HIGH-VELOCITY CLOUDS RELATED TO THE MAGELLANIC SYSTEM

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1. Introduction
The results of the interaction between the Milky Way and the Magellanic Clouds are revealed through several high velocity complexes which are connected to the Clouds. The exact mechanism of their formation is under some debate, but they remain the only group of high-velocity clouds (HVCs) for which we have an origin and roughly a distance. Given that, the Magellanic HVCs can be used as a calibrator for other HVCs, while also providing an opportunity to closely investigate the remnants of an interacting system. These HVCs may hold the key to the star formation history, kinematic structure, and present Hubble type of the Magellanic Clouds, and their proximity to the Milky Way allows us to estimate key Galactic parameters.

The HVCs related to the Magellanic System can be classified into three major complexes: the Magellanic Bridge, an HI connection between the Clouds; the Magellanic Stream, which trails the clouds and is one of the largest HI features in the sky outside of our Galaxy; and the Leading Arm, a more diffuse HI filament which leads the Clouds. In terms of HVCs, these features have been studied rather extensively. In this review, I will first describe the observational results for each complex and subsequently discuss their origin and relationship to the overall HVC population. All of the HI data presented are from the HI Parkes All-Sky Survey (HIPASS) (Barnes et al. 2001; Putman et al. 2001).

2. The Magellanic Bridge
2.1. HI STRUCTURE AND KINEMATICS
The Magellanic Bridge is a continuous filament of HI which stretches from the body of Small Magellanic Cloud (SMC) to an extended arm of the
Large Magellanic Cloud (LMC) (see Figure 1). The Bridge merges almost seamlessly with the SMC, but the boundary between the Bridge and SMC is usually defined at \((\ell, b) = (295^\circ, -41.5^\circ)\) and \(v_{\text{LSR}} = 125 \text{ km s}^{-1}\), where the loop which extends from the SMC at approximately \((\ell, b) = (297^\circ, 44^\circ)\) rejoins the tail of the SMC (also known as Shapley’s wing). This is also the boundary that was originally chosen based on stellar associations (Westerlund & Glaspey 1971); however, with the increasing numbers of stellar associations found in the Bridge, this boundary is also somewhat ambiguous (see §2.2). The Bridge emerges from the SMC’s tail at the high column densities of \(10^{21} \text{ cm}^{-2}\) and remains clumpy, but gradually decreases in column density to \(10^{20} \text{ cm}^{-2}\) at \((\ell, b) = (287^\circ, -35.5^\circ)\). At this latter position, the Bridge joins with what appears to be an extended spiral arm of the LMC (Kim et al. 1998; Putman et al. 1999). South of the Bridge in Galactic coordinates, especially on the SMC-side, the chaotic beginnings of the Magellanic Stream are present. In general, the Bridge is a more orderly feature than the Stream, possibly representing the Bridge’s shorter history or a more stable environment. The Bridge has an HI mass of approximately \(5.5 \times 10^7 \, M_\odot\), but this value is highly dependent on whether extensions into the SMC, LMC and Stream are included.

The Bridge has a regular velocity gradient along its main filament, gradually increasing in velocity and decreasing in spatial width as it approaches the LMC. The final dense pockets of emission do not disappear until 350 km s\(^{-1}\) at \((\ell, b) = (283^\circ, -42^\circ)\). McGee & Newton (1986) report on line profiles which contain up to 5 components throughout the Bridge (with a velocity resolution of 4.1 km s\(^{-1}\)). They report systematic profile variations in the central Bridge region, but sporadic differences in the regions of the Bridge which extend into the Magellanic Stream, possibly indicating a more turbulent environment. The presentation of high resolution data has begun with the Australia Telescope Compact Array (ATCA) observations of Stanimirovic et al. (1997). Detailed kinematic information will also soon be available with Parkes multibeam narrow-band observations. HI absorption studies find that the cool atomic phase gas exists in the Bridge, indicating that the pressure in this region is surprisingly high and that stars may have formed from the Bridge material directly, rather than being drawn out from the SMC (Kobulnicky & Dickey 1999). Sensitive CO studies of the Bridge would be an interesting future pursuit.
2.2. STARS!

The Magellanic Bridge is the only HVC which has stars associated with it, and in this respect it may be inaccurate to call it an HVC\(^1\). The stars are very scarce and the gas to star ratio remains extremely high, so it is conceivable that future stellar searches may find stars associated with other HVCs. Early stellar searches in the SMC tail included the discovery of a number of B-type giants and dwarfs (e.g. Sanduleak 1969). Searches for blue stars then continued throughout the Bridge (e.g. Irwin et al. 1990), and were identified from \((\ell, b) = (296^\circ, -41^\circ)\) to at least \((\ell, b) = (287^\circ, -36^\circ)\). Demers & Battinelli (1998) find that the stars in the tail of the SMC (also called the wing) have little distance variation, indicating that it does not have a substantial depth. On the other hand, at the tip of the SMC tail/wing, there are two Bridge associations within 17\(^\prime\) (300 pc at 55 kpc) which are \(\approx 5\) kpc apart along the line of sight. In general, the stars in the Bridge show a distance gradient expected for a feature linking the LMC (at 50 kpc) and the SMC (at 60 kpc). The stars do not form a continuous link as the HI does, but are found in loose associations scattered throughout the SMC tail and decreasing in number towards the central region of the Bridge.

Chemical abundances for the stars in the Bridge were thought to be consistent with an SMC origin (Rolleston et al. 1993; Hambly et al. 1994); however, recent determinations by Rolleston & McKenna (1999) suggest they are deficient by \(\sim 0.6\) dex compared to similar B-type stars in the SMC. The ages of the Bridge stars range from 10 - 25 Myr, much younger than expected if they were torn from the SMC 200 Myr ago as most tidal models predict. This indicates that the Bridge is actually a star forming region, but searches for ongoing star formation have not yet been successful. By considering all of the stars in the Bridge, Grondin et al. (1992) find that the Bridge’s IMF is shallower than that of the Milky Way or the Clouds. This favors the formation of massive stars and may indicate that cloud-cloud collisions are the dominant star formation trigger (Scoville et al. 1986; Christodoulou et al. 1997). There has been no detection of a horizontal branch star population in the Bridge, indicating that the halos of the two clouds do not meet (Grondin et al. 1992). Kunkel et al. (1997) have found an abundance of intermediate-age (several Gyr) carbon stars scattered throughout the Bridge region, with possible extensions into the beginning of the Stream. Diffuse \(H_\alpha\) emission also appears to be prevalent in the Bridge region closest to the SMC (Johnson et al. 1982; Marcelin et al. 1985), as would be expected with the presence of hot young stars. However,

\(^1\)Also, although the Bridge is an HVC in the Galactic reference frame, it is not technically an HVC in the Magellanic reference frame, unlike the Stream and Leading Arm.
there are also several non-detections in the central region of the Magellanic Bridge (Veilleux et al. 2001).

3. The Magellanic Stream

3.1. HI STRUCTURE AND KINEMATICS

The Magellanic Stream, discovered 25 yrs ago (Wannier & Wrixon 1972; Mathewson et al. 1974), is a complex arc of neutral hydrogen which starts from the Magellanic Clouds and trails for over 100°. The Stream contains $\approx 2 \times 10^8 \ M_\odot$ of neutral hydrogen (at an average distance of 55 kpc) and has a velocity gradient of over 700 km s$^{-1}$ from head to tip, 390 km s$^{-1}$ greater than that due to Galactic rotation alone. Recent HIPASS observations of the Magellanic Stream provide almost a two-fold improvement in spatial resolution over previous survey data, and depict increasing complexity in the Stream’s structure (see Figure 2). In particular the maps reveal multiple filaments at the Stream’s head, a twisting ladder structure along the Stream’s length, and small dense clouds which extend 20° from the Stream’s main filament. A broad overview of the HI properties of the Magellanic Stream is presented below. See Putman et al. (2001) for a full description.

The beginning of the Stream is rather chaotic, as it spews out from several locations north of the SMC and Bridge at $v_{LSR} = 90 - 240$ km s$^{-1}$ (see Figures 2 & 3). There is a slight discontinuity in velocity as the HI enters the Stream from the Bridge. Figure 3 shows how the Stream becomes more negative in velocity as it extends away from the Clouds, and how there are multiple initial filaments which come to a clumpy end at $l \approx -60°$ and
The main filament of the Stream continues towards the South Galactic Pole, where it reaches 0 km s\(^{-1}\).\(^2\) It then proceeds north to \((\ell, b) \approx (90^\circ, -40^\circ)\), \(v_{LSR} \approx -450\) km s\(^{-1}\), and column densities of only a few \(\times 10^{18}\) cm\(^{-2}\) (versus a few \(\times 10^{19}\) cm\(^{-2}\) at the Stream’s head). Relative to the Galactic Center, the radial velocity of the Stream gradually becomes more negative from the head (\(\sim 50\) km s\(^{-1}\)) to the tip (\(\sim -200\) km s\(^{-1}\)).

The main filament of the Stream is not as complex as the head, but it is also a complicated structure which appears to be made up of two distinct components. The splitting of the Stream into two filaments is evident throughout, but is most obvious beyond the multiple filaments at the Stream’s head. The two filaments run parallel for the length of the Stream and begin to merge towards the tail (much as if one were looking down a long straight road). There are also several horse-shoe shaped structures which join the two filaments at several positions. This helical structure may represent the orbit of the Magellanic Clouds about each other, with the two filaments representing material from the Bridge and SMC.

Small compact clouds are found throughout Figs. 2 and 3, surrounding the Stream’s main filament in both position and velocity. Many of the small clouds, both in and about the Stream, show head-tail structures (i.e. a dense core with a diffuse extension of approximately twice the diameter of the core (tadpoles)) and hollow bow-shock signatures (also noted by Mathewson et al. (1979)). This is especially true at the Stream’s head, with the tails generally pointing away from the Clouds. This could be depicting the Stream’s interaction with the Galaxy’s halo (Pietz et al. 1996), or it could simply represent the way the gas has been stripped from the Clouds. Some of the small clouds of positive velocity HI about the South Galactic Pole in Figs. 2 and 3 are actually galaxies of the Sculptor Group. It has been argued that the abundance of small clouds between these galaxies are not associated with the Stream, but are members of the Sculptor Group (Mathewson et al. 1975; Haynes & Roberts 1979). Considering the Stream’s clumpy nature throughout this area, it would be difficult to make a confident claim of a cloud’s association with the Sculptor Group or other dwarf galaxies (e.g. Carignan et al. 1998). However, it is curious how the clumps remain in the southern region of the Sculptor Group from velocities of \(-240\) to \(+240\) km s\(^{-1}\), and do not follow the Stream as closely in velocity as other clumps along its length. Could these clumps be the remnants of an ejection from the Galactic Centre, or possibly intergalactic HI clouds along the Coma-Sculptor-Local Group supergalactic filament (Tully & Fisher 1987; Jerjen, Freeman & Binggeli 1998)? H\(\alpha\) observations, metal-

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\(^2\)When the Stream’s velocity coincides with that of the Milky Way (\(\approx 0\) km s\(^{-1}\)), detailed information is lost in the Galactic emission and in the data reduction, which has problems when the emission completely fills the scan (see Putman et al. 2001).
licity and distance determinations should help distinguish between these possibilities.

The small-scale HI spatial structure of the Stream has not yet been investigated, but ATCA observations are being actively pursued. HIPASS has a velocity resolution of only 26 km s$^{-1}$ with Hanning smoothing, but higher velocity resolution observations (1 km s$^{-1}$) are in progress with the Parkes narrow-band facility (Brüens et al. 2000). Higher velocity resolution observations have also been completed in the past by Haynes (1979), who noted the complex, multi-profile nature of the Stream in the region near the South Galactic Pole, by Cohen (1982), who found the Stream to also have a strong transverse velocity gradient, and by Morras (1983; 1985), who noted the bifurcation of the Stream. The northern tip of the Stream was studied by Wayte (1989). He notes the continued bifurcation of the Stream and a complex velocity structure which may indicate that the tail of the Stream is breaking up into many individual clouds at different velocities. The line profiles of the clouds at the tip show a core/envelope structure reminiscent of some non-Magellanic HVCs (Wakker & van Woerden 1997). If these non-Magellanic HVCs are generally less distant than the majority of the Stream (see van Woerden et al. (1999) for some distances), this change in profile may indicate that the tip of the Stream is getting closer to the Galaxy. Tidal or ram pressure forces may be responsible for stripping off the clouds’ outer layers.

3.2. OPTICAL OBSERVATIONS

A new method of studying the Magellanic Stream has come with the discovery that the Stream can be detected in Hα emission (e.g. Weiner & Williams 1996). The detections vary tremendously in surface brightness (0.04 − 0.4 Rayleighs), and are usually in regions of high HI column density (> 10$^{19}$ cm$^{-2}$). There does not appear to be a correlation between the Hα emission measure and HI column density, however the current lack of high-resolution HI data makes this difficult to test. It is possible that Hα emission will be detected beyond the HI contours of the Stream as this has been observed for other complexes (Tufte et al. 1998) and may indicate the presence of an ionized sheath. Other lines have also now been detected, including [NII], [SII], and a non-detection of [OIII] (Bland-Hawthorn et al. 1999). It is not clear how the emission line results should be interpreted. Earlier suggestions that ram-pressure is responsible for the Hα emission seem less secure in light of the line ratios and the higher resolution HI maps which show that the strong detections do not always correlate with the leading edges of HI condensations (Putman & Gibson 1999). Bland-Hawthorn & Maloney (1999) conclude that shock ionization requires unrealistically high halo den-
sities at $d \approx 50 \text{kpc}$ and suggest ionizing photons from the Galaxy are the main cause for the emission. On the other hand, the Hα emission measures in the Stream are generally $\sim 2$ times higher than HVCs which have upper distance limits of $\sim 10 \text{kpc}$ (Tuft et al. 1998). It remains to be seen if the contribution of ionizing photons from the LMC, or the effects of shadowing and nearby spiral arms, can account for this difference. If the escape of ionizing photons from the Galaxy and the Magellanic Clouds can be accurately determined, the emission measures can be used to determine the distance to various points along the Stream (Bland-Hawthorn & Maloney 1999). A complete map of the Stream’s ionized gas would be a very interesting complement to the HI data presented here.

There have been numerous searches for stars which are associated with the Stream, as they might be expected if the Stream were formed via a gravitational interaction. All of the searches for stars within the HI contours of the Stream have been negative, with most of the searches being based on the assumption that the Stream is young and should be populated by A-F stars. Brück & Hawkins (1983) claimed no stellar Stream counterpart based on star counts down to magnitude 20.5 in B in the section of the Stream closest to the Clouds. Recillas-Cruz (1982) and Tanaka & Hamajima (1982) did a similar search of the tip of the Stream and found no excess of A-type stars. Guhathakurta & Reitzel (1998) recently used the Keck telescope to complete a deep stellar search in a $5' \times 7'$ region at $(\ell, b) \approx 60^\circ, -68^\circ$ (within MS IV) and claimed an upper limit on the Stream’s star-to-gas ratio of 0.1 (5% that of the LMC). It is possible that these results are still not definitive, given the young population of stars searched for in the early searches and the limited area covered by the Keck search; but a more likely explanation is that the HI Stream does not contain stars. There is still the possibility of an offset stellar stream (as seen in many other interacting systems; Hibbard & Yun 1999) or a stellar stream that is significantly less extended than the Stream due to the initial HI distribution of the Clouds being more extended (Yoshizawa 1998). A possible offset stellar tidal counterpart has been found by Majewski et al. (1999), who searched for giant stars about the Clouds and found interesting populations in a region north of the LMC.

3.3. METALLICITY & DISTANCE DETERMINATIONS

Metallicity and abundance determinations for the Magellanic Stream are consistent with a Magellanic Clouds origin. The Stream’s primary metallicity determination uses Fairall 9 as a probe and has been investigated by Gibson et al. (2000), Lu et al. (1994) and Songaila (1981), all of whom obtained consistent results. Recently, Gibson et al. used GHRS data and new HI observations to obtain a $S/\text{H}$ of 0.21 solar, extremely close to the
metallicity of the SMC. They also detected Mg II near the tip of the Stream which indicates that the Stream gas extends at least 15° from the HI shown in Figure 2. Lu et al. (1994) found Si/H \( \gtrsim 0.2 \) solar and S/H \( \lesssim 0.3 \) solar along the Fairall 9 sightline. They find the subsequent Si/S ratio to be greater than or equal to 0.6 the solar ratio, which indicates that dust depletion is not prevalent in the Stream (Si is easily depleted onto dust grains)\(^3\). This is consistent with the lack of extinction and infrared emission from the Stream (Fong et al. 1987). The extinction result is based primarily on galaxy counts (see also Mathewson et al. 1979) and, though inconclusive, the results suggest at most a very small level of extinction.

Sembach et al. (2000) have detected O VI associated with the Magellanic Stream, indicating that hot gas must be present. It is very difficult to produce O VI with photoionization and they suggest movement through a hot Galactic halo medium may be responsible. Lu et al. also have a possible detection of C IV absorption at the position of Fairall 9. This suggests, along with the Hα detections discussed above, that the metallicity estimates are subject to an ionization correction. Another uncertainty in the metallicity determinations is the HI column density. The above determinations are based on fairly low spatial resolution HI data (15.'5 or 34.'), and HVCs have been known to vary by a factor of five in column density on scales of only 1' (WvW97). The metallicity determinations remain clear in their indication of the Stream being made up of non-primordial gas and are consistent with the Stream originating from the Magellanic Clouds.

Distance estimates for the Stream are based largely on theoretical interaction models (see section 5.2 for a full description). Watanabe (1981) made the assumption that the shape of the Stream clouds (i.e. elongation) is determined by the strength of the Galactic tidal disruption force and estimates the Stream lies between 36 - 50 kpc. Hα observations also have the potential to provide distance information (see section 3.2).

4. The Leading Arm

4.1. HI STRUCTURE AND KINEMATICS

The Leading Arm is made up of a string of clouds on the leading side of the Magellanic Clouds which have only recently been clarified as being connected to each other and the Magellanic System through HIPASS observations (Putman et al. 1998). The beginning of the Leading Arm protrudes from the Magellanic Bridge and LMC along several clumpy filaments (see Figure 4). The multiple filaments give the appearance that the Leading Arm is associated with both of the Clouds. The Leading Arm is relatively

\(^3\)They assumed the intrinsic Si/S ratio was the same as the Sun's.
Figure 2. An integrated intensity map of the Magellanic Stream \( (v_{LSR} = -400 \text{ to } +400 \text{ km s}^{-1}) \), which includes the region shown in Figure 1, part of the Leading Arm shown in Figure 4 and the full extent of the Magellanic Stream. The Stream passes through the velocity of Galactic emission at \( (\ell, b) \approx 315^\circ, -80^\circ \), and the emission between +/- 20 km s\(^{-1}\) in this region has been excluded (see Putman et al. (2000) for the channel maps). The intensity values are on a logarithmic scale, with everything above \( 6 \times 10^{20} \text{ cm}^{-2} \) black and the faintest levels at approximately \( 2 \times 10^{18} \text{ cm}^{-2} \).

Figure 3. Velocity distribution of the Magellanic Stream ranging from -450 km s\(^{-1}\) (light grey) to 380 km s\(^{-1}\) (dark).

thin (~ 1/4 the width of the trailing Stream), but roughly continuous until the Galactic Plane, where it abruptly shifts in Galactic Longitude from 307° to 290°. The Leading Arm is very clumpy, with diffuse filaments connecting the clumps. These filaments were missed in previous surveys due to sparse spatial sampling (Mathewson & Ford 1984; Morras 1982), and it was thought that the clumps were isolated high-velocity clouds. There are also dense clouds about the main filament of the Leading Arm (primarily on the lower longitude side), similar to the small clouds which surround the Stream.
The Leading Arm’s velocity distribution is somewhat confusing, and this may be due to the projection of the feature. It emanates from the Clouds at \( v_{\text{lsr}} \approx 180 \text{ km s}^{-1} \) and its velocity steadily increases until it reaches 356 km s\(^{-1}\) at \((\ell, b) = (302^\circ, -17^\circ)\). From this position it decreases in velocity to \( \approx 200 \text{ km s}^{-1}\) as it moves towards the Galactic Plane (see Putman et al. (1998) for channel maps). When the Arm shifts in position by 15\(^\circ\) in longitude at the Plane, it also shifts in velocity, starting at \( \approx 320 \text{ km s}^{-1}\) at latitude \( +8^\circ\) and extending to 150 km s\(^{-1}\) at latitude \( +30^\circ\).

Relative to the Galactic Center, the Leading Arm extends in velocity from \( v_{\text{gsr}} = -29 \) to 178 km s\(^{-1}\). The metallicity determination discussed below suggests that the feature at positive latitudes is a continuation of Magellanic material; however, it is difficult to reproduce the Leading Arm’s initial \( \sim 60^\circ\) deflection angle from the great circle defined by the Stream, while also retaining the positive latitude clouds as tidal debris (Gardiner 1999). Verschuur (1975) suggested that the high positive velocity features which make up the Leading Arm are actually distant spiral features which form an intergalactic bridge between the Clouds and the Milky Way. This seems unlikely since the HIPASS observations show the Leading Arm’s velocity to be distinct from the velocity of the Galactic HI in this direction (\( \sim 120 \text{ km s}^{-1}\); Burton 1988).

It appears as if the data shown in Figure 4 represent the full extent of the Leading Arm feature, as maps further north of \( b = 30^\circ\) do not show any obvious continuation of emission. It is curious that the filament abruptly ends at a relatively high column density; however, there could be more tenuous or fully ionized gas further along. The Leading Arm is not as ordered or massive as the Stream, possibly due to its leading position or age. The mass of the Leading Arm is approximately \( 2 \times 10^7 M_\odot\), an order of magnitude less massive than the Stream, assuming they are both at the distance of the Magellanic Clouds.

High resolution ATCA observations are in progress for many positions along the Leading Arm. Wakker et al. (1999) have already analyzed ATCA data for a position on the positive latitude side of the Plane and found velocity widths of 5-10 km s\(^{-1}\) and column density contrasts of a factor of 3 on arc minute scales. They also note the two-component velocity structure of this cloud, similar to other non-Magellanic HVCs, and derive a pressure of \( 18000 R^{-1}D^{-1} \text{ K cm}^{-3}\) (where \( R \) is the resolution in arc minutes and \( D \) is the distance to the cloud). Other observations of the Leading Arm include the work of Bajaja et al. (1989), Morras & Bajaja (1983) and Morras (1982); all of which are at a lower spatial resolution but higher velocity resolution than the data shown here.
Figure 4. A HIPASS peak intensity map which shows the full extent of the Leading Arm, as well as the Magellanic Clouds, the Bridge and the beginning of the Stream (as labelled). The position of the background galaxy, NGC 3783, is also noted (see §4.2). To avoid the emission from the Galactic Plane (which extends out to 120 km s$^{-1}$ in this direction), only velocities between 130 and 400 km s$^{-1}$ were used. (Thus the strange appearance of the SMC which begins at $\approx 80$ km s$^{-1}$.) Many features are intentionally saturated to bring out the low level emission. It is a linear intensity scale ranging from approximately 0.1 to 2 K (black).

4.2. METALLICITY DETERMINATION

Apart from the fact that the Leading Arm emanates from the Magellanic System, the strongest evidence that it is made of Magellanic material comes from the Lu et al. (1998) metallicity determination for HVC 287.5+22.5+240. Derived from GHRS spectra of the background galaxy NGC 3783 (see Figure 4 for position), a S/H of $\approx 0.25\odot$ was found, consistent with the metallicity of the Magellanic Clouds. They also found Fe/H = 0.033$\odot$, with the subsolar Fe/S ratio indicating dust may be present. This filament lies spatially (and kinematically) in a region where tidal models predict gaseous tidal debris to reside, and the metallicity determination suggests that despite the offset positioning of this filament, it is indeed part of the Magellanic Leading Arm. The position of the Seyfert galaxy ESO265-G23 is another possible background source which can be used to determine the Leading Arm’s metallicity; however it appears to be just off the HI contours in the HIPASS map (see Putman & Gibson 1999). This position may either have a very low column density or represent the ionized medium of the Arm.
5. Theoretical Origin Models

5.1. BRIDGE

It is generally agreed that the LMC and SMC are bound and that the Bridge was formed via a tidal encounter between the two Clouds (e.g. Gardiner & Noguchi 1996 (hereafter GN96); Moore & Davis 1994). The finding of stars in the Bridge region supports the tidal model, though the young stellar population may have been born in the Bridge (see §2.2). Few models can simultaneously reproduce both the Bridge and the Stream accurately. GN96 are relatively successful by refining the models of Lin & Lynden Bell (1982) and Murai & Fujimoto (1980). They find that the Magellanic Bridge was most likely pulled from the SMC 0.2 Gyr ago during a close encounter between the two Clouds (at 7 kpc separation). The GN96 model, in which the SMC is composed of both a disk and a halo, nicely explains the different bridge and tail HI components and the velocity distribution of the young (early-type) and old (carbon star) stellar populations.

In contrast to GN96, Kunkel et al. (1994) attempt to reproduce the properties of the SMC and Bridge by leaving the LMC and SMC unbound and ignoring the effect of the Galaxy (i.e. they do not reproduce the Magellanic Stream). They suggest that the carbon stars are part of the tidal bridge, separate from the HI and embedded in some type of ionized medium. Heller & Rohlfs (1994) agree with GN96 that the two Clouds are bound, but argue that they have remained in a stable binary system for the last $10^{10}$ years and that tidal forces from the Galaxy were not strong enough to pull out the Magellanic Stream. They suggest the Bridge or intercloud region was formed 0.5 Gyr ago when there was a close encounter between the LMC and SMC, and this also marks the beginning of the formation of the Magellanic Stream. The chaotic nature of the HI features north of the Bridge (at the head of the Stream) indicates that the Bridge and Stream were not formed in conjunction or that one is pulling material from the other. In the best model of Li (1999), the Clouds have only been gravitationally affecting each other for the past 2 Gyr, as he also finds that when the Clouds are a lifelong binary, the interaction between the two Clouds does not allow the Magellanic Stream to form.

All of the models assume that the Bridge is made up of material from the SMC, with the LMC ripping material from its less massive companion. The HIPASS data show an extension of the LMC which suggests that the LMC also contributes to the Bridge’s mass (see Figure 1). This feature may be reproduced when the potential of the LMC is modelled more realistically.
5.2. STREAM AND LEADING ARM

The Stream is the result of an interaction between the Galaxy and the Clouds; its link to the Magellanic System and spatial and kinematic continuity are the primary clues for this conclusion. The exact form of the interaction is not yet fully understood, but its striking appearance has attracted an abundance of theoretical attention. Many of the early models were created before the tangential velocity of the Clouds was known\(^4\), or they were simply unable to reproduce the observed data. This section summarizes the more recent developments in our theoretical understanding of the Magellanic HVC’s formation and evolution. The models have generally been variations on two themes: gravitational tides from the Milky Way pulling the Stream from the Clouds, and ram-pressure stripping of the Stream gas as the Clouds interact with some form of Galactic gas. The finding of the tidal Leading Arm feature (Putman et al. 1998) indicates that tidal forces are the dominant mechanism responsible for the formation of the Stream, but it is likely that other mechanisms also play a role in the Stream’s evolution.

5.2.1. Tidal Models

Tidal models have gradually become more complex to match the increasing detail revealed in the observations. One of the most recent and advanced N-body tidal models is that of GN96 which simulates the SMC as a collection of self-gravitating particles and the LMC as a point mass. GN96 is an adaptation of early tidal models (e.g. Murai & Fujimoto 1980; Lin & Lynden-Bell 1982), where the Clouds are in a polar orbit leading the Stream and are presently close to perigalacticon (see also Gardiner et al. 1994; Lin et al. 1995). To achieve the high negative velocities at the Stream’s tip, these models invoked a Galaxy with a massive halo (\(\sim 10^{12} M_\odot\)) which extends out to \(\sim 200\) kpc, consistent with recent results (e.g. Kochanek 1996). GN96 (and other recent tidal models) predict that the Stream was pulled from the SMC 1.5-2 Gyr ago, when a tidal encounter between the two Clouds (at 14 kpc separation) coincided with their previous perigalactic passage. The Stream was drawn into its present position as the Clouds moved from apogalacticon (\(\sim 0.9\) Gyr ago) to their present position, just past perigalacticon. GN96 find that the Stream consists of two separate streams, a main filament along the observed position of the MS and a less densely populated secondary filament (this secondary stream is also a prediction of Tanaka (1981)). This splitting of the Stream is seen in the HIPASS data shown in Figs. 2 and 3; however the separation of the two components is significantly

\(^4\)Proper motion measurements have now shown the Clouds are leading the Stream with a total galactocentric transverse velocity of 215±48 km s\(^{-1}\) (Jones et al. 1994).
larger in the model and the cause of the separation remains unclear. The
dual filaments may represent multiple close encounters between the two
Clouds, resulting in two major gas concentrations which were subsequently
drawn into the Stream. The fact that the filaments are at approximately
the same velocity argues for a similar origin. GN96 reproduce the velocity
distribution of the Stream fairly accurately (see Figure 5), but the variation
in column density along the Stream requires further work.

An advancement on GN96 has been developed by Yoshizawa (1998), who
incorporates gas dynamics (via a sticky-particle method) and star formation
into the numerical code (see Figure 6). The simulations find the beginning of
the Stream to consist of multiple filaments, much as depicted in Figs. 2 and
3. The simulated Stream then becomes very narrow due to gas dissipation
from cloud-cloud collisions, and the bifurcation found in previous models
is lost. An important result of the Yoshizawa models is the demonstration
that stars should not be drawn out along the Stream, but remain restricted
to a ~ 10–15 degree region surrounding the Clouds (appearing clump-like,
or perhaps in several dispersed streams). The lack of stars in the Stream
has been a major argument against the Stream having a tidal origin (e.g.
Moore & Davis 1994). Yoshizawa (1998) preferentially disrupts the gas by
having the initial gas distribution of the Clouds more extended than the
stellar component (a common occurrence - e.g. Broeils & van Woerden 1994;
Yun et al. 1994). As mentioned in §3.2, recent observational work indicates
that there may be an excess of giants at distances expected for tidal debris
from the Magellanic Clouds and distributed in patterns suggestive of the
small stellar streams predicted by Yoshizawa’s models (Majewski et al. 1999).

A natural result of the tidal model is a leading counterpart to the Stream, the Leading Arm. The original tidal models presumed that the interaction could be represented as a two-body problem between the Galaxy and the LMC, which resulted in symmetric leading and trailing streams of material. The more recent models of GN96 and Yoshizawa (1998) treat the interaction as a more realistic 3-body problem (Galaxy, LMC and SMC) and the perturbative nature of the LMC+SMC interaction leads to HI features which are clearly non-symmetric. The strong gravitational perturbation of the LMC pulls most of the material in the leading section back towards the Clouds, leaving a much weakened leading feature compared to the Stream. GN96 predicts a leading arm which, between the Magellanic Clouds and the Galactic Plane, has a mass $\sim 1/3$ that of the entire trailing Stream, a relatively flat velocity gradient, and a deviation from the Great Circle defined by the trailing Stream of $\sim 30^\circ$. The newly-discovered Leading Arm has a mass $\sim 1/10$ that of the Stream (assuming the Arm and the Stream are at the same distance) and a deviation angle closer to $\sim 60^\circ$. Though the Leading Arm does not match the predictions of the tidal models exactly, there are several additions to the current models which could change this situation. The differences in the mass and projected orientation could be due to the shape of the LMC’s potential in tidal models (presently a rigid spheroid), a triaxial distribution of Galactic halo mass (Lin et al. 1995), and/or a perturbation by another satellite of the Milky Way (e.g. the Sgr dwarf). The addition of a small amount of drag to the tidal model (Gardiner 1999) is able to reproduce the angle of deflection from the Stream’s
Great Circle and the velocity distribution of the Leading Arm (see Figure 5), but it also introduces an extended anomalous component which wraps around to join the Stream and is not observed. The hydrodynamical models of Li (1999) indicate that a tidal interaction is not a tidy process and that multiple clumps of material would be drawn from the Clouds, along with the continuous streams. This could explain the rest of the debris seen in Figs. 2 and 3. They also find that the LMC has a substantial effect on the distribution of the leading gas, and that the stellar component of the Clouds remains largely confined.

5.2.2. Ram-Pressure Models
As noted above, combining aspects of the ram-pressure models to the tidal ones may be the key to reproducing all of the observational features of the Stream and Arm. Mathewson, Schwarz & Murray (1977) were the first to suggest that the Stream was formed via thermal instabilities in the wake of the Clouds during their passage through the Galaxy’s hot halo. These instabilities form cold clouds which lose their buoyancy and sink towards the Galactic center. Variations on this model were subsequently developed and simulated. Liu (1992) proposed cold gas from the Clouds was dragged into their wake, and gravitational forces from the Milky Way accelerated the gas down the vortex. Meurer et al. (1985) simulated the tearing of cloudlets from the Bridge as the Magellanic Clouds passed through the hot gaseous halo of our Galaxy and they stretched out the Stream with tidal and drag forces. Meurer et al. are able to produce a reasonable model of the Stream (magnitude of the spatial and velocity extent within a factor of 2) with a broad range of parameters, but their best model puts the Stream clouds at an average distance of 38 kpc. Sofue (1994) also produces the Stream by passing the Clouds through Galactic halo and disk gases and elongates it with the Galaxy’s potential. A leading stream is formed in the Sofue model when the Stream begins to rotate around the Galaxy at a higher angular velocity than the LMC and it wraps all the way around; but this is at the expense of the predicted extent and velocity profile of the Stream. In all of Sofue’s simulations the Stream accretes onto the Galaxy within a few Gyr.

Moore & Davis (1994) have a similar, but more detailed model compared to the Meurer et al. and Sofue models. They pass the Clouds through an extended ionized Galactic disk which strips off 20% of the Clouds’ least bound HI into the Stream. The main interaction is thought to have taken place 0.5 Gyr ago at a distance of 65 kpc and they propose that the material responsible for the stripping is an extension of the Galactic HI disk which has column densities $< 10^{19} \, \text{cm}^{-2}$ and is ionized by the extragalactic background radiation. Moore & Davis are able to explain the Stream’s column density gradient and the high negative velocities at the Stream’s tip,
as the gas with the lowest column density loses the most orbital angular momentum and falls to a distance of 20 kpc from the Galaxy with a velocity of $-380 \text{ km s}^{-1}$ ($v_{\text{lsr}}$). Without the addition of a braking effect from an extended dilute halo of ionized gas, the stripped material actually begins to lead the Magellanic Clouds. This is because the gas clouds lose energy when initially stripped from the Clouds, which causes the apogalactic distance of their orbit to decrease. As their orbital period decreases they overtake the Clouds as projected on the sky.

A slightly different approach to the ram pressure model was taken by Heller & Rohlfs (1994) and Mathewson et al. (1987). Heller & Rohlfs mark the beginning of the formation of the Stream at 0.5 Gyr ago when the Magellanic Clouds had a close encounter with each other and much of the HI was disrupted from the core of the LMC and SMC into the Bridge region or some other extended configuration. The Stream was subsequently swept out by a strong wind generated by the orbital motion of the Clouds through the Galactic halo. Mathewson et al. (1987) propose a discrete ram-pressure model in which the Stream’s formation is due to the Clouds’ interaction with high-velocity clouds presently found on the leading side of the Clouds. Detailed results are not available, but the fact that these leading clouds are shown here as the continuous Leading Arm casts doubt on this model.

Besides the further development and combination of the models currently in existence, there are several observational tests which can be carried out to distinguish between the origin scenarios. As previously discussed, continuing the search for a stellar counterpart to the HI Stream and Leading Arm is of importance. Abundance determinations will also be a crucial tool for confirming the origin of some of the more remote clouds which are proposed members of the Magellanic System. Searching for soft x-ray emission along the Stream and investigating the optical line ratios may provide insight into the mechanisms responsible for putting the Stream in its current state. Understanding the ionized component of the Stream is an important future goal. If it is determined that photoionization is the dominant ionizing mechanism, mapping the Stream in Hα emission has the potential to reveal the three-dimensional distribution of the Stream (Bland-Hawthorn & Maloney 1999; Bland-Hawthorn et al. 1999; see also §3.2). Because ram pressure models put the tip of the Stream at $\sim 20 - 50 \text{ kpc}$ (e.g. Moore & Davis 1994; Heller & Rohlfs 1994), and tidal models put the tip at $\sim 70 - 100 \text{ kpc}$ (e.g. Gardiner 1999), Hα observations of MS VI, in particular, might provide an elegant test for the competing models. It will be difficult to reproduce the detail revealed in the HIPASS Stream observations, but the gross properties should be matched before any interaction model is adopted. These properties include: a chaotic beginning consisting
of multiple filaments, dual streams, narrowing of the main filament towards the tip and a broadening at the very end, compact clouds which surround the main filament, and a continuous velocity structure.

6. Relationships to other HVCs?

It has been suggested that the complexes described here are what is left of a polar ring of Magellanic debris (e.g. Mathewson et al. 1987). In fact, it is still possible that all HVCs originated as part of the Magellanic Cloud/Milky Way interaction (Mathewson et al. 1974), but the evidence points against it considering the survival timescales, HVC abundance and distance measurements (Wakker & van Woerden 1997), and the predicted position and velocity distribution of the Magellanic remnants (Wakker & Bregman 1990). A more likely possibility is that other high velocity complexes are the remnants of previous non-Magellanic interactions and/or torn apart Galactic satellites. When developing models to explain the global HVC population, it is important that the HVCs which are known to be part of the Magellanic System are excluded. For instance the identification of the Leading Arm eliminates many of the extreme positive velocity clouds, and the dense clumps about the Magellanic Stream are also likely to be interaction related and should be excluded from analyses which attempt to match such clouds to a Local Group origin (e.g. Braun & Burton 1999). When the Magellanic HVCs are no longer included in the overall population of HVCs, the sky covering fraction goes down by at least 5% (Wakker & van Woerden 1997). It also leads to a serious deficiency of HVCs in the southern sky and at positive velocities. If most of the positive velocity HVCs can be classified as Magellanic debris or Galactic extensions we may be able to reconsider various origin scenarios which are unable to produce high positive velocity gas.

In the quest to understand the global origin of HVCs, one of the most important roles of the Magellanic complexes is to provide a basis for observational comparisons. The major HVC questions concern their origin and environment, and are highly dependent on the clouds’ distances. Since the Magellanic HVCs are known to have originated from the Clouds and lie at distances in the tens of kiloparsecs, they can be used as a calibrator to investigate the HVC phenomena. To begin, the overall spatial structure of the Magellanic complexes and other HVCs has similarities and differences on both large and small scales. The long filamentary structure of the Stream and Arm appears to be common throughout HVCs and may indicate that more clouds either have a tidal origin or are currently being tidally stretched. If assumptions are made about the density fall-off of the halo, the length of the head-tail and bow shock structures may allow an estimate
of the clouds’ distances (Mebold, pers. comm.). The small scale structure of
HVCs supplies information about the physical conditions within the clouds,
and an indication of the amount of turbulence or ordered structure. The
future high resolution HI observations of the Magellanic complexes should
be compared to similar HVC observations (e.g. Wakker & Schwarz 1991).
The Magellanic Bridge is useful as it can be used to examine the effects
of star formation on HI structure and to explore what has triggered this
process. The kinematic structure of the HI can also provide clues to the for-
mation and evolution of HVCs. While many of the Magellanic HVCs show
a single component line profile, other HVCs show two-component profiles,
indicative of a core-envelope structure or a two-phase medium. The Mag-
ellanic Stream and Bridge also show a systematic variation in velocity and
column density which is uncommon in high velocity complexes. There are
useful comparisons to made at all wavelengths, including optical emission
and absorption line observations to determine abundances and ionization
conditions. These types of comparisons will clarify some of the current un-
knowns about the Magellanic complexes and their relation to the entire
population of high-velocity clouds.

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