

THE SOURCE OF IONIZATION ALONG THE MAGELLANIC STREAM

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ABSTRACT

Since its discovery in 1996, the source of the bright H α emission (up to 750 mR¹) along the Magellanic Stream has remained a mystery. There is no evidence of ionising 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 H α 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 plough into gas ablated from the upstream clouds, leading to shock ionisation at the leading edges of the downstream clouds. Since the following clouds also experience ablation, and weaker H α (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 10⁴K may be an important constituent of galactic accretion. The observed H α 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 $_{\odot}$ yr⁻¹, roughly twice the rate deduced from H I observations alone.

Subject headings: Galaxies: interaction, evolution, Magellanic Clouds – shock waves – instabilities – hydrodynamics

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; Matthewson et al 1979), there have been repeated attempts to explain the Stream in terms of tidal and/or viscous forces (q.v. Mastrogiuseppe et al. 2005; Connors, Kawata & Gibson 2005). 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 H α 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 $D \approx 55$ kpc, the expected H α signal excited by the cosmic and Galactic UV backgrounds are about 3 mR 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, Vogel & Williams 2002). This signal cannot have a stellar origin since repeated attempts to detect stars along the Stream have failed (e.g. Osthheimer, Majewski & Kunkel 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 ($\eta = \rho_c/\rho_h$) necessary for confinement can be orders of magnitude larger than that required to achieve shock-induced H α emission (e.g. Quilis & Moore 2001). Indeed, the best estimates of the halo density at the distance of the Stream ($\rho_h \sim 10^{-4}$ cm⁻³; Bregman 2007) are far too tenuous to induce strong H α emission at a cloud face. It is therefore surprising to discover that the brightest H α 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 towards explaining the H α 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 $\tau_{KH} \approx \lambda\eta^{0.5}/v_h$ where λ is the wavelength of the growing mode, and v_h is the apparent speed of the halo medium ($v_h \approx 350$ km s⁻¹; see §2). For cloud sizes of order a few kiloparsecs and $\xi \approx 10^4$, the KH timescale can be much less than an orbital time ($\tau_{MS} \approx 2\pi D/v_h \approx 1$ Gyr). Once an upstream cloud becomes disrupted, the fragments are slowed with respect to the LMC-SMC orbital speed and are subsequently ploughed into by the following clouds. In §2, the new hydrodynamical models are described and

¹1 Rayleigh (R) = 10⁶/4 π photons cm⁻² s⁻¹ sr⁻¹, equivalent to 5.7 $\times 10^{-18}$ erg cm⁻² s⁻¹ arcsec⁻² at H α .

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, White & Blondin 1993; Klein, McKee & Colella 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 favoured over other schemes (e.g. Smooth Particle Hydrodynamics). We have therefore investigated the dynamics of the Magellanic Stream with two independent hydrodynamics codes, *Fyris* (Sutherland 2007) 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 non-equilibrium ionization, but we get comparable gas evolution from either code¹.

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 α line emission is clearly resolved at 20–30 km s⁻¹ FWHM, and shares the same radial velocity as the H I emission within the measurement errors (Weiner et al 2002; G. Madsen 2007, personal communication). This provides an important constraint on the physical processes involved in exciting the Balmer emission.

In order to explain the H α detections along the Stream, we concentrate our efforts on the disruption of the clouds labelled MS I–IV (Brüms et al. 2005). The Stream is trailing the LMC-SMC system in a counter-clockwise, 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, personal 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.

FIG. 1.— The initial fractal distribution of H I at 20 Myr, shown in contours, before the wind action has taken hold. The upper figure is in the $x-z$ frame as seen from above; the lower figure is the projected distribution on the plane of the sky ($x-y$ plane). Both distributions are integrated along the third axis. The logged H I contours correspond to 18.5 (dotted), 19.0, 19.5, 20.0, and 20.5 (heavy) cm⁻². The greyscale shows weak levels of H α along the Stream where black corresponds to 300 mR.

Here we employ a 3D 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 towards the observer. The grid is initially filled with two gas components.

¹ Further details on the codes and comparative simulations are provided at <http://www.aao.gov.au/astro/MS>.

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 $T_h = 1.75 \times 10^6$ K. Embedded in the hot halo is (initially) cold H I material with a total H I 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. 1); the mean volume and column densities are 0.02 cm⁻³ and 2×10^{19} cm⁻² respectively. The 3D spatial power spectrum ($P(k) \propto k^{-5/3}$) 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, $\xi = P_c/P_h$. If the cloud is to survive the impact of the hot halo, then $\xi \gtrsim 1$. 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_c is

$$\tau_c = 60(d_c/2 \text{ kpc})^{-1}(v_h/350 \text{ km s}^{-1})^{-1}(\eta/100)^{0.5} \text{ Myr.} \quad (1)$$

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

For low η , 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 I clouds, so the halo gas is given an initial transverse velocity of 350 km s⁻¹. The observations reveal that the mean H α emission has a slow trend along the Stream which requires the Stream to move through the halo at a small angle of attack (20°) 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 (transsonic), with a Mach number of 1.75.

A unique feature of the *Fyris* simulations is that they include non-equilibrium cooling through time-dependent ionisation 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 [Fe/H]=-1.0 (cf. Gibson et al. 2000); a higher value accentuates the cooling and results in denser gas, and therefore stronger H α emission along the Stream.

3. RESULTS

The results of the simulations are shown in Figs. 2–4; we provide animations of the disrupting stream at <http://www.aao.gov.au/astro/MS>. 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

FIG. 2.— The dependence of the evolving fractions of H^0 and H^+ on column density as the shock cascade progresses. The timesteps are 70 (red), 120 (magenta), 170 (blue), 220 (green) and 270 Myr (black). The lowest column H^0 becomes progressively more compressed with time but the highest column H^0 is shredded in the cascade process; the fraction of ionized gas increases with time. The pile-up of electrons at low column densities arises from the x-ray halo.

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 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 Fig. 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^0 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 $\text{H}\alpha$ emission, $v_s \gtrsim 35 \text{ km s}^{-1}$ such that $\eta \lesssim 100$. In Fig. 3, we see the steady rise in $\text{H}\alpha$ 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 $1.5 \times 10^{47} \text{ phot s}^{-1} \text{ kpc}^{-1}$. The predicted luminosity-weighted line widths of 20 km s^{-1} FWHM (Fig. 3, inset) are consistent with the $\text{H}\alpha$ kinematics. In Fig. 4, the $\text{H}\alpha$ emission is superimposed onto the projected H^0 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 $\text{H}\alpha$ 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 $\text{H}\alpha$ 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 pre-cursor shocks (e.g. Heng & McCray 2007), but these require conditions that are unlikely to be operating along the Stream.

FIG. 3.— The evolving distribution of projected $\text{H}\alpha$ emission as the shock cascade progresses. The timesteps are explained in Fig. 2. The extreme emission measures increase with time and reach the observed mean values after 120 Myr. The mean and peak emission measures along the Stream are indicated, along with the approximate contributions from the cosmic and Galactic UV backgrounds. **Inset:** The evolving $\text{H}\alpha$ line width as the shock cascade progresses; the velocity scale is with respect to the reference frame of the initial H^0 gas. The solid lines are flux-weighted line profiles; the dashed lines are volume-weighted profiles that reveal more extreme kinematics at the lowest densities.

FIG. 4.— The predicted H^0 (contours) and $\text{H}\alpha$ (greyscale) distributions after 120 Myr; the intensity levels are given in Fig. 1. The angle of attack in the $[x,y,z]$ coordinate frame is indicated. The $\text{H}\alpha$ emission is largely, but not exclusively, associated with dense H^0 gas.

4. DISCUSSION

We have seen that the brightest $\text{H}\alpha$ emission along the Stream can be understood in terms of shock ionization and heating in a transsonic (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^0 observations. Slow Balmer-dominated shocks of this kind (e.g. Chevalier & Raymond 1978) produce partially ionized media where a significant fraction of the $\text{H}\alpha$ emission is due to collisional excitation. This can lead to Balmer decrements ($\text{H}\alpha/\text{H}\beta$ 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. OI, SII), 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. OVI) are only possible towards fortuitous background sources (Sembach et al. 2001; Bregman 2007). The predicted EUV/x-ray emissivity from the post-shock 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 equation (1)), but at the expense of substantially diminished $\text{H}\alpha$ surface brightness. In this respect, we consider η to be fairly well bounded by observation and theory.

What happens to the gas shedded from the dense clouds? Much of the diffuse gas will become mixed with the hot halo gas suggesting a warm accretion towards the inner Galactic halo. If most of the Stream gas enters the Galaxy via this process, the derived gas accretion rate is $\sim 0.4 M_\odot \text{ yr}^{-1}$. The higher value compared to H^0 (e.g.

Peek et al. 2007) is due to the gas already shredded, not seen by radio telescopes now. In our model, the HVCs observed today are unlikely to have been dislodged from the Stream by the process described here. These may have come from an earlier stage of the LMC-SMC interaction with the outer disk of the Galaxy.

The “shock cascade” interpretation for the Stream clears up a nagging uncertainty about the H α distance scale for high-velocity clouds. Bland-Hawthorn et al (1998) first showed that distance limits to HVCs can be determined from their observed H α strength due to ionization by the Galactic radiation field, now confirmed by clouds with reliable distance brackets from the stellar absorption line technique (Wakker 2001). HVCs have smaller kinetic energies compared to the Stream clouds, and their interactions with the halo gas are not expected to produce significant shock-induced or mixing layer H α emission, thereby supporting the use of H α as a crude distance indicator.

Here, we have not attempted to reproduce the HI observations of the Stream in detail. This is left to a subsequent paper where we explore a larger parameter space and include a more detailed comparison with the HI and H α power spectrum, inter alia. We introduce additional physics, in particular, the rotation of the hot halo, a range of Stream orbits through the halo gas, the gravitational field of the Galaxy, and so on.

If we are to arrive at a satisfactory understanding of the Stream interaction with the halo, future deep H α surveys will be essential. It is plausible that current H α observations are still missing a substantial amount of gas, in contrast to the deepest HI observations. We can compare the particle column density inferred from

HI and H α imaging surveys. The limiting HI column density is about $N_H \approx \langle n_H \rangle L \approx 10^{18} \text{ cm}^{-2}$ where $\langle n_H \rangle$ is the mean atomic hydrogen density, and L is the depth through the slab. By comparison, the H α surface brightness can be expressed as an equivalent emission measure, $E_m \approx \langle n_e^2 \rangle L \approx \langle n_e \rangle N_e$. Here n_e and N_e are the local and column electron density. The limiting value of E_m in H α imaging is about 100 mR, and therefore $N_e \approx 10^{18} / \langle n_e \rangle \text{ cm}^{-2}$. Whether the ionized and neutral gas are mixed or distinct, we can hide a lot more ionized gas below the imaging threshold for a fixed L , particularly if the gas is at low density ($\langle n_e \rangle \ll 0.1 \text{ cm}^{-3}$). A small or variable volume filling factor can complicate this picture but, in general, the ionized gas still wins out because of ionization of low density HI by the cosmic UV background (Maloney 1993). In summary, even within the constraints of the cosmic microwave background (see Maloney & Bland-Hawthorn 1999), a substantial fraction of the gas can be missed if it occupies a large volume in the form of a low density plasma.

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