High-resolution N-body Simulations of Galactic Cannibalism: The Magellanic Stream

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Abstract

Hierarchical clustering represents the favoured paradigm for galaxy formation throughout the Universe; due to its proximity, the Magellanic system offers one of the few opportunities for astrophysicists to decompose the full six-dimensional phase-space history of a satellite in the midst of being cannibalised by its host galaxy. The availability of improved observational data for the Magellanic Stream and parallel advances in computational power has led us to revisit the canonical tidal model describing the disruption of the Small Magellanic Cloud and the consequent formation of the Stream. We suggest improvements to the tidal model in light of these recent advances.

Keywords: methods: N-body simulations – galaxies: interactions – Magellanic Clouds –

1 Introduction

With the release of the Wilkinson Microwave Anisotropy Probe (WMAP) results (Spergel et al. 2003), the Cold Dark Matter (CDM) has essentially shifted from a "favoured" paradigm to what is now referred to as the "concordance model". Hierarchical clustering is an important component of CDM models, one in which the first objects to collapse in the Universe were small, with subsequent merging of these objects coupled with collapse on increasingly larger scales as the Universe ages. Such merger- and accretion-driven evolution appears to have peaked over the redshift range $\sim 2 - 5$ (e.g. Murali et al. 2002), but equally important, continues to the present-day. Indeed, our own Local Group provides several spectacular examples of hierarchical clustering "in action", including the disrupting Sagittarius dwarf (Ibata et al. 1994), the putative Canis Major dwarf (Martin et al. 2003), and perhaps the most visually stunning of all, the debris associated with the interacting Large and Small Magellanic Clouds (LMC and SMC, respectively, hereafter) – the so-called Magellanic Stream (Mathewson et al 1974). Disrupting satellites such as these are the best local laboratory to understand the physical processes of "galactic cannibalism", as we have the luxury of obtaining detailed observations pertaining to the respective systems' star formation histories (e.g. Harris & Zaritsky 2001; Smecker-Hane et al. 2002) and internal chemical evolution via stellar abundance patterns for individual stars within the satellites (Tolstoy et al. 2003).

One of the most obvious of manifestations of cannibalism within the Local Group is that of the aforementioned Magellanic Stream. The Magellanic Stream (MS) is a remarkably colinear band of (primarily) neutral hydrogen (HI) stretching from horizon-to-horizon through the South Galactic Pole, emanating from the Magellanic System. van Kuilenburg (1972)[1] discovered a lengthy high-velocity gas stream near the South Galactic Pole, while Wannier & Wrixon (1972) noted that the feature had a large and smoothly varying velocity (from $v_{LSR} \sim 0$ to $-400\,\mathrm{km\,s}^{-1}$, or $v_{GSR} \sim 0$ to $-200\,\mathrm{km\,s}^{-1}$), and was over $60°$ long (but only $\sim 4°$ wide). Mathewson et al. (1974) finally confirmed the connection between this feature and the Magellanic Clouds (MCs), suggesting the stream was $180°$ in length, lying on a great circle. They showed the stream was clumpy, and gave the designations MSI–VI to the six dominant clumps (Mathewson et al. 1977). Most recently, Putman et al. (1998) showed what is now considered to be the full extent of the stream, with the identification of a leading arm feature (LAF) definitively associated with the Magellanic System. Indirect supporting evidence for both the trailing and leading arm streams being associated directly with the disrupting Magellanic Clouds is also provided by the similarity in chemical "fingerprints" between the gas in the streams and the gas in the Clouds (Lu et al. 1998; Gibson et al. 2000).

Building upon the seminal work of Murai & Fujimoto (1980), recent observational and theoretical analyses are consistent with the suggestion that the Clouds are close to peri-Galacticon. For example, the Galactocentric radial velocities of the Clouds are small at $84\,\mathrm{km\,s}^{-1}$ (van der Marel et al. 2002) and $7\,\mathrm{km\,s}^{-1}$ (Hardy, Suntzeff & Azzopardi 1989; Gardiner, Sawa & Fujimoto 1994 – hereafter GSF94) for the LMC and SMC, respectively, compared with their respective transverse velocities in the Galactocentric frame of $280\,\mathrm{km\,s}^{-1}$ (van der Marel et al. 2002) and $\sim 200\,\mathrm{km\,s}^{-1}$ (Lin, Jones & Klemola 1995) consistent with this hypothesis. The closest approach to date, both between the Clouds and between the MCs and the Milky Way occurred $\sim 200\,\mathrm{Myr}$ ago, and the orbital period of the SMC about the LMC is $\sim 900\,\mathrm{Myr}$, with the Clouds as a pair orbiting the Galaxy with a period of order $1.5\,\mathrm{Gyr}$ (e.g. GSF94). Early models from Murai & Fujimoto (1980) and Lin & Lynden-Bell (1982), supplemented with the recent proper motion work from Jones, Klemola & Lin (1994) have provided us with an accurate representation of the present-day orbital characteristics of the Magellanic System. The determination of the orbital sense of the system demonstrates clearly that the MS is an extension stretching beyond the present galactocentric distance of the MCs, rather than a bridge joining the MCs with the Galaxy, and

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[1]Anomalously high-velocity gas features near the South Galactic Pole had actually been known since the work of Dieter (1965), but the link to the Magellanic System was not fully appreciated until that of Mathewson et al. (1974).

leading them (Lin & Lynden-Bell 1982; Lin et al. 1995), and also that the MCs are close to peri-Galacticon.

Considerable debate exists within the literature as to whether the Magellanic Stream is the result of ram pressure stripping (Moore & Davis 1994; Mastropietro et al. 2004) or gravitational tidal effects in which the Stream material is either stripped off the LMC (Weinberg 2000), the SMC (e.g. Gardiner & Noguchi 1996 – hereafter GN96), or a common envelope (the inter-Cloud region; e.g. Heller & Rohlfs 1994). The observations of the LAF (Putman et al. 1998) show that tidal forces account for at least some fraction of the "force" shaping the existence of the Stream, even as the observed Hα emission measured along the Stream suggest that some additional ram pressure heating effects may be present (Weiner & Williams 1996; cf. Putman et al. 2003b).

Yoshizawa & Noguchi (2003; hereafter YN03) have provided recently a significant improvement to the now canonical "tidal" model of GN96, via the inclusion of gas dynamics and star formation. In a prescient forebearer to YN03, Gardiner (1999) also provided important extensions to his earlier GN96 work using new constraints introduced by the recent discovery of the LAF, the addition of a drag term into the particle force equations, and an improved modelling of the LMC's disk potential. These latter modifications have the beneficial effect of mildly deflecting the orientation of the LAF with respect to the Magellanic System in a manner more consistent with the Putman et al. (1998) dataset.

Encouraged by the success of these earlier studies, we are undertaking a comprehensive computational program aimed at providing the definitive deconstruction of this Rosetta Stone of hierarchical clustering – the disrupting Magellanic System. We now have access to the full HIPASS South *and* North dataset, data which was not available to Putman et al. (1998), allowing us to improve upon the observational constraints on both the trailing Stream and leading arm. Our *ultimate* product will be the construction of a model which includes all relevant physical processes, including gas dynamics, ram pressure, radiative cooling, star formation, and chemical enrichment, all treated *self-consistently* for the first time, in a hope to understand the physical processes of galactic cannibalism. Our cosmological chemodynamical code GCD+ (Kawata & Gibson 2003a,b) affords the power and flexibility to attack this problem in a manner previously inaccessible.

What follows represents the first of a series of papers devoted to this system; this Paper I shows preliminary results based solely upon very high-resolution N-body simulations undertaken without the gas component of GCD+ implemented. This first step was required in order to allow a full exploration of orbital parameter space prior to the introduction of gas into the modelling. The reason for doing so is that current observational constraints on the system still allow one some flexibility in choosing a unique orbital configuration for the system, partly due to our less-than-optimal understanding of the LMC and SMC masses. The spatial orientation and nature of any SMC disk is also poorly constrained. Since N-body simulations are less computationally "expensive", we can survey different orbits for the Clouds, and determine our best orbital configuration(s). In what follows we present our current best N-body model for the Magellanic Stream, compare this model with the extant observational data, and provide a roadmap for our

future work, highlighting the successes and failures of the currently accepted canonical tidal model for the formation of the Magellanic Stream.

2   Simulations

The basic framework of both GN96 and YN03 was adopted in our study. The Milky Way (MW) and LMC were represented as fixed potentials – the MW with a flat rotation curve of $220\,\mathrm{km\,s^{-1}}$, and the LMC as a Plummer potential with core radius of $3\,\mathrm{kpc}$ and a mass of $2\times10^{10}\,\mathrm{M_\odot}$. Canonical wisdom suggests that the Stream results mainly from the tidal disruption of the SMC (e.g. GSF94; GN96; Maddison et al. 2002; YN03), with minimal contribution from the LMC, and is traditionally invoked (as we have done here) as a reasonable justification for this assumption (cf. Mastropietro et al. 2004). The SMC was modelled as a self-gravitating system of particles. The orbits for both the LMC and SMC were pre-calculated (see GN96 for details), as derived by GSF94. The models were computed from $T_i \le -2\,\mathrm{Gyr}$ to the present epoch ($T = 0$), but note in passing that the results are not dependent upon the specific starting epoch (GSF94).

We performed an extensive parameter search over those variables which remain poorly-constrained by observation. For the LMC and SMC, we varied the ratio of the halo and disk masses between 1:1 and 5:3, the ratio of the tidal radius of the halo-to-disk truncation radius (albeit the ratio was restricted to values near unity), the scale height of the disk (retaining a spherical halo with only marginal deviations from sphericity), the velocity dispersion in the disk, and the total masses of both clouds. For the LMC, the mass range sampled was $8 - 20\times10^9\,\mathrm{M_\odot}$ (Schommer et al. 1992; Kunkel et al. 1997; van der Marel et al. 2002). The parameters that most affected the position and quality of the simulated Stream were the initial angle of the SMC disk relative to the MW (surveyed over 2 dimensions on a 45° grid), and the radius of the (non-stellar) disk (varied over radii between 2 and 7 kpc, on a 0.5 kpc grid). We also performed convergence tests, both on the number of particles and the starting epoch T_i. Full results of *all* tests will be the subject of Paper II; for brevity, we only present our preferred N-body model (based on kinematic and spatial similarities to the observational data for the MS and LAF) here.

The initial particle distribution of our SMC disk was generated using a modified version of galactICs (Kuijken & Dubinski 1995); a two-component disk+halo model was the result of this first stage. These particles were then evolved using the GCD+ parallel tree N-body code described by Kawata & Gibson (2003a,b). As noted earlier, the preliminary work presented here was undertaken using only the N-body component of GCD+; full gas dynamics, star formation, cooling, and chemical evolution will be explored in Paper III. In our initial low-resolution runs we typically used 20000 disk particles and 33000 halo particles (to maintain an equal mass between disk and halo particles). We emphasise though that our high-resolution runs were undertaken at a resolution ten times higher, corresponding to a resolution ∼ 40 times greater than that employed by GN96 and YN03. Such resolution allowed us to examine features of the MS, LAF, and SMC, in a manner not previ-
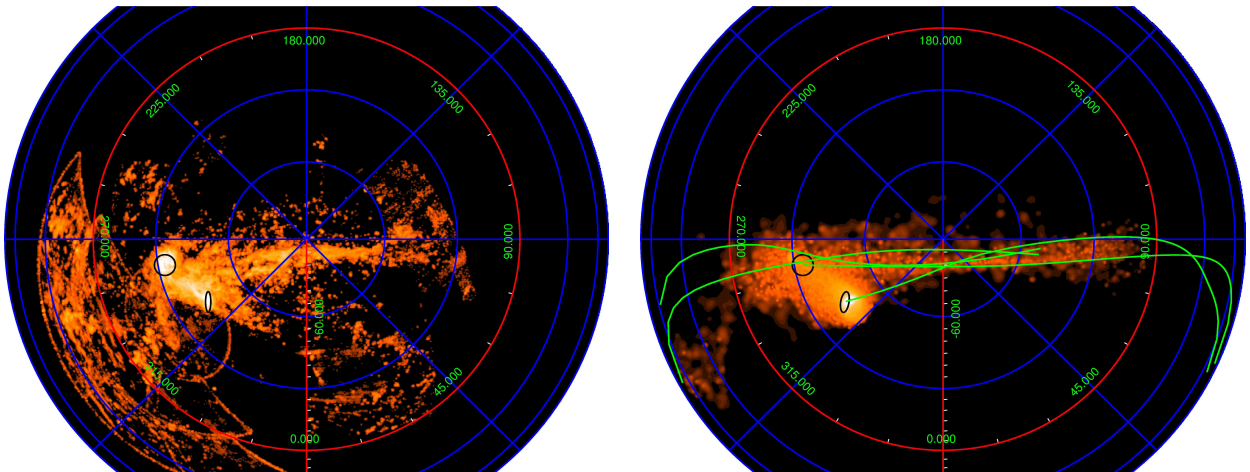
Figure 1: Observed (left) and modelled (right) flux of the Magellanic Stream (trailing to the right of the Clouds in these panels) and LAF (to the left) on a logarithmic scale, in units of $\log_{10}(\text{Jy/beam} \cdot \text{km s}^{-1})$ – peak flux of $1000\,\text{Jy/beam} \cdot \text{km s}^{-1}$, and minimum flux of $0.01\,\text{Jy/beam} \cdot \text{km s}^{-1}$, on an all sky Zenith Equal Area projection. Since only the SMC has been modelled, the flux around the LMC is underestimated. The projection of the initial SMC disk at the angle used in the simulation has been overlaid on the simulation at $(l,b) \sim (300°, -45°)$, as has the approximate size of the Plummer core radius of the LMC at $(l,b) \sim (280°, -30°)$. The orbit calculated from the best model parameters has also been plotted in the right panel. The LAF (Putman et al. 1998) is seen to extend from $(l,b) \sim (290°, -30°)$ down to $(l,b) \sim (310°, 0°)$ and then back up to $(l,b) \sim (290°, 20°)$ and *possibly* onto $(l,b) \sim (265°, 20°)$ in the left panel, and from $(l,b) \sim (280°, -10°)$ to $(l,b) \sim (305°, 40°)$ and then to $(l,b) \sim (290°, 50°)$ in the right. The inter-Cloud bridge joins the two clouds and forms a common envelope around them. The Magellanic Stream is seen twisting to the right of the clouds, with many small clumps separated from the main stream in both panels.

ously possible, since smaller fractional differences in particle density become statistically significant. We performed stability tests on the initial SMC particle configurations removed from the influence of the potentials of both the host MW and LMC. The disk and halo were evolved together for 2 Gyr and this "relaxed" particle distribution input into the MS simulation proper.

We found an improved match to the observational data when starting our simulations at $T_i = -3\,\text{Gyr}$, marginally earlier than the $T_i = -2\,\text{Gyr}$ typically adopted (GN96; Gardiner 1999; YN03). Our initial SMC disk was slightly larger than that used by GN96 (5.5 kpc vs 5.0 kpc); in addition, our SMC disk mass was marginally less massive $(1.125 \times 10^9\,\text{M}_\odot$ vs $1.5 \times 10^9\,\text{M}_\odot$; with the total mass of the SMC being $3 \times 10^9\,\text{M}_\odot)$. Finally, since the initial angles were calculated on a regular grid, the chosen angle was slightly different here – $(\theta, \phi) = (45°, 225°)$, instead of $(\theta, \phi) = (45°, 230°)$. The LMC was surveyed over 8, 10, 15 and $20 \times 10^9\,\text{M}_\odot$, with the latter being favoured for the choice of grid parameters adopted.

3 Results

Consistent with earlier models (e.g. GN96; YN03), an encounter between the MW and the Clouds 1.5 Gyr ago drew out the tidal features that later became the LAF and MS under the tidal forces of the Galaxy (most of the LAF material was pulled back into the inter-Cloud region by the LMC). A stronger interaction between the LMC and SMC $\sim 200\,\text{Myr}$ ago resulted in an inter-Cloud Magellanic Bridge that has not yet had time to disperse.

Assuming an HI gas fraction of 0.76, and a conversion factor between simulated column density in units of $\text{atoms} \cdot \text{cm}^{-2}$ and HI flux in units of $\text{Jy/beam} \cdot \text{km s}^{-1}$, of $0.76 \times 1/(0.8 \times 1.823 \times 10^{18})$ (Barnes et al. 2001), Figure 1 shows both the observed HI flux of the Magellanic Stream and the simulated HI flux for our best model. We see that the gross features of the Stream are reproduced and conclude (as previous workers have) that the LAF appears as a consequence of tidal interactions. A failing of the model lies in the discrepancy between the exact projected positions of the observed and simulated LAFs, primarily in relation to the respective points from which they appear to "emanate". The actual angle of deflection in both panels is quite similar, but the observed "bend" in the LAF back towards the great circle from $(l,b) \sim (310°, 0°)$ to $(l,b) \sim (290°, 20°)$ and *possibly* onto $(l,b) \sim (265°, 20°)$ is not reproduced. The increase in resolution of our best model over the previous models allow us to see more detail in the LAF. We see there is possibly a small "kink" back towards the great circle from $(l,b) \sim (305°, 40°)$ to $(l,b) \sim (290°, 50°)$, that was not apparent in low resolution runs with the same initial conditions. The definition of the LAF is somewhat ambiguous in the model (particularly in the delineation between LAF and SMC gas), but nevertheless, we find that the mass ratio between our simulated MS and LAF is ~ 5. The observed *mass* ratio is difficult to
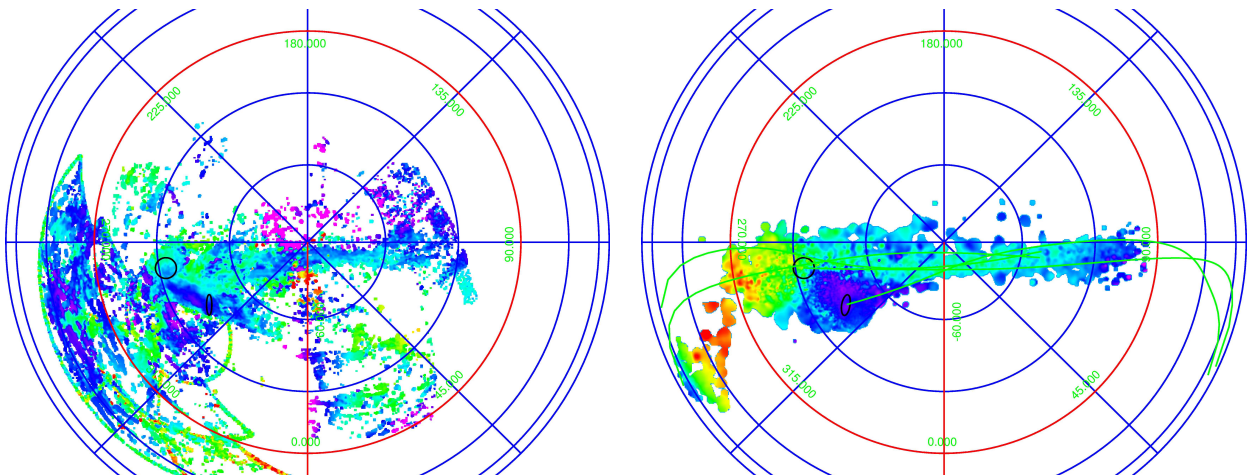
Figure 2: As in Figure 1, but now showing the first moment (with the mean velocity gradient subtracted equally from both images). The limiting column density employed in the simulation data is 2×10^{17}cm^{-2}. The velocity scale ranges from $-100\,\mathrm{km\,s^{-1}}$ (purple) to $+200\,\mathrm{km\,s^{-1}}$ (red).

quantify as one has no *direct* measure of the gas mass in either the MS or LAF – one is restricted to the HI *flux* ratio (Putman et al. 1998). Under the assumption that the MS and LAF are at a comparable distance, the observed HI gas mass ratio is $\gtrsim 10$ (Putman et al. 1998; Putman 2000). The simulated MS shown in Figure 1 is comparable in mass with that observed – assuming (i) a Stream distance of 50 kpc and (ii) an uncertain conversion from N-body to gas particle mass – the simulated MSI–MSVI clumps correspond to a mass of $\sim 2.5\times10^7\,\mathrm{M_\odot}$, within a factor of four of the inferred empirical gas mass (Putman et al. 2003).

Figure 2 shows the first moment map of both the observed (left panel) and simulated (right) Streams after subtraction of the observed gross velocity gradient – i.e., the velocity "residuals" with respect to the smooth underlying gradient.[2] Any differences in the geometries between the simulated and observed Streams can have a significant impact on the velocity maps, due to the (a) reference frame transformation from both the simulation "cube" and observations to the Galactic Standard of Rest, and (b) the position-dependency of the velocity gradient subtraction (see Figure 4 for the overall trend with position in the simulation). With this in mind, we see that there is surprisingly good agreement between data and model over the entire MS and LAF in velocity space. Figure 3 shows the second moment maps. The model admittedly does not reproduce the velocity dispersion in the inter-Cloud region very well (the MS and LAF are in better agreement though). This discrepancy *may* be solved by the inclusion of an appropriate treatment of gas dynamics (due to the dissipative nature of the gas); this will be explored in Paper III of this series.

It is worth drawing attention to the observed bifurcation and twisting of the Stream described in some detail by Morras (1983). Putman et al. (2003) claim that this spatial bifurcation results from the binary motion of the

SMC around the LMC (Putman et al. 2003). In this picture, the filaments of the bifurcation are associated with gas stripped from the SMC and inter-Cloud region of the LMC–SMC system. In our simulations, this "helix-like" twisting of the filaments is a natural consequence of the SMC–LMC orbits "twisting" about each other – the orbital overlays of Figure 1 (right panel) show the near one-to-one correlation between observed filaments locations and the projected orbits of the Clouds. This spatial bifurcation (and a kinetic bifurcation seen in Figure 4) are obvious only in our high resolution simulation.

The preliminary simulations described here also yield a velocity bifurcation of $\sim 100\,\mathrm{km\,s^{-1}}$ along the first $\sim 40°$ of the MS trailing the SMC ($-50° < \theta < -10°$). Figure 4 shows the velocity in the Local Standard of Rest plotted against the Magellanic longitude (where θ is defined with a somewhat different origin to that adopted by Wannier & Wrixon 1972 and Mathewson et al. 1974). A kinematical bifurcation also appears to be evident in the Putman et al. (2003; Fig. 11) dataset, particularly over the range $-30° < \theta < +10°$, comparable both spatially and kinematically with that seen in Figure 4 here. This bifurcation requires further analysis and will be the subject of Paper II of this series.

4   Discussion and Conclusion

The combined neutral hydrogen gas mass in the Magellanic Clouds, Stream, Leading Arm, and inter-Cloud region, is in excess of $10^9\,\mathrm{M_\odot}$, within a factor of three or so of the HI mass of the Milky Way itself. Within the framework of hierarchical clustering, this represents a significant reservoir of potential fuel for future generations of star formation. Our aim is to properly model the formation, evolution, and ultimate fate of the gas (and stars) associated with the Magellanic System.

The past decade has seen a wealth of new observational data for the System appear in the literature, in addition

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[2]By fitting two Fourier components to the observed MS and LAF, as a function of Magellanic longitude (as defined in Wannier & Wrixon 1972).
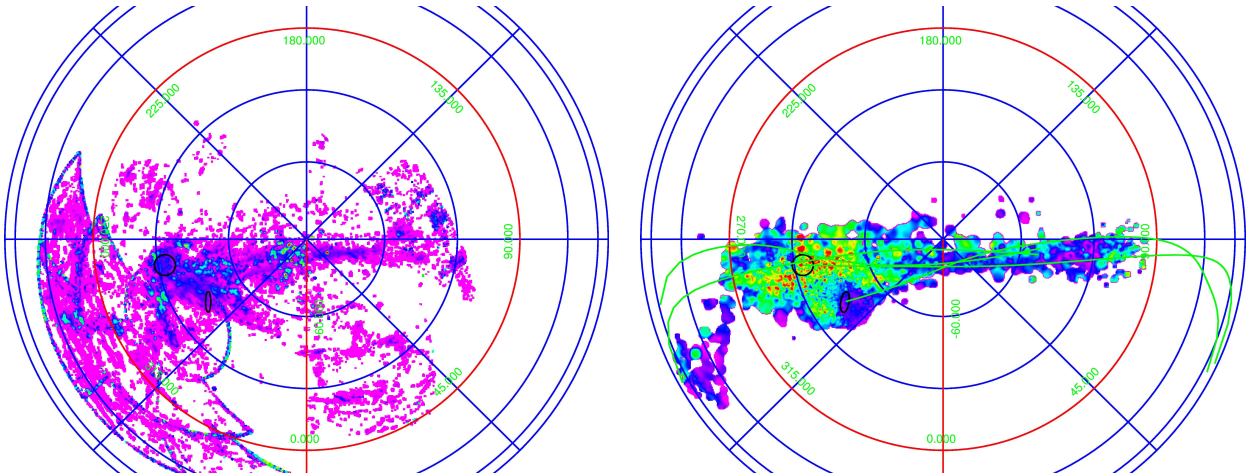
Figure 3: As in Figure 2, but now showing the second moment. The limiting column density employed in the simulation data is as in Figure 2. The velocity dispersion ranges from from $10\,\mathrm{km\,s^{-1}}$ (purple) to $90\,\mathrm{km\,s^{-1}}$ (red).

to the benefits of Moore's Law currently governing the increase in computational power. In combination, the two have allowed us to formulate improved models for the Magellanic Stream, a "Rosetta Stone" for the hierarchical clustering scenario of galaxy formation. We have presented here a simulation with ~ 40 times the resolution of previous simulations of the Stream, enabling us to examine more subtle features (kinematically and spatially) not previously considered in the models. Our gross results parallel those of Gardiner & Noguchi (1996) and Yoshizawa & Noguchi (2003), partly by construction, but the improved resolution and parameter space coverage here are unique. The gross features of both the trailing Stream and Leading Arm Feature are successfully recovered.

The bifurcation of the Stream observed both spatially (Morras 1983) and kinematically (Putman et al. 2003) had been previously suggested to be due to the "twisting" motion of the SMC's orbit about the LMC. Our simulations are consistent with this picture, with the thinnest part of the Stream corresponding to the location where the orbits cross at $(l, b) \sim (45°, 80°)$. The presence of this helix-like structure is an important test for any simulation that wishes to model the Magellanic System.

Despite the successes of the model, the comparisons we have made to date have uncovered several unresolved problems. First, there is still too little flux in the modelled MS, with the observed Stream (within the MSI–VI clumps) having 3–4 times (Putman et al. 2003) more mass than the modelled stream. Second, both the MS and LAF are too "long" in the models, with the LAF also being somewhat displaced from that observed. Third, the ratio of LAF-to-MS gas mass appears to be too high in the simulations, by a factor of at least 3–4. Fourth, while the LAF seems to have the correct deviation angle (cf. Gardiner 1999) relative to the great circle traced by the MS, its origin is somewhat offset from that inferred by the Putman et al. (1998) dataset. Finally, the velocity dispersion of the currently modelled inter-Cloud region remains too high, but we speculate that the inclusion of gas dissipation in our future studies may alleviate this discrepancy.

Paper II of this series will contain the full details of the parameter space coverage undertaken in our work, as well as a thorough examination of the spatial and kinematical bifurcations alluded to in Section 3. Paper III incorporates gas dynamics, star formation, radiative cooling, feedback, and chemical enrichment throughout the Magellanic System. We will re-examine the orbits of the Clouds coupled with improved potentials for the LMC and Galaxy, as additional data becomes available (particularly on the shape of the Galactic potential – e.g. Martinez-Delgado et al. 2003; Bellazzini 2003; Helmi 2003). A drag force term will also be introduced into the model, akin to that adopted by Gardiner (1999), in an attempt to better reproduce the geometry of the LAF.

The tools employed in analysing the simulations described here will shortly be released to the public – this software package affords any user the ability to project virtually any N-body simulation into various projections representative of the observer's "plane", including the production of FITS files suitable for further analysis by any other astronomical software package.

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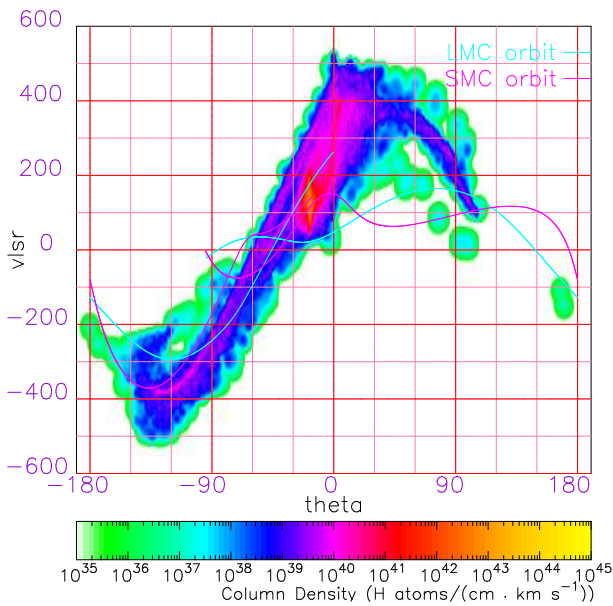
Figure 4: A "column density" plot of velocity relative to the local standard of rest (in $\mathrm{km\,s^{-1}}$) for our preferred N-body model plotted against Magellanic Longitude θ, where the "density" is in units of $\log_{10}(\mathrm{HI\ atoms}/(\mathrm{cm}\cdot\mathrm{km\,s^{-1}}))$. The current LMC position defines the origin, $\theta = 0$ in this system. The orbit of the two Clouds are overlaid. The MS (LAF) extends to negative (positive) θ in this projection.

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