THE SOURCE OF IONIZATION ALONG THE MAGELLANIC STREAM

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ABSTRACT

Since its discovery in 1996, the source of the bright Hα emission (up to 750 mR) along the Magellanic Stream has remained a mystery. There is no evidence of ionizing stars within the H i stream, and the extended hot halo is far too tenuous to drive strong shocks into the clouds. We now present a hydrodynamical model that explains the known properties of the Hα emission and provides new insights on the lifetime of the Stream clouds. The upstream clouds are gradually disrupted due to their interaction with the hot halo gas. The clouds that follow plow into gas ablated from the upstream clouds, leading to shock ionization at the leading edges of the downstream clouds. Since the following clouds also experience ablation, and weaker Hα (100–200 mR) is quite extensive, a disruptive cascade must be operating along much of the Stream. In our model, the clouds are evolving on timescales of 100–200 Myr, such that the Stream must be replenished by the Magellanic Clouds at a fairly constant rate. The ablated material falls onto the Galaxy as a warm drizzle, which suggests that diffuse ionized gas at 104 K may be an important constituent of galactic accretion. The observed Hα emission provides a new constraint on the rate of disruption of the Stream and, consequently, the infall rate of metal-poor gas onto the Galaxy. When the ionized component of the Stream is fully accounted for, the rate of gas accretion is 0.4 M⊙ yr⁻¹, roughly twice the rate deduced from H i observations alone.

Subject headings: galaxies: evolution — galaxies: interactions — hydrodynamics — instabilities — Magellanic Clouds — shock waves

1. INTRODUCTION

How do galaxies get their gas? This important question has never been fully answered, either through observation or through numerical simulation. H i observations of the nearby universe suggest that galaxy mergers and collisions are an important aspect of this process (Hibbard & van Gorkom 1996), but tidal interactions do not guarantee that the gas settles to one or other galaxy. The most spectacular interaction phenomenon is the Magellanic H i Stream that trails from the LMC-SMC system (10 : 1 mass ratio) in orbit about the Galaxy. Since its discovery (Wannier & Wrixon 1972; Mathewson et al. 1974), there have been repeated attempts to explain the Stream in terms of tidal and/or viscous forces (q.v. Mastropietro et al. 2005; Connors et al. 2006). Indeed, the Stream has become a benchmark against which to judge the credibility of N-body + gas codes in explaining gas processes in galaxies. A fully consistent model of the Stream continues to elude even the most sophisticated codes.

Here we demonstrate that Hα detections along the Stream (Weiner & Williams 1996; Putman et al. 2003) are providing new insights on the present state and evolution of the H i gas. At a distance of D ≈ 55 kpc, the expected Hα signals excited by the cosmic and Galactic UV backgrounds are about 3 and 25 mR, respectively (Bland-Hawthorn & Maloney 1999, 2002), significantly lower than the mean signal of 100–200 mR and much lower than the few bright detections in the range 400–750 mR (Weiner et al. 2002). This signal cannot have a stellar origin since repeated attempts to detect stars along the Stream have failed (e.g., Ostheimer et al. 1997).

Some of the Stream clouds exhibit compression fronts and head-tail morphologies (Brüns et al. 2005), and this is suggestive of confinement by a tenuous external medium. But the cloud : halo density ratio (η = ρc/ρh) necessary for confinement can be orders of magnitude larger than that required to achieve shock-induced Hα emission (e.g., Quilis & Moore 2001). Indeed, the best estimates of the halo density at the distance of the Stream (ρh ≈ 10⁻¹⁸ cm⁻³; Bregman 2007) are far too tenuous to induce strong Hα emission at a cloud face. It is therefore surprising to discover that the brightest Hα detections lie at the leading edges of H i clouds (Weiner et al. 2002) and thus appear to indicate that shock processes are somehow involved.

We now present a model that goes a long way toward explaining the Hα mystery. The basic premise is that a tenuous external medium not only confines clouds but also disrupts them with the passage of time. The growth time for Kelvin-Helmholtz (KH) instabilities is given by τKH ≈ λνl/vb, where λ is the wavelength of the growing mode and vb is the apparent speed of the halo medium (vb ≈ 350 km s⁻¹; see § 2).

For cloud sizes of order a few kiloparsecs and ξ ≈ 10⁴, the KH timescale can be much less than an orbital time (τKH ≈ 2πDvb/vb ≈ 1 Gyr). Once an upstream cloud becomes disrupted, the fragments are slowed with respect to the LMC-SMC orbital speed and are subsequently plowed into by the following clouds. In § 2, the new hydrodynamical models are described, and the results are presented in § 3. In § 4, we discuss the implications of our model and suggest avenues for future research.

2. A NEW HYDRODYNAMICAL MODEL

There have been many attempts to understand how gas clouds interact with an ambient medium (Murray et al. 1993; Klein et al. 1994). In order to capture the evolution of a system involving instabilities with large density gradients correctly, grid-based methods (Liska & Wendroff 1999; Agertz et al. 2007) are favored over other schemes (e.g., smoothed particle hydrodynamics). We have therefore investigated the dynamics of the Magellanic Stream with two independent hydrodynamics codes, Fyris (R. S. Sutherland 2008, in preparation) and Ramses (Teyssier 2002), that solve the equations of gas dynamics with...
adaptive mesh refinement. The results shown here are from the *Fyris* code because it includes nonequilibrium ionization, but we get comparable gas evolution from either code.\(^5\)

The brightest emission is found along the leading edges of clouds MS II, III, and IV with values as high as 750 mR for MS II. The H\(^\alpha\) line emission is clearly resolved at 20–30 km s\(^{-1}\) FWHM and shares the same radial velocity as the H\(^\alpha\) emission within the measurement errors (Weiner et al. 2002; G. Madsen 2007, private communication). This provides an important constraint on the physical processes involved in exciting the Balmer emission.

In order to explain the H\(^\alpha\) detections along the Stream, we concentrate our efforts on the disruption of the clouds labeled MS I–IV (Brüns et al. 2005). The Stream is trailing the LMC-SMC system in a counterclockwise, near-polar orbit as viewed from the Sun. The gas appears to extend from the LMC dislodged through tidal disruption, although some contribution from drag must also be operating (Moore & Davis 1994). Recently, the *Hubble Space Telescope* has determined an orbital velocity of 378 \(\pm\) 18 km s\(^{-1}\) for the LMC. While this is higher than earlier claims, the result has been confirmed by independent researchers (T. Pryor 2007, private communication). Besla et al. (2007) conclude that the origin of the Stream may no longer be adequately explained with existing numerical models. The Stream velocity along its orbit must be comparable to the motion of the LMC; we adopt a value of \(v_{\text{MS}} \approx 350\) km s\(^{-1}\).

Here we employ a three-dimensional Cartesian grid with dimensions 18 \(\times\) 9 \(\times\) 9 kpc \([x, y, z] = (432, 216, 216)\) cells to model a section of the Stream where \(x\) is directed along the Stream arc and the \(z\)-axis points toward the observer. The grid is initially filled with two gas components. The first is a hot thin medium representing the halo corona. If we adopt a rigorously isothermal halo for the Galaxy, with parameters from Battaglia et al. (2005), the virial temperature at a radial distance of 55 kpc is \(T_v = 1.75 \times 10^6\) K. Embedded in the hot halo is (initially) cold H\(^\alpha\) material with a total H\(^\alpha\) mass of 3 \(\times 10^7\) M\(_{\odot}\). The cold gas has a fractal distribution and is initially confined to a cylinder with a diameter of 4 kpc and length 18 kpc (Fig. 2.1); the mean volume and column densities are 0.02 cm\(^{-3}\) and 2 \(\times\) 10\(^{19}\) cm\(^{-2}\), respectively. The three-dimensional spatial power spectrum \(\tilde{P}(k) \propto k^{-5/3}\) describes a Kolmogorov turbulent medium with a minimum wavenumber \(k\) corresponding to a spatial scale of 2.25 kpc, comparable to the size of observed clouds along the Stream.

A key parameter of the models is the ratio of the cloud to halo pressure, \(\xi = P_i/P_h\). If the cloud is to survive the impact of the hot halo, then \(\xi \geq 1\). A shocked cloud is destroyed in about the time it takes for the internal cloud shock to cross the cloud, during which time the cool material mixes and ablates into the gas streaming past. Only massive clouds with dense cores can survive the powerful shocks. An approximate lifetime for a spherical cloud of diameter \(d\) is

\[
\tau_c = 60(d/2 \text{kpc})^{-1}(v_c/350\text{ km s}^{-1})(\eta/100)^{0.5} \text{ Myr.} \tag{1}
\]

For \(\eta\) in the range of 100–1000, this corresponds to 60–180 Myr for individual clouds. With a view to explaining the H\(^\alpha\) observations, we focus our simulations on the lower end of this range.

For low \(\eta\), the density of the hot medium is \(n_h = 2 \times 10^{-4}\) cm\(^{-3}\). The simulations are undertaken in the frame of the cold H\(^\alpha\) clouds, so the halo gas is given an initial transverse velocity of 350 km s\(^{-1}\). The observations reveal that the mean H\(^\alpha\) emission has a slow trend along the Stream that requires the Stream to move through the halo at a small angle of attack (20\(^\circ\)) in the plane of the sky (see Fig. 1). Thus, the velocity of the hot gas as seen by the Stream is \((v_x, v_y) = (-330, -141)\) km s\(^{-1}\). The adiabatic sound speed of the halo gas is 200 km s\(^{-1}\), such that the drift velocity is mildly supersonic (transonic), with a Mach number of 1.75. A unique feature of the *Fyris* simulations is that they include nonequilibrium cooling through time-dependent ionization calculations (cf. Rosen & Smith 2004). When shocks occur within the inviscid fluid, the jump shock conditions are solved across the discontinuity. This allows us to calculate the Balmer emission produced in shocks and additionally from turbulent mixing along the Stream (e.g., Slavin et al. 1993). We adopt a conservative value for the gas metallicity of \([\text{Fe/H}] = -1.0\) (cf. Gibson et al. 2000); a higher value accentuates the cooling and results in denser gas and therefore stronger H\(^\alpha\) emission along the Stream.

### 3. RESULTS

The results of the simulations are shown in Figures 2–4.\(^6\) In our model, the fractal Stream experiences a "hot wind" moving in the opposite direction. The sides of the Stream clouds are subject to gas ablation via KH instabilities due to the reduced pressure (Bernoulli’s theorem). The ablated gas is slowed dramatically by the hot wind and is transported behind the cloud. As higher order modes grow, the fundamental mode associated with the cloud size will eventually fragment it. The ablated gas now plays the role of a "cool wind" that is swept up by the pursuing clouds leading to shock ionization and ablation of the downstream clouds. The newly ablated material continues the

\(^{5}\) Further details on the codes and comparative simulations are provided at http://www.aao.gov.au/astro/MS.

\(^{6}\) We provide animations of the disrupting stream at http://www.aao.gov.au/astro/MS.
trend along the length of the Stream. The pursuing gas cloud transfers momentum to the ablated upstream gas and accelerates it; this results in Rayleigh-Taylor (RT) instabilities, especially at the stagnation point in the front of the cloud. We rapidly approach a nonlinear regime where the KH and RT instabilities become strongly entangled, and the internal motions become highly turbulent. The simulations track the progression of the shock fronts as they propagate into the cloudlets.

In Figure 2, we show the predicted conversion of neutral to ionized hydrogen due largely to cascading shocks along the Stream. The drift of the peak to higher columns is due to the shocks eroding away the outer layers, thereby progressing into increasingly dense cloud cores. The ablated gas drives a shock into the H\textsc{i} material with a shock speed of \( v_s \), measured in the cloud frame. At the shock interface, once ram pressure equilibrium is reached, we find \( v_s \approx v_h \eta^{-0.5} \). In order to produce significant H\textalpha\ emission, \( v_h \approx 35 \) km s\(^{-1}\) such that \( \eta \lesssim 100 \). In Figure 3, we see the steady rise in H\textalpha\ emission along the Stream, reaching 100–200 mR after 120 Myr, and the most extreme observed values after 170 Myr. The power-law decline to bright emission measures is a direct consequence of the shock cascade. The shock-induced ionization rate is \( \dot{\omega} = \frac{1.5 \times 10^{47}}{1 \text{ kpc}} \) photons s\(^{-1}\). The predicted luminosity-weighted line widths of 20 km s\(^{-1}\) FWHM (Fig. 3, inset) are consistent with the H\textalpha\ kinematics. In Figure 4, the H\textalpha\ emission is superimposed onto the projected H\textsc{i} emission: much of it lies at the leading edges of clouds, although there are occasional cloudlets where ionized gas dominates over the neutral column. Some of the brightest emission peaks appear to be due to limb brightening, while others arise from chance alignments.

The simulations track the degree of turbulent mixing between the hot and cool media brought on by KH instabilities (e.g., Kahn 1980). The turbulent layer grows as the flow develops, mixing up hot and cool gas at a characteristic temperature of about 10\(^4\) K. In certain situations, a sizeable H\textalpha\ luminosity can be generated (e.g., Canto & Raga 1991) and the expected line widths are comparable to those observed in the Stream (§ 2). Indeed, the simulations reveal that the fractal clouds develop a warm ionized skin along the entire length of the Stream. But the characteristic H\textalpha\ emission (denoted by the shifting peak in Fig. 3) is comparable to the fluorescence excited by the Galactic UV field (Bland-Hawthorn & Maloney 2002). We note with interest that narrow Balmer lines can arise from precursor shocks (e.g., Heng & McCray 2007), but these require conditions that are unlikely to be operating along the Stream.

4. DISCUSSION

We have seen that the brightest H\textalpha\ emission along the Stream can be understood in terms of shock ionization and heating in a transonic (low Mach number) flow. For the first time, the Balmer
emission (and associated emission lines) provides diagnostic information at any position along the Stream that is independent of the H i observations. Slow Balmer-dominated shocks of this kind (e.g., Chevalier & Raymond 1978) produce partially ionized media where a significant fraction of the H α emission is due to collisional excitation. This can lead to Balmer decrements (Hα/Hβ ratio) in excess of 4, i.e., significantly enhanced over the pure recombination ratio of about 3, that will be fairly straightforward to verify in the brightest regions of the Stream.

The shock models predict a range of low-ionization emission lines (e.g., O i, S ii), some of which will be detectable even though suppressed by the low gas-phase metallicity. There are likely to be EUV absorption-line diagnostics through the shock interfaces revealing more extreme kinematics (Fig. 3, inset), but these detections (e.g., O vi) are only possible toward fortuitous background sources (Sembach et al. 2001; Bregman 2007). The predicted EUV/X-ray emissivity from the postshock regions is much too low to be detected in emission.

The characteristic timescale for large changes is roughly 100–200 Myr, and so the Stream needs to be replenished by the outer disk of the LMC at a fairly constant rate (e.g., Mastropietro et al. 2005). The timescale can be extended with larger η-values (see eq. [1]) but at the expense of substantially diminished Hα surface brightness. In this respect, we can consider η to be fairly well bounded by observation and theory.

What happens to the gas shredded from the dense clouds? Much of the diffuse gas will become mixed with the hot halo gas, suggesting a warm accretion toward the inner Galactic halo. Much of the diffuse gas will become mixed with the hot halo to be fairly well bounded by observation and theory. The predicted EUV/X-ray emissivity from the postshock interfaces revealing more extreme kinematics (Fig. 3, inset), but these detections (e.g., O vi) are only possible toward fortuitous background sources (Sembach et al. 2001; Bregman 2007). The predicted EUV/X-ray emissivity from the postshock regions is much too low to be detected in emission.

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