THE SOURCE OF THE MAGELLANIC STREAM AND ITS LEADING ARM

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Abstract

We explore the nature of the Magellanic Stream with the new Leiden-Argentine-Bonn (LAB) all-sky H I survey (Kalberla et al. 2005). We decompose the H I profiles into Gaussians using an automated Gaussian analysis program similar to that by Haud (2000). We find that the Magellanic Stream is composed of two filaments, as first pointed out by Putman et al. (2003), that are distinct in velocity. Using the velocity coherence of the filaments, one of them can be traced back to its origin in the 30 Doradus region of the Large Magellanic Cloud (LMC). The first complex of the Leading arm, LA I, can also be traced back to the 30 Dor region in the LMC in velocity and position, indicating that a large portion of the Leading Arm Feature originates in the LMC. Therefore, at least 1/2 of the Stream and most of the Leading Arm originates in the LMC, contrary to previous reports that the Magellanic Stream originates in the Small Magellanic Cloud (SMC) and Bridge and that the Leading Arm originates in the SMC. The two filaments of the Magellanic Stream show strong periodic patterns in position and a sinusoidal pattern in velocity. One hypothesis for the origin of these patterns in the LMC filament is that it is an imprint of the LMC rotation curve. If this hypothesis is true, then the drift rate of the Stream gas away from the Magellanic Clouds is \( \sim 83.7 \text{ km s}^{-1} \) and the age of the Magellanic Stream is \( \sim 1.07 \) Gyr old. The Parkes high-resolution H I data of the LMC (Staveley-Smith et al. 2003) shows gas outflows from supergiant shells in the 30 Dor region which are creating the Leading Arm and LMC filament of the Magellanic Stream. This method for blowing out gas from the LMC has not been previously taken into account and probably plays an important role in creating the Magellanic Stream and its Leading Arm. Our findings can serve as new constraints on future simulations of the Magellanic System.

Introduction

One of the most striking and interesting features of the large-scale expansion and structure of the universe is the way in which galaxies form and cluster. Under the current concordance cold dark matter cosmology, structures form at early times through hierarchical accretion and merging of dark matter subhalos – i.e. natal dwarf galaxies (e.g., White & Rees 1978; Davis et al. 1985; Navarro, Frenk & White 1996, 1997; Moore et al. 1999). However, the process of accretion onto large spiral galaxies, such as our Milk Way (MW), continues until late times (Bullock & Johnston 2005). This disruption and accretion of small galaxies invariably gives rise to gaseous and stellar tidal streams that continue to orbit the accreting galaxy and serve as “fossil” relics of the cannibalistic activity that has occurred. Many striking examples of disruption are known around our Milky Way, including the Sagittarius stream (Majewski et al. 2003), the Monoceros stream (Yanny et al. 2003), the orphan stream (Belakurov et al. 2006; Grillmair 2006a), and the antecenter stream (Grillmair 2006b). There are likely numerous more streams that remain to be discovered. One of the most prominent and well-known of all streams is the Magellanic Stream (MS), which stretches over 100° across the southern sky behind the Magellanic Clouds. Since the Large and Small Magellanic Clouds are the most massive satellites of the Milky Way, their interaction with the Milky Way must have greatly influenced the growth and evolution of their host galaxy. The MW-LMC-SMC system is an important laboratory with which we can study the formation, evolution and interaction of galaxies.

Recently, some large scale H I surveys were completed that enabled a more detailed study of the Magellanic Stream. Putman et al. used the HIPASS data (Barnes et al. 2001) to discover a leading arm of the Magellanic Stream (Putman et al. 1998). This feature was predicted by the tidal models and its discovery lent a lot of support to the tidal origin of the Stream. It is very difficult for a leading arm to be created by ram pressure forces and has been a problem for that theory. The HIPASS data has also shown that the Stream is spatially bifurcated (Putman et al. 2003, hereafter P03) The Parkes narrow-beam survey of the Magellanic Stream by (Brüns et al. 2005, hereafter B05) is the first high velocity resolution look at the Stream. Mastropietro et al. (2005) performed a large ram pressure (+tidal forces) simulation of the Magellanic stream (only the LMC) and were able to reproduce the general features of the Stream including its extend, shape, column density gradient and velocity gradient. It did not reproduce the spatial bifurcation of the stream nor the leading arm feature. The recent N-body tidal simulations by Connors et al. (2004, 2006) give the closest reproduction of the Stream to date, including the spatial bifurcation of the stream, the leading arm (and its bent shape) and velocity distribution. In these models most of the particles are stripped from the SMC during a close encounter with the LMC+MW \( \sim 1.5 \) Gyr ago. A
problem with most tidal models is that they have trouble reproducing the column density gradient along the Stream while ram pressure models are able to match this feature of the observations much better.

The exact origin of the Magellanic Stream, whether tidal or ram pressure, is still under debate. It appears likely, however, that some facets of each theory will be required to reproduce all of the observed properties of the Stream. It is quite important to know the correct model of the formation of the Magellanic Stream in order to properly interpret and understand the observations. Much can be learned about galaxy formation and evolution, the Milky Way’s mass and halo, and the dynamical and star formation histories of two of our closest neighbors. Therefore, continued research in this area is quite important.

**Description of Leiden-Argentine-Bonn (LAB) data**

The Leiden-Argentine-Bonn all-sky H\textsc{i} survey (Kalberla et al. 2005) is a combination of the Leiden/Dwingeloo Survey (LDS: Hartmann & Burton 1997) in the north and the Instituto Argentino de Radioastronomía Survey (IAR: Arnal et al. 2000, and Bajaja et al. 2005) in the south. The survey has a velocity resolution of 1.3 km s\(^{-1}\), a spatial resolution of 36\('\) on a grid spacing of 30\('\), and was corrected for stray radiation. The survey was interpolated onto a grid of spacing 0.5 in \(b\) and 0.5/\(\cos(b)\) in \(l\). The velocity range of \(-450\) km s\(^{-1}\) to +400 km s\(^{-1}\) is good for galactic work. The RMS noise is 0.09 K. One of the advantages of the LAB survey over previous work is the high velocity resolution.

**Description of Automated Gaussian Decomposition**

To improve our ability to trace filaments of the MS we wrote an automated Gaussian analysis program in the Interactive Data Language (IDL)\(^1\) with an algorithm similar to that used by Haud (2000).

The general algorithm to decompose an H\textsc{i} profile proceeds in two stages. In the first stage new Gaussians are added to the fits until the R.M.S. of the residuals (observed – fit) drops below the noise level, or any new Gaussians do not improve the fit significantly. In the second stage an attempt is made to reduce the number of Gaussians in the fit without increasing the R.M.S. of the residuals too much.

**The Origin of the Magellanic Stream Filaments**

The two filament structure of the MS, previously pointed out by P03 (but also by Cohen 1982 and Morras 1983), is clearly visible and separated in our data–cube of Gaussian centers. They can be easily distinguished by

\(^1\)A product of ITT Visual Information Systems, formerly Research Systems, Inc.
Fig. 3.— Integrated intensity (sum of Gaussian areas) of the Magellanic Cloud and Stream H I Gaussians (at their central $V_{\text{LSR}}$ velocity). (a) Column density, $N_{\text{HI}}$, in units of $10^{19}$ atoms/cm$^2$ (a blowup of Figure 1b). A large bifurcation of the Magellanic Stream into two filaments (first pointed out by P03) can be seen for $-20 \lesssim L_{\text{MS}} \lesssim -40^\circ$. Other bifurcations are seen farther down the Stream. (b) $L_{\text{MS}}$ vs. $V_{\text{LSR}}$ (hue indicates $B_{\text{MS}}$, and brightness indicates integrated intensity along $B_{\text{MS}}$). This shows the two filaments of the Magellanic Stream bifurcated in velocity from $-40 < L_{\text{MS}} < -20^\circ$. One of the filaments is lost near $(L_{\text{MS}}, V_{\text{LSR}}) \approx (-16.5, +220$ km s$^{-1}$). More velocity bifurcations are evident at more negative velocities. The two filaments show strong periodic patterns for $-5 \lesssim L_{\text{MS}} \lesssim -40^\circ$, after which they follow a fairly linear negative velocity gradient ($-95 \lesssim L_{\text{MS}} \lesssim -40^\circ$).

From Fig. 4 it is clear that one of the filaments connects to the LMC (the “LMC filament”). Putman et al. (1998) pointed out an “emission filament” emanating from the LMC, but claimed it went into the Bridge, and McGee & Newton (1986) saw possible indications of an LMC filament. However, this is the first conclusive evidence that any part of the MS comes from the LMC. P03 claimed that the two MS filaments came from the SMC and Bridge, and almost all subsequent tidal simulations (Connors et al. 2006, and references therein) used as their starting point an N-body for the SMC and a static potential from the LMC. It is now evident that these simulations are partially wrong or incomplete at best.

In order to track the LMC filament back to its origin in the LMC we used a boundary cut in the $L_{\text{MS}}$ vs. $V_{\text{LSR}}$ plot (the dashed lines in Fig. 5a). Figure 5b shows the distribution of the LMC filament on the sky. The filament emanates from an H I hotspot on the southeastern, or leading, edge of the LMC, namely the 30 Doradus region (by 30 Doradus “region” we mean the entire region of high–density H I in the south-east of the LMC, $0^5_{\text{h}}34_{\text{m}}^< \lesssim RA \lesssim 0^5_{\text{h}}52_{\text{m}}^<$, $-68^\circ28' \lesssim \text{DEC} \lesssim -71^\circ53'$). This can be even more clearly seen by overlaying the high resolution H I data of the LMC from Staveley-Smith et al. (2003) (Fig. 6b). The LMC filament is clearly arm “B” seen by Staveley-Smith et al. (2003). The 30 Dor region is a natural place for an H I stream to originate, due to the high-density of H I, and it is perhaps not surprising that one
Fig. 5.— The two Magellanic Stream filaments isolated by velocity cuts. The LMC filament: (a) \( L_{\text{MS}} \) vs. \( V_{\text{LSR}} \) for the Magellanic Cloud and Stream H I Gaussians showing the the two filaments (same as Figure 3b). The gray dashed lines show the velocity limits used to isolate the LMC filament. (b) Column density, \( N_{\text{HI}} \), (in units of \( 10^{19} \) atoms/cm\(^2\)), of the H I Gaussians for the LMC filament selected by the velocity cut shown in panel (a). The association of the LMC filament with the LMC and the spatial periodic patterns are apparent. The second filament: (c) \( L_{\text{MS}} \) vs. \( V_{\text{LSR}} \) for the Magellanic Cloud and Stream H I Gaussians showing the the two filaments (same as Figure 3b). The gray dashed lines show the velocity limits used to isolate the second filament. (d) Column density, \( N_{\text{HI}} \), (in units of \( 10^{19} \) atoms/cm\(^2\)), of the H I Gaussians for the second filament selected by the velocity cut shown in panel (c). The second filament can only be distinguished for \( V_{\text{LSR}} \lesssim -17^\circ \) and its origin remains unclear. The top color bar indicates \( B_{\text{MS}} \) for panels (a) and (c), while the bottom color bar indicates column density, \( N_{\text{HI}} \), (in units of \( 10^{19} \) atoms/cm\(^2\)) for panels (b) and (d).

Fig. 6.— Maps of the integrated intensity (sum of Gaussian areas) of the LMC and LMC filament H I Gaussians on the sky after a velocity filter (see Fig.5a) was applied (close up of Fig.5b). These maps show that the LMC filament is emanating from the 30 Doradus region in the LMC when either the LAB data only (a) or the LAB data and the high-resolution H I data (255.0 < \( V_{\text{LSR}} \) < 288.0 km s\(^{-1}\)) from Staveley-Smith et al. (2003) are substituted in the dashed lined box. A square root transfer function was used.

Fig. 7.— The two Magellanic Stream filaments as we have extracted them with velocity filters shown in Figure 5 on the sky (using a square root transfer function). The LMC filament is shown in red and the second filament in green. Most of the LMC is included in the velocity filter of the LMC filament. Yellow indicates regions where the two filaments overlap. Unfortunately, the two filaments cannot be easily separated in position or radial velocity for \( L_{\text{MS}} \lesssim -45^\circ \).

The Origin of the Leading Arm Feature

The Leading Arm Feature (LAF) consists of three complexes of gas north of the Magellanic Clouds that were first discovered by Mathewson et al. (1974) and Wannier & Wrixon (1972) and were further explored by Mathewson et al. (1979), Morras (1982) and Bajaja et al. (1989). From the beginning they were believed to be as-
associated with the Magellanic Clouds, but there was no evidence of a direct connection. With deep, reprocessed HIPASS data Putman et al. (1998) discovered that the LAF gas is indeed associated with the Magellanic Clouds and is a leading feature of the Magellanic Stream, and hence the name Leading Arm Feature. The association of the LAF with the Magellanic Clouds and the MS gave a lot of support to the tidal origin of the MS as compared to the ram-pressure origin, since a leading feature of the MS would not be expected if ram-pressure were the dominant force.

In Fig. 1 the three complexes of the LAF can be clearly seen at positive $L_{\text{MS}}$: LA I: $(3^\circ < L_{\text{MS}} < 29^\circ, -34^\circ < B_{\text{MS}} < -6^\circ)$; LA II: $(36^\circ < L_{\text{MS}} < 61^\circ, -17^\circ < B_{\text{MS}} < -10^\circ)$; and LA III: $(35^\circ < L_{\text{MS}} < 62^\circ, -2^\circ < B_{\text{MS}} < 11^\circ)$ (nomenclature by B05). Our analysis focuses on LA I.

LA I is the closest LAF complex to the LMC and consists of three nearly rectangular $\sim 2.5^\circ \times 8^\circ$ clumps, or concentrations, of gas which each lie almost parallel to $B_{\text{MS}}$, and combined form a linear feature making an angle with $L_{\text{MS}}$ of $\sim 40^\circ$ (Fig. 1). Putman et al. (1998) showed that the two concentrations nearest the LMC are nearly continuous (see their Fig.3) and it is therefore very likely that the entire LA I feature is a physically connected structure. The first concentration of LA I is very close to the south–eastern edge of the LMC both in position and radial velocity. However, Putman et al. (1998) claim that the Leading Arm material comes mainly from the SMC based on a filamentary feature, that is nearly parallel with $L_{\text{MS}}$, that begins near the SMC and stretches to the first concentration of LA I (see their Fig.1). Staveley-Smith et al. (2003, hereafter S03) noted several tidal HI features of the LMC and remarked that tidal arm E pointed to the Leading Arm clouds, which lay beyond their survey, but that deep reprocessed HIPASS data (Putman et al. 2003) showed a continuous connection between arm E and the Leading Arm. However, later on S03 state that the Leading Arm gas mainly arises from the SMC, and only some LMC gas ‘‘leaks’’ into the Leading Arm. We investigate the association of the Leading Arm with the LMC.

The radial velocity of the LA I complexes is very similar to that of the LMC (Fig.2). This can be seen especially well in Fig.8b where the first concentration of LA I ($-17^\circ < B_{\text{MS}} < -10^\circ$) is connected in position and velocity to an extension of the LMC ($-10^\circ < B_{\text{MS}} < -5^\circ$). In order to better probe the association of LA I to the LMC we used a velocity cut of $250 < V_{\text{LSR}} < 320$ km s$^{-1}$. The distribution of this gas on the sky is shown in Figure 9a. In Figure 9b we also overlay the S03 high resolution ATCA HI data over our own (using the same velocity cut) to confirm our result. This shows S03’s tidal arm E extending out of the LMC and the first two concentrations of LA I. Arm E has the same elongated shape (parallel to $B_{\text{MS}}$) and continues the spatial progression of the three LA concentrations (more positive $B_{\text{MS}}$ as you move to lower $L_{\text{MS}}$). It also continues the velocity trend with $B_{\text{MS}}$ as seen in Fig.8b. There is a gap of a few degrees between the end of arm E and the beginning of the first concentration of LA I (although there is a small clump of gas between them). However, our data also show gaps between the three concentrations of LA I that the deeper HIPASS data show are continuous. Therefore, it is likely that arm E and the first concentration of LA I are also continuous. For all of these reasons, we conclude that LA I is physically connected to arm E (which starts in the 30 Doradus region) and has its origins in the LMC. Therefore, both the trailing LMC filament of the MS and LA I have their origin in the 30 Dor region of the LMC. We discuss these implications further in section 6.

The horizontal feature south of the LMC which seems to connect the SMC to the Leading Arm does connect to the southern end of arm E in position and velocity. However, it is unclear in which direction this gas is moving. If it is moving to positive $L_{\text{MS}}$, then it might be possible for the SMC to be contributing some gas to the Leading Arm. If it is, however, moving to negative $L_{\text{MS}}$, then it is very likely that it is originating from the end of arm E and is part of the trailing Magellanic Stream. The structures and periodic patterns of this horizontal feature look much like the filaments of the Magellanic Stream and when extrapolated seems to connect to the second Mag-
ellanic Stream filament (see Fig.4 of P03). If this is the case, then the entire Magellanic Stream and the Leading Arm originate from LMC gas.

**Discussion**

**The Large Magellanic Cloud as Progenitor of the Magellanic Stream and Leading Arm Feature:**

We have shown strong evidence that the Magellanic Stream and the Leading Arm can be traced back to the LMC and originate there. This is contrary to most of the current literature which has largely supported the SMC origin of the Magellanic Stream. Several observational papers have claimed that the MS and LAF originate in the SMC (Putman et al. 2003, Brüns et al. 2005), and most modeling papers (especially the tidal ones) have started with this assumption and only use a N-body SMC with a static LMC potential (Gardiner & Noguchi 1996; Yoshizawa & Noguchi 2003; Connors et al. 2004, 2006). It is no surprise that these models always showed the Magellanic Stream forming from the SMC and not the LMC. Models that represented both the LMC and SMC as N-bodies (Murai & Fujimoto 1980, Ružička et al. 2006) also concluded that most of the Magellanic Stream came from the SMC, however, these simulations showed some debris did come off the LMC and this debris followed the position and velocity distribution of the Stream. The main reason the SMC was favored was because more material came off the SMC than the LMC. The reasons cited for this is that the SMC potential is weaker than the LMC’s and that the LMC had a much larger tidal influence on the SMC than vice versa. Even though these statements are correct and probably are the reasons for why more debris was stripped from the SMC than the LMC in these models, none of the simulations included LMC star formation and supernova remnants which greatly contribute to gas outflow in the LMC. Once the supernova remnants blow out the gas it can easily be swept away by tidal and/or ram pressure forces. Therefore, the effects of supernova remnants greatly increases the contribution of LMC gas to the Magellanic Stream gas. If these effects are included in future simulations of the Magellanic System, we believe it is likely that most of the debris will come from the LMC, as we have found in our work.

With the discovery of the two filaments of the MS (Putman et al. 2003) it was suggested that one of the filaments originates from the Bridge, and that the Bridge might be older than originally thought. However, now that this filament has been shown to originate in the LMC, there is no reason to think that the Bridge is old. In fact, the recent study of stellar populations in the Bridge (Harris 2006) showed that there are no old stars, only young stars, and that star formation started in the Bridge 200–300 Myr ago.

**Origins in 30 Doradus:**

The current metallicity of the LMC and SMC is [Fe/H] = −0.2 and [Fe/H] = −0.6 respectively (Russell & Dopita 1992), and the average metallicity of the Magellanic Stream is [Fe/H] = −0.6 (Wakker 2001). At first glance it appears that the metallicity information points towards a SMC origin of the MS. However, it is not the current metallicity of the Magellanic Clouds that is important, but the metallicity at the time that the Magellanic Stream left the Clouds about 1.5 Gyr ago. According to Pagel & Tautvaisiene (1998) the metallicities of the Clouds was ~0.2 dex lower 1.5 Gyr ago, which would put them at [Fe/H] = −0.4 (LMC) and [Fe/H] = −0.8 (SMC). This makes it more difficult to use the metallicity information to determine the origin of the MS in one of the Clouds, since the MS metallicity falls between them.

As mentioned above, there has been some debate on the age of the Magellanic Bridge. One of the reasons it was thought to be old is because the metallicity of the gas is so low, [Fe/H] = −1.1 (Lehner 2002), compared to [Fe/H] = −0.6 for the SMC where it is thought to have originated. Since the current evidence supports a young (~200 Myr) origin of the Bridge (see above) there is a real problem reconciling the metallicity of the Bridge with that of the Magellanic Clouds. One likely explanation given by Lehner (2002) is that the Magellanic gas
mixed with an unenriched component. If this happened for the Bridge only \(\sim 200 \) Myr then it probably also happened for the Magellanic Stream \(\sim 1.5 \) Gyr ago. Therefore, it appears that the metallicity situation of the Magellanic System is very complicated and still unclear, and that an LMC origin of the Magellanic Stream and LAF can not be ruled out on this basis.

**Relevance to the Tidal vs. Ram Pressure Models:**

At first glance our findings appear to strengthen the case for ram pressure somewhat since most tidal models to not show appreciable debris from the LMC. However, tidal models have not yet included the important effects of blowout from supergiant shells (and magnetic fields), which will cause more debris to come off the LMC. Moreover, it seems quite evident that both ram pressure and tidal forces are present and needed to explain the observations of the Magellanic Stream and the Leading Arm. The LAF cannot be satisfactorily explained without a tidal force, and ram pressure forces are evidently at work in building the steep density gradient in the leading edge of the LMC. Ram pressure forces, in combination with tidal forces, can also likely help explain the column density gradient along the Magellanic Stream and the imbalance of mass in the MS and LAF, since it will be more difficult to move material ahead of the MCs due to the extra force pushing it backwards.

However, our work does address an issue that has plagued tidal models, namely the lack of stars in the stream. If most of the MS+LAF gas was blown out of the LMC from supergiant shells in the 30 Dor region, as suggested here, then no stars would be expected in the Stream. The forces operating in the supergiant shells that blow out the gas (superwind and supernovae shocks) do not affect the stars, and therefore the mystery of the lack of stars in the Stream is easily explained.

**New Constraints for Modeling of the Magellanic Stream:**

There are many patterns in the MS and LAF that are clues about the processes that formed them. The most obvious clues are the periodic patterns. There are three concentrations in LA I, elongated along \(B_{\text{MS}} (\sim 2 \times 7')\), that look very similar and that are each offset by \(\sim 12'\) in \(L_{\text{MS}}\) and \(\sim 9.5'\) in \(B_{\text{MS}}\) from the previous one. LA II and LA III are also very similar and nearly parallel to each other (and elongated along \(L_{\text{MS}}\)). The two filaments of the Magellanic Stream exhibit strong periodic patterns in position, and are composed of clumps elongated along \(L_{\text{MS}}\) with sizes of \(\sim 1.5 \times 6.0'\), surprisingly similar to the LA I clumps, indicating that they probably were formed by similar processes. The two MS filaments are very similar and mirror each other in their features (from \(L_{\text{MS}} \approx -15\) to \(-45\)), only shifted by \(\sim 5'\) in \(L_{\text{MS}}\) and \(\sim 1'\) in \(B_{\text{MS}}\). Furthermore, the two MS filaments show strong periodic patterns (nearly sinusoidal) in velocity. Not only do all of these patterns serve as clues to the processes that formed the Magellanic Stream, but they also represent very distinct observational characteristics of the MS that serve as constraints for future modeling work.

**Summary and Conclusions**

An automated Gaussian decomposition on the entire LAB \(\text{H I}\) survey was performed and the results analyzed in order to better understand the structure and origins of the Magellanic Stream and its Leading Arm. The two MS filaments, previously pointed out by P03, are distinct in radial velocity, and one of the filaments (the LMC filament) can be tracked back to the 30 Doradus region in the LMC. Therefore, at least 1/2 of the MS originates in the LMC contrary to previous papers that claimed the MS originated in the SMC and Bridge. The first complex of the Leading arm, LA I, can be traced back to the 30 Dor region in the LMC in velocity and position, indicating that a large portion of the Leading Arm Feature originates in the LMC contrary to previous reports that most of the LAF gas originates in the SMC. The two filaments of the MS show strong periodic patterns in position and a sinusoidal pattern in velocity. One hypothesis for the origin of these patterns in the LMC filament is that it is an imprint of the rotation curve. If this hypothesis is true, then the drift rate of the MS gas away from the Magellanic Clouds is \(\sim 83.7 \) km s\(^{-1}\) and the age of the MS is \(\sim 1.07\) Gyr old. The high-resolution \(\text{H I}\) data of the LMC (Staveley-Smith et al. 2003) shows strong signs of outflows from supergiant shells in the 30 Dor region which is giving rise to the outflow of gas from the LMC which is creating the Leading Arm and LMC filament of the Magellanic Stream. Our findings can serve as new constraints on future modeling and will help improve our understanding of the Magellanic System.

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