larger mean velocity (160.7+5.6kms$^{-1}$) for a sample of C-stars which they ascribed to the SMC Wing but their field appears to be coincident with one of the zones of positive GRF velocity indicated by the red-giant stars, adjacent to the SE edge of the bar. A contour plot of the velocity surface derived from our sample of several hundred C-stars (constructed following the above procedure) has a broadly similar pattern to the corresponding RGB star map but hints at larger velocities much further out in the Wing region towards the eastern limit of our survey (figure [13]).

In contrast to our work, Harris & Zaritsky (2006) found evidence of a velocity gradient of +8.3kms$^{-1}$ deg$^{-1}$ at PA$\approx$23$^\circ$, east of north, in their investigation of 2046 red-giants drawn from 12 fields located mainly around the SMC Bar. Given the apparent discrepancy between their result and that of the present work, we have explored their conclusion further. Considering the somewhat limited extent of their survey in the NW-SE direction, it is conceivable that a comparatively shallow gradient along this axis may have been concealed by their larger measurement uncertainties. Alternatively, the position-angle may have been incorrectly referenced (e.g. from due E, rather than due N), with the value quoted by Harris & Zaritsky (2006) perhaps in error by −90$^\circ$. We have re-evaluated the direction of the steepest velocity gradient in our RGB ensemble using a sub-sample of 1038 stars from roughly the same region of the SMC Bar (figure [13]). These Galactic and, despite the smaller sample size, in every case the parameters of the resulting velocity curve were consistent with the steepest gradient lying along an approximately NW to SE direction (peak amplitude of between 4–6kms$^{-1}$ and a position-angle at the maximum differential velocity in the range PA$\approx$25–45$^\circ$). Next, we applied the above procedure to their 2046 stars and found the differential velocity curve to have a peak amplitude of approximately 6kms$^{-1}$ and a position-angle at the maximum value of PA$\approx$45$^\circ$. The broad agreement between the values obtained from their dataset and ours suggests that the likely explanation for the disparity between the two results is that

| Field | $N_{\text{tot}}$ | $v_r$ | $\sigma_{v_r}$ | $\Delta v_r$ |
|-------|----------------|-------|---------------|-------------|
| C1    | 34             | +145.7±3.7 | 20.8±2.8 | +2.9±3.7 |
| C2    | 34             | +147.5±4.3 | 24.3±3.2 | +1.3±4.3 |
| C3    | 65             | +146.7±3.1 | 24.2±2.3 | -2.4±3.0 |
| C4    | 42             | +154.0±4.4 | 20.8±3.2 | +2.3±4.3 |
| 3D05  | 13             | +141.8±6.6 | 22.4±4.8 | +15.4±6.9 |
| 3D06  | 4              | +150.0±12.5 | 22.6±6.7 | +17.8±14.3 |
| 3D07  | 14             | +128.8±6.9 | 24.7±5.1 | -7.0±6.4 |
| 3D08  | 11             | +139.3±6.4 | 19.8±4.7 | -2.9±7.3 |
| 3D09  | 8              | +132.0±8.6 | 22.8±6.4 | -5.6±8.4 |
| 3D10  | 11             | +150.7±9.0 | 28.5±6.5 | +1.0±8.9 |
| 3D11  | 15             | +159.5±6.3 | 23.1±4.6 | -5.8±6.2 |
| 3D12  | 21             | +162.3±5.0 | 21.6±3.7 | +4.7±5.1 |
| 3D13  | 19             | +150.6±5.1 | 21.1±3.8 | +0.0±5.1 |
| 3D14  | 22             | +159.7±5.6 | 25.1±4.0 | +5.0±5.5 |
| 3D15  | 18             | +171.4±6.4 | 26.0±4.7 | +10.9±6.1 |
| 3D16  | 7              | +173.0±10.9 | 27.2±8.0 | +5.8±11.2 |
| 5D19  | 6              | +138.7±13.5 | 31.2±7.5 | -2.2±14.6 |
| 5D22  | 8              | +148.7±7.2 | 18.8±5.3 | -7.7±7.0 |

Figure 13. A 6.0$^\circ\times$6.5$^\circ$ contour map of the carbon star GRF velocity surface after subtraction of a solid body model of the centre-of-mass proper motion of the SMC. Other details of this plot are the same as in figure [2].
the position-angle quoted in Harris & Zaritsky (2006) was inadvertently referenced from E.

Our contour plot of the RGB star velocity surface also reveals a sizeable kinematic structure towards the NW of our survey area, where GRF velocities reach values of \( v > +10 \text{ km s}^{-1} \). This region appears linked to the positive velocities SE of the central SMC via the southern end of the Bar. In the prominent eastern, Wing region of the Cloud, the velocity field displays no overwhelming trend. The lack of a strong, positive signal in the NE zone of our RGB star velocity field contrasts with the findings of kinematical studies of the HI gas (e.g. Stanimirović et al. 2004), which were taken to be indicative of systematic rotation around the minor axis of the Bar. In fact, there is a substantial pool of low velocities further to the NE, which is also evident as a secondary peak (centered on the 115-130 km s\(^{-1}\) bin) in the histograms for fields 3D7, 3D8 and 3D10 (e.g. see figure 8). De Propris et al. (2010) have also noted the velocity distribution of the RGB stars to the east (and the south) of the SMC center to be bi-modal, but their reported peaks are at approximately 160 km s\(^{-1}\) and 200 km s\(^{-1}\), somewhat larger than the values we observe. This region of our survey encompasses a small sample of red clump stars spectroscopically examined by Hatzipanagou et al. (1997) and with which they identified a positive correlation between velocity and distance. Nidever et al. (2013) have recently identified two relatively distinctive intermediate-age stellar structures, in terms of distance (approximately 55 kpc and 67 kpc), projected several degrees to the east and north of the Cloud.

### 4.5 Old/intermediate versus young stellar population

To gain further insight, we have compared our results to those from another large-scale 2dF based kinematical study of the stellar population of the Cloud. Evans & Howarth (2008) observed 2045 massive stars and also identified a trend of increasing radial velocity from NW to SE, across the bar. It was concluded that this velocity gradient of approximately \(+25 \text{ km s}^{-1} \text{ deg}^{-1}\) at a position-angle \( PA \approx 126^\circ \) could not be attributed solely to variation in the viewing angle of the SMC’s centre-of-mass motion. In accord with earlier investigations (e.g. Mathewson et al. 1988; Ardeberg & Maurice 1979), they found the stars in the Wing to have significantly larger velocities than those of the Bar (\( v_{\text{Wing}} \approx 195 \text{ km s}^{-1}\)). Interestingly, most of the objects in this region turned out to be amongst the earliest spectral-types surveyed in their work (i.e. O and early-B), which concurs with the finding of Cignoni et al. (2013) that there has been a substantial increase in the rate of star formation here within the last 200 Myr. However, the majority of the later-type supergiants that were observed to concentrate in two main elongated aggregates to the west of \( \alpha = 01^h 12^m \), one extending NE-SW along the Bar (W) and the other, from the NE end of the Bar, south along \( \alpha = 01^h 05^m \) (E) (figure 15). The 2dF spectroscopic fibre allocation process could conceivably have led to some apparent differences in the spatial distributions of these massive star populations but there is some evidence of the E aggregate in a density isolophet contour plot for SMC stars with ages in the range 0.1 Gyr < \( \tau \) < 0.3 Gyr and 0.3 Gyr < \( \tau \) < 1 Gyr. This structure is not apparent in the corresponding plot for the youngest objects with \( \tau < 0.1 \) Gyr (figure 4 of Belcheva et al. 2011). There are also hints of this bi-modality in the spatial distribution of SMC star clusters with ages less than 3.5 Gyr (e.g. figure 15 of Rafelski & Zaritsky 2005). Evans & Howarth (2008) advised that their 2dF based velocity measurements were likely to be marginally over-estimated (by a mean of \(+10 \text{ km s}^{-1}\)). The results of our examination (i.e. cross-matching with the catalogues of Maurice et al. 1987; Mathewson et al. 1982; Ardeberg & Maurice 1979) point to a systematic error that is somewhat dependent on spectral-type. While it maybe as large as \(+20 \text{ km s}^{-1}\) for the O and early-B objects, it appears to be smaller than \(+10 \text{ km s}^{-1}\) for the latest stars in the study. Consequently, in performing a direct comparison between the radial velocities of our red-giants and the massive stars, we have worked with only their F/G supergiants. After considering, as above, the relative space motion of the Cloud’s centre of mass,
we determine that these two aggregates of massive stars, E and W as discussed above, are dominated by positive and negative GRF velocities, respectively. These groupings appear to loosely correspond to the location and sign of the main velocity zones we observe in the RGB star velocity map (figure 14). Figure 15 shows the differences in the mean radial velocities of both the F/G supergiants and a sub-sample of our red-giant stars, drawn from roughly the same region of sky, on either side of a bi-secting line that passes through the optical center of the Cloud, (α=00° 53′, δ=−72° 50′) (de Vaucouleurs & Freeman 1972), as a function of this line’s position-angle. The sinusoidal-like forms of these curves have distinct amplitudes (∆<v_r> max ≈ 16 kms⁻¹ and ∆<v_r> max ≈ 4.5 kms⁻¹) but have very similar phases (PA≈26° and PA≈30°). This conclusion is not changed significantly if, like Evans & Howarth (2008), we had adopted α=01° 00′, δ=−73° 00′ as the center. The inferred velocity gradients perpendicular to these position-angles are +20.0±0.8kms⁻¹ deg⁻¹ and +6.1±0.1kms⁻¹ deg⁻¹ for the F/G supergiants and the red-giants stars, respectively. The former can easily account for the small slope of +6.5 kms⁻¹ deg⁻¹ measured in the F/G star GRF velocities along a PA≈60°, the direction of the steepest velocity gradient observed in the HI gas (Stanimirović et al. 2004). It also appears plausible that the slope of +10kms⁻¹ deg⁻¹ along this direction reported by Evans & Howarth (2008) is merely a manifestation of the gradient they identified along a PA≈126°.

Despite some marked differences between the kinematics of the intermediate/old and the massive stellar populations in the SMC (e.g. the lack of an obvious Wing related structure in the complete red-giant sample), there appear to be several similarities (e.g. both display a velocity gradient along a NW-SE direction). We emphasise here that HI maps of the Cloud also provide some weak evidence of a velocity gradient extending from NW to SE, at least across the southern portion of the Bar (see figure 5 of Stanimirović et al. 2004).

5 Interpretation and Discussion

5.1 Systemic rotational motion

We have split our red-giant sample into quartiles on the basis of their metallicities. Considering the form of the SMC age-metallicity relation and its relative invariance across the galaxy (e.g. Noël et al. 2009; Pianta 2012; Cignoni et al. 2013), this is effectively a sub-division of the stellar population in age, with the more metal rich stars typically being significantly younger (e.g. Dobbie et al. 2014). The metallicity of each red-giant was determined from measurements of the equivalent widths of the CaII triplet lines and full details of this process are provided elsewhere (Dobbie et al. 2014). Subsequently, we have undertaken a comparison of the kinematics of the upper and the lower quartiles ([Fe/H]>-0.86 and [Fe/H]<-1.15, respectively) to gain greater understanding of the structure of the SMC. For each subsample we have constructed a contour plot of the radial velocities remaining after accounting for the center-of-mass motion of the Cloud (figures 16 and 17). We have also determined the line-of-sight velocity and dispersion profiles of these sub-samples and the F/G supergiants, along a line through the optical center at PA=120°, which we found in Section 4.6 aligned with the maximum velocity gradient (figure 16). The latter population shows substantial changes in velocity along this axis, reaching approximately +30kms⁻¹ at the south-eastern limit of the Evans & Howarth survey coverage (corresponding to a projected distance from the SMC center of approximately 1kpc). Away from the north-western limit of our survey region (discussed further below), our metal poor and presumed older red-giants display a line-of-sight velocity profile that is effectively flat (χ²=7.9 for 9 degrees of freedom). The line-of-sight velocity profile of our metal rich and generally younger red-giant sub-sample displays a significant gradient, albeit less pronounced than that of the F/G supergiants, reaching 8-10kms⁻¹, 1-1.5 kpc from the centre. Considering that it is a combination of random and systemic rotational...
motions of stars around a galaxy which act to balance the gravitational potential of the system, it is interesting that these latter stars also have a significantly smaller mean line-of-sight velocity dispersion, $\sigma_{v_{los}} \approx 22.3 \pm 0.6 \text{km s}^{-1}$, than the older metal poor red-giants, $\sigma_{v_{los}} \approx 26.1 \pm 0.7 \text{km s}^{-1}$ (at angular distances $>1.5^\circ$). As stars age, repeated gravitational encounters increase the random component of their mean velocities (e.g. Binney & Tremaine 2008). The increased velocity dispersion and lower apparent rotation velocity of the metal-poor RGB stars relative to the metal-rich portion of the sample supports the contention that an age-metallicity relation exists in the SMC.

The inferred gradient of 30-35 km s$^{-1}$ deg$^{-1}$ in the F/G star population is comparable in magnitude to that predicted by the Bekki & Chiba (2009) simulations of the SMC/LMC/Galaxy interaction, although it is significantly less than anticipated by the N-body calculations of Gardiner & Norbury (1996). The intermediate and old stellar populations are also anticipated to display a velocity gradient but the models attribute this largely to streaming motions along the tidal structures of the Cloud (e.g. Diaz & Bekki 2012). However, it is not immediately obvious why our two subsamples display different line-of-sight velocity profiles since strong tidal forces from an interaction with the LMC (or the Galaxy) within the last few 100 Myr would have presumably affected all our intermediate-age red-giant stars.

In view of the coincidence of the position-angles of the velocity gradients in our red-giant and the F/G supergiant samples and our observation that the generally younger red-giants with greater metallicities exhibit a larger systemic motion and a lower mean velocity dispersion, we conjecture that the velocity pattern we detect is related to systemic rotation of disk-like structure. This notion is supported by the intriguing alignment of the Cloud’s coherent magnetic field almost perpendicular to the Bar, as mapped through the polarisation of radio continuum emission and optical starlight (e.g. Mathewson & Ford 1970; Mao et al. 2008). The magnetic fields of both the Galaxy and the LMC are observed to trace the spiral structure of their disks. Wayte (1990) previously concluded from his analysis of the SMC magnetic field that the Bar is not a true bar structure and instead, interaction with the LMC prompted an extension of the Cloud towards the NE and the formation of the Wing.

5.2 Modelling the velocities as a putative SMC disk

To investigate the above possibility, we have attempted to replicate the measured radial velocities of the metal-rich red-giants by adding a disk component to the kinematical model of Section 4.3 following the formalism of van der Marel et al. (2002). This time we have assumed a distance to the SMC of 60 kpc and adopted a tangential velocity of $v_t = 386 \text{ km s}^{-1}$ at position-angle $\Theta_o = 145.4^\circ$ as derived from the most recent Kallivayalil et al. (2013) center of mass proper motion measurement. We have also initially fixed the inclination angle of our disk component at $i = 5^\circ$, which is comparable to that determined by Subramanian & Subramanian (2012) and Haschke et al. (2012) from the distribution of the red clump and RR Lyrae members of the Cloud and adopted the optical determination of the center. In lieu of the results of the previous section, we have also assumed a somewhat smaller intrinsic line-of-sight velocity dispersion of $\sigma_{v_{los}} = 22.3 \text{ km s}^{-1}$. This model was matched to the observations by locating the global minimum of a $\chi^2$ goodness-of-fit statistic, allowing the parameters $\Theta_o$, $R_0$, $\eta$, $V_0$, $\Theta_v$ and $v_{aph}$ (following the notation of van der Marel et al. respectively, the position-angle of the line of nodes, east of north, the disk velocity scaling radius, disk velocity scaling index, maximum disk velocity, the rate of change of the disk inclination angle and the systemic velocity) to vary freely. Our best fit model representation of the data, with parameters $\Theta_o = 127 \pm 9^\circ$, $R_0 = 0.04 \pm 0.04 \text{ kpc}$, $\eta = 3.69 \pm 0.9$, $V_0 = 91 \pm 11 \text{ km s}^{-1}$, $\Theta_v = 0.48 \pm 0.19 \text{ mas yr}^{-1}$ and $v_{aph} = 148.3 \pm 0.8 \text{ km s}^{-1}$, has a $\chi^2 = 778.2$ for 760 degrees of freedom (the uncertainties were determined using a bootstrap with random replacement approach). The corresponding model without a disk component has a $\chi^2 = 824.9$ for 765 degrees of freedom.

Considering the distribution of the F-statistic for $\nu_1 = 5$ and $\nu_2 = 760$, we find the addition of the disk component to the kinematic model provides a significant improvement to our reproduction of the observations. However, empirical studies of low luminosity, late-type systems have highlighted that their rotation curves attain lower circular velocities than those of more massive galaxies (e.g. Rubin et al. 1985; Broeils 1992; Swaters et al. 2009). With an integrated apparent B magnitude of 2.58$ \pm 0.07$ mag. (Bothun & Thompson 1988), a distance of 60 kpc and $B-R = 1$ mag. (Swaters 1999), we estimate the absolute $R$ magnitude of the SMC to be only $M_R \approx -17.3$ mag. and anticipate the circular velocity of the cold HI disk to reach only $V_c \approx 60-70 \text{ km s}^{-1}$ several disk scale lengths from the center. While these latter values are comparable to the velocities determined at the limits of the HI study of Stanimirović et al. (2004), they are substantially less than those delineated by the rotation curve of our virtually face on disk model, even before any allowance is made for the asymmetric drift velocity of the red-giant population. Moreover, our estimate of $V_0$ is even larger if we adopt instead the HI center as the kinematic center.

We have performed a rough assessment of the asymmetric drift by noting that for an inclination angle of $i = 5^\circ$, the observed velocity dispersion is effectively $\sigma_z$, the vertical component in the disk. Adopting the disk geometry from the fit above, we have determined the radial gradient of the spatial density of stars in the SMC ($\nu$) by modelling the azimuthally averaged brightness profile of the galaxy as measured from 3.36 \text{ \mu m WISE imaging (Wright et al. 2010). We used a function of the form $\nu = \nu_0 \exp(-\frac{R}{R_{exp}})$, where the exponential scale length, $R_{exp}$, is found to have a value of 0.76$ \pm 0.08$ kpc. Subsequently, assuming that in the putative SMC disk $\sigma_\nu \approx 0.7 \sigma_R \approx \sigma_\phi$ (the latter two variables represent the radial and azimuthal components of the disk velocity dispersion, respectively), which Hunter et al. (2005) argues to be appropriate at least...
for spiral galaxies (e.g. NGC 488, the Milky Way), we have followed (Hinz et al. 2001) to estimate the asymmetric drift velocity ranges from 22 kms\(^{-1}\) at 0.75 kpc to 55 kms\(^{-1}\) at 2.75 kpc. In light of these sizeable corrections, it appears quite unlikely that the velocity signature we observe in the red-giant stars can be attributed to a disk that is viewed at a low inclination angle. This conclusion is independent of the parameterisation of the disk rotation curve.

Needless to say, we can obtain plausible values for the circular velocity of the disk if the inclination angle is assumed to be larger. For example, with \(i \approx 60^\circ\), which is comparable to inclination estimates derived from the younger stellar populations in the Cloud (e.g. Haschek et al. 2012, Laney & Stobie 1986). The best fitting disk model has \(V_0 \approx 20\) kms\(^{-1}\) (with \(\Theta \approx 122^\circ, R_0 \approx 8.7\) kpc, \(\eta \approx 0.01, \sigma \approx 0.5\) mas yr\(^{-1}\) and \(v_{\phi,\perp} \approx 148\) kms\(^{-1}\)). The initial rise of this parameterised rotation curve is rather abrupt and seemingly unphysical. However, the asymmetric drift velocity of the RGB star population beyond the inner few 100 pc is substantial and renders the raw rotation curve, which we are modelling, effectively flat at all larger disk radii. To explore alternative inclination angles further, we have also probed the red-giant line-of-sight velocities with a tilted ring model (Begeman 1987). For this part of the investigation we have adopted six radius intervals with width 0.5 kpc from 0.0–3.0 kpc and have fixed the inclination angle at \(i = 25^\circ\), which is similar to that estimated in the pioneering study of the SMC by de Vaucouleurs (1955) and intermediate to the values discussed above. We have also anchored the kinematic center and the rate of change of the inclination angle at the values preferred from our analysis above. The line-of-nodes position-angle and the velocity of each ring were permitted to vary freely in the fitting process. The results, both raw and after accounting for the generally substantial asymmetric drift velocity, are shown in figure 19 where for the latter, we have taken \(\sigma_{\phi,\perp} \approx \sigma_c\) (e.g. Hunter et al. 2005).

At this assumed inclination angle, the inferred rotation curve rises relatively swiftly to 20 kms\(^{-1}\) and continues to increase gradually to approximately 50 kms\(^{-1}\) at a radial distance of 2–2.5 kpc. Within the significant uncertainties, it is comparable to the empirical data for other low luminosity, gas-rich systems which almost invariably show a slow, steady rise in circular velocity with increasing galacto-centric distance that generally continues to the outermost measurement point (e.g. UGC 7603, UGC 7971, UGC 8490 Swaters et al. 2009). It is also similar to the HI disk velocities measured for the dwarf irregular NGC 6822, which rise to \(V_c \approx 50\) kms\(^{-1}\) around 3 kpc from the center (Weldrake et al. 2003). This dark dominated galaxy is similar in luminosity (\(M_B \approx -15.5\)) to the SMC but has a much lower velocity dispersion. The line-of-sight velocity dispersion of the SMC red-giants is effectively constant with galacto-centric distance, with no evidence for a decrease towards larger radii as anticipated for a disk embedded in a dark halo (\(\sigma_c \propto R^{-1}\)). A mild positive correlation between radial distance and the velocity dispersion of the carbon stars several kpc out in the LMC has been attributed to disk flaring (Alves & Nelson 2000).

The impact of systemic rotation with a magnitude of \(V_c \approx 25\) kms\(^{-1}\) at an inclination angle of 25° on estimates of the SMC centre-of-mass tangential velocity is only a few percent and within the uncertainties that propagate from the HST proper motion measurements of (e.g. \(\mu_{\alpha,\sin} \approx 0.04\) mas yr\(^{-1}\)) (Kallivayalil et al. 2013). Given the locations of their five proper motion measurements, the details of this minor effect are heavily dependent on the position of the disk rotation center. For example, if this corresponds to the optical center, then the contribution of the systemic motion is predominantly in a SE direction, so the current centre-of-mass tangential velocity determination will be slightly overestimated. Conversely, if the HI center represents the stellar rotation center then the disk component to the tangential motion is predominantly in a N/NW direction, resulting in a slight underestimate of the centre-of-mass tangential velocity. The effect of systemic rotation is even smaller if the disk is being viewed at a larger inclination angle e.g. \(i \approx 60^\circ\).

We note that the position-angle inferred for the disk line-of-nodes changes abruptly by around 180° at a projected galacto-centric distance of approximately 2.5 kpc. This might have been anticipated from an inspection of figure 3 which reveals a large region of generally positive velocities towards the far WNW of our survey region (higher velocities are also evident in this region in the RGB star radial velocity study of De Propis et al. 2010). If the red-giant stars here are also part of a disk structure in the same plane, then they appear to be counter-rotating with respect to the inner 2-3 kpc of the SMC. Alternatively, these objects might compose a disk rotating in a similar sense to the inner regions that is merely viewed at a quite different inclination angle. However, counter-rotation of gas has been observed in other irregular galaxies such as NGC 4448 and IC 10 (e.g. Hunter et al. 1998). The latter object is a slightly less luminous (\(M_B \approx -15.5\)) cousin of the SMC that has recently entered an epoch of intense star formation (Wilcots & Miller 1998). The gas in its central regions displays a modest rotational signature, peaking at 30–35 kms\(^{-1}\), but at galacto-centric distances greater than 1–2 kpc there are several HI structures with velocities that run counter to expectations based on the continuation of the kinematic trends of the inner galaxy (Wilcots & Miller 1998) have suggested that IC 10 may have recently accreted this material from an extended reservoir, leading to the current burst of star formation.

The accretion of a gas rich dwarf galaxy has been invoked by several investigators (e.g. Zaritsky et al. 2000, Rafelski & Zaritsky 2005, Bekki 2008, Subramanian & Subramaniam 2012) to account for the stark differences in the morphologies of the SMC’s young and older stellar populations and/or the substantial variations in the Cloud’s star formation rate within the last few Gyr. However, as discussed further in Dobbs et al. (2014), recent theoretical exploration of the chemical evolution of the SMC, which treats a major gas rich accretion event, anticipates a fairly pronounced dip in the age/metallicity relation (Tsujimoto & Bekki 2009), for which there is little support from recent empirical determinations that consider both star clusters and field stars (Pratt 2011, 2012). Additionally, studies of the LMC indicate it has experienced substantial increases in star formation activity at similar times to the SMC (e.g. Harris & Zaritsky 2009, Smecker-Hane et al. 2002), disfavouring a triggering mechanism that was specific to the evolutionary history of the latter. Considering this and given the proximity of the SMC to the LMC and the Galaxy, their history of tidal interaction and the results of N-body simulations within the literature, in the next section we discuss another explanation, which we consider more likely, for these apparently counter-rotating stars.

### 5.3 Tidal speculation

The larger the galacto-centric distance of a star, the more susceptible it typically is to being dislodged by the forces which arise in a galaxy-galaxy interaction (e.g. Mihos & Hernquist 1994). A two-sample Kolmogorov-Smirnov test on the normalised cumulative radial distributions for the upper and the lower metallicity quartiles of our red-giants (constructed by adopting the semi-major axis of an ellipse, with \(a/b=1.5\) and an origin at the center of the Cloud, on which a star lies, as a proxy for its galacto-centric dis-
Figure 19. Velocities (top, open circles), velocity dispersions (middle, filled circles) and line-of-nodes position-angles (lower, filled triangles) from our tilted ring analysis of the metal rich red-giant sample. Estimates of the circular velocity of the putative SMC disk, accounting for asymmetric drift, are also shown (top, filled squares). The HI rotation curves of several dwarf galaxies e.g. UGC 7603 (middle curve), UGC 7971 (bottom curve), UGC 8490 (upper curve), are also overplotted in the top panel.

The influence of tidal forces on the SMC could also be a plausible explanation for the moderate rate of change of the inclination-angle we infer for the putative disk in our modelling of the line-of-sight velocities of the centrally concentrated metal-rich red-giants ($\beta \approx 140^\circ$ Gyr$^{-1}$). Piatek & Pryor (1995) have demonstrated using an N-body simulation of a dwarf spheroidal interacting with a larger galaxy that the effects of tidal forces can be manifest as an apparent rotation around the minor axis of the satellite. However, it is not clear if the viewing geometry here is conducive to this. These simulations also indicate that stars residing at smaller galacto-centric radii are dislodged in a galaxy-galaxy interaction since an additional factor which dictates their fate is velocity along the line-of-centers (Piatek & Pryor 1995). While the changing inclination of the LMC’s disk has been attributed to the impact of tidal torques from the Clouds (van der Marel et al. 2002), further investigation of the SMC kinematics indicates that the non-negligible value of $\beta$ here stems from the protrusion of lower velocities towards the Wing region, lower velocities towards the NE of our survey area and an excess of positive stellar GRF velocities just beyond the SW end of the SMC Bar (see figure 17). The two zones of negative GRF velocities, at least, appear to lie in with features previously touted as having formed as a result of the most recent encounter with the LMC. In view of the kinematics and the locations of the stars towards the Wing and around the SW end of the Bar it is tempting to associate them with, respectively, the lower velocity foreground complex proposed by (Nidever et al. 2013) as an intermediate-age stellar component of the Magellanic-Bridge and the structure in the W and NW of our survey area that we have advanced as a stellar analogue of the “Counter-Bridge”. However, the signs of the velocities in both regions appear to be contrary to expectations from simulations of the SMCs evolution (e.g. Diaz & Bekki 2012, Gardiner & Noguchi 1996). Perhaps at least part of this discrepancy is due to an incorrect assumption in these calculations of the orientation of the SMC stellar disk. Nonetheless, these new observations and prior theoretical and empirical studies (e.g. Bekki & Chiba 2009, Olsen et al. 2011) paint a complex picture of an intermediate-age stellar population in the SMC that is subject to substantial tidal stripping. Given the expected distances...
The source of the discrepancy may be due to degeneracies in the arrangement of the Cloud’s coherent magnetic field across the Bar that the F/G supergiants examined here would have had only a model formalism for linear (or nearly linear) rotation curves (see circa 200 Myr in which to dynamically separate from the HI gas. Observations (PA below).

The position angle of the SMC kinematic axis derived from HI observations is consistent in phase with that observed in the young, massive stellar population by Evans & Howarth (2008). The line-of-sight velocity and velocity dispersion profiles for the most metal poor red-giants, with the tidal “Counter-Bridge” tail predicted by N-body and hydrodynamical simulations of the SMCs most recent interaction with the LMC.

6 SUMMARY

We have acquired optical spectroscopy for a sample of 3037 predominantly RGB stars distributed across 37.5 deg² of the SMC and have measured their radial velocities to an accuracy of better than 5 km s⁻¹. The main results of our analysis of these datasets, as illustrated in figure 20, are:

- We have found a velocity gradient in the rest frame of the SMC which is consistent in phase with that observed in the young, massive stellar population by Evans & Howarth (2008). The line-of-sight velocity and velocity dispersion profiles for the most metal poor giants, the most metal rich red-giants and the F/G supergiants, along a PA ≈ 120°, the direction of the steepest gradient, and the arrangement of the Cloud’s coherent magnetic field across the Bar suggest this arises from the systemic rotation of disk structure.

- The orientation of this putative stellar disk is discordant with the position angle of the SMC kinematic axis derived from HI observations (PA ≈ 60°). This inconsistency is challenging considering that the F/G supergiants examined here would have had only a model for linear (or nearly linear) rotation curves (see below).

- An almost face-on viewing angle (i ≈ 5°) has been favoured by recent studies of the intermediate and old stellar populations of the SMC. Analyses of the line-of-sight velocity of the most metal-rich SMC red-giant stars, following the disk formalism of van der Marel et al. (2002) and with a tilted ring model, show that for such low inclinations the inferred circular velocities (Vₖ ≳ 90 km s⁻¹) are much larger than those typically observed in a galaxy of the SMC’s luminosity (Vₖ ≈ 60–70 km s⁻¹). It is thus unlikely that the velocity patterns seen in these stars are attributable to a disk viewed nearly face-on.

- Assuming a larger inclination angle (e.g. i ≈ 25°), comparable to that determined by de Vaucouleurs (1955), we can infer a rotation curve for an SMC disk that, within the uncertainties of our analysis, is accordant with those of similarly luminous galaxies such as NGC 6822. If a disk with a kinematic major-axis along a PA ≈ 120° is the correct interpretation of the observed velocity patterns within the central regions of our survey area then some revision to simulations of the evolution of the Cloud may be required as these are generally tuned to the disk plane lying in a NE-SW direction at the present epoch. However, the neglect of this systemic rotation has only a minor impact on estimates of the Cloud’s centre-of-mass tangential motion.

- Considering the proximity of the SMC to the LMC and the Galaxy, their history of tidal interaction and the different spatial distributions of the young and old stars within the Cloud, we associate a kinematical structure towards the far north-west of our survey area, that is particularly evident in the velocities of our most metal poor red-giants, with the tidal “Counter-Bridge” tail suggested by N-body and hydrodynamical simulations of the SMCs most recent interaction with the LMC.

- The moderate rate of change of the disk inclination angle, Ω ≈ 140° Gyr⁻¹, inferred by our modelling, is also likely attributable to the influence of tidal forces on the SMC. The protrusion of lower velocities towards the Wing region and an excess of positive stellar GRF velocities just beyond the SW end of the SMC Bar, observed in kinematics of the younger, metal-rich RGB stars, are probably associated with a lower velocity foreground complex proposed by Nidever et al. (2013) as an intermediate-age stellar component of the Magellanic-Bridge and the structure in the W and NW of our survey area that we advance as a stellar analogue of the “Counter-Bridge”, respectively.

- The disagreement between disk parameters derived from HI and stellar velocities opens the question of how to appropriately model a system in which multiple processes contribute similar amounts to the observed velocities. For example, the inferred rate of change of inclination of the HI disk of about 400° Gyr⁻¹ (Indu & Subramaniam 2014, in prep) is much larger than that for the stellar disk and represents a radial velocity gradient of approximately 5.5 km s⁻¹ kpc⁻¹ along the major axis of the disk. This is of the same order as the apparent velocity gradient induced by the transverse motion of the centre of mass, and not much smaller than the disk rotation velocities we derive. The Ω and Vₖ contributions are defined to be perpendicular to each other, and so model algorithms are likely to trade one against the other when the rotation curve is linear. In the SMC case, we also have to consider that the proper motion is directed nearly parallel to the stellar disk position angle. This degeneracy is likely to be broken only when significant samples of stars beyond the radius at which the rotation curve flattens out are measured, and the data considered in the light of the origins of any torques that could significantly alter the disk angular momentum.

- A more spatially extensive radial velocity survey of the young stellar population, including sources located north of the δ ≈ 72° limit of the Evans & Howarth work, would help address questions.
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