THE ASTROPHYSICAL JOURNAL, 529:L81–L84, 2000 February 1

THE MAGELLANIC STREAM AND THE DENSITY OF CORONAL GAS IN THE GALACTIC HALO

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Received 1999 August 20; accepted 1999 December 7; published 1999 December 30

ABSTRACT

The properties of the Magellanic Stream constrain the density of coronal gas in the distant Galactic halo. We show that motion through ambient gas can strongly heat Stream clouds, driving mass loss and causing evaporation. If the ambient gas density is too high, then evaporation occurs on unreasonably short timescales. Since heating dominates drag, tidal stripping appears to be responsible for producing the Stream. Requiring the survival of the cloud MS IV for 500 Myr sets an upper limit on the halo gas density of $n_h < 10^{-5}$ cm $^{-3}$ at 50 kpc, roughly a factor of 10 lower than that estimated from the drag model of Moore & Davis. Implications for models of the evolution of gas in galaxy halos are discussed.

Subject headings: galaxies: evolution — galaxies: halos — Galaxy: halo — ISM: clouds — Magellanic Clouds — quasars: absorption lines

1. INTRODUCTION

In current pictures of hierarchical galaxy formation, the initial collapse and continuing accretion of gas-rich fragments produces and maintains an extended halo of diffuse, hot gas surrounding galaxies (White & Rees 1978; White & Frenk 1991). This gaseous halo fills the dark matter potential and is roughly in hydrostatic equilibrium out to distances of order the virial radius. The inner, more dense regions cool through thermal brehmsstrahlung and slowly accrete into the central regions of galaxies. In the Milky Way, this scenario predicts gas at a temperature $T_h \sim 10^6$ K at distances $R \gtrsim 50$ kpc from the Galactic center.

It is difficult to identify this gas directly from X-ray observations because of the difficulty in determining distances (Snowden 1998). Consequently, although it is clear that there is a diffuse background in the 0.1–2.0 keV range, it is very difficult to determine how much of the emission is local (within a few hundred parsecs), from an extended halo, or extragalactic in origin (Snowden 1998; Snowden et al. 1998). Although most of the emission at 0.25 keV does arise locally (Snowden et al. 1998), most at 0.75 keV does not. This component presumably contains emission originating in the Galactic halo and in extragalactic sources—however, the relative contributions are poorly constrained. Searches for extensive X-ray halos around local, late-type galaxies have also proved unsuccessful. Benson et al. (1999) examined archival *ROSAT* images of three nearby, massive spiral galaxies but detected no emission and established upper limits that are far below the predicted luminosities (White & Frenk 1991; Kauffman, White, & Guideroni 1993; Cole et al. 1994).

Given the difficulty of observing this gas directly, it is useful to infer its existence and properties indirectly. Some of the best evidence comes from the metal absorption lines associated with galaxies seen in quasar spectra (Bahcall & Spitzer 1969; Steidel 1998) and also seen in high-velocity clouds in the Milky Way (Sembach et al. 1999). The Magellanic Stream offers another potential probe of hot gas in the Milky Way halo. The Stream is a long H I filament, apparently trailing the Magellanic Clouds (Jones, Klemola, & Lin 1994) and mostly confined to discrete clouds, which have properties very similar to those of other high-velocity clouds (Wakker & van Woerden 1997; Blitz et al. 1999). Because the Stream will interact with ambient halo gas, its observable characteristics should constrain the properties of the diffuse medium.

Early on, Mathewson, Schwarz, & Murray (1977) proposed that the Magellanic Stream represents the turbulent wake of the Magellanic Clouds as they pass through a diffuse halo medium; however, Bregman (1979) identified a variety of observational and theoretical difficulties with this model and concluded that the tidal stripping model (Murai & Fujimoto 1980; Lin & Lynden-Bell 1982; Gardiner & Noguchi 1996) provides a better explanation. Moore & Davis (1994) modified the gas-dynamic model to include stripping by an extended ionized disk and drag by a diffuse halo: their model matches the Stream kinematics well by incorporating drag from a diffuse gas distribution at 50 kpc that satisfies all known limits. However, the model remains controversial (e.g., Wakker & van Woerden 1997), so that inferences about halo gas properties are correspondingly uncertain.

In the present Letter, we reconcile these competing views of Magellanic Stream formation and, in doing so, establish limits on the density of diffuse gas at the current distance of the Magellanic Clouds. In brief, we show that the motion of individual Stream clouds through ambient, ionized gas is dominated not by drag, but by strong heating from accretion. The accretion of ambient gas heats the cloud through thermalization of the bulk flow and through the ionic and electronic enthalpy of accreted gas. Weak radiative cooling leads to mass loss and cloud evaporation. Requiring cloud survival indicates that only the tidal stripping model for the Magellanic Stream is viable. Furthermore, the survival requirement places strong limits on the density of ionized gas in the halo. The constraint is roughly an order of magnitude lower than previously inferred. Discussion of the cloud-gas interaction and the survival constraint is presented in § 2. The implications are examined in § 3.

2. LIMITS ON HALO GAS

The Magellanic Stream is concentrated primarily in a bead-like sequence of six discrete clouds at high Galactic latitude (Mathewson et al. 1977). The cloud MS IV is located near the "tip" of the stream at $l = 80°$, $b = -70°$, roughly 60° across the sky from the Magellanic Clouds (Cohen 1982). The mean H I column density $N_{\rm H\,I} = 6 \times 10^{19}$ cm^{-2} (Mathewson et al. 1977), which is intermediate between the denser clouds that lie close to the LMC and the more diffuse clouds at the very tip of the Stream. However, it is also rather centrally condensed with a peak column density of roughly 1.3×10^{20} cm^{-2} (Cohen 1982). The cloud has approximate H I mass $M_c = 4500 \times (d/\mathrm{kpc})^2\ M_\odot$, radius $R_c = 15(d/\mathrm{kpc})$ pc, and temperature $T_c = 10^4$ K as determined from the line widths (Cohen 1982). Assuming a pure hydrogen cloud, the mass and radius give a mean number density $n_c = 0.27(50\ \mathrm{kpc}/d)$ cm^{-3}.

The kinematics and age of MS IV depend on the formation model. In the most recent tidal model (Gardiner & Noguchi 1996), the eccentricity of the Magellanic Clouds is relatively small, so that MS IV, having been tidally stripped at perigalacticon roughly 1.5 Gyr ago and following nearly the same orbit, would have a velocity of 220 km s^{-1} at roughly 50 kpc. In the gas drag model, Moore & Davis (1994) argue that the Stream was torn from the Magellanic Clouds during passage at 65 kpc through an extended, ionized portion of the Galactic disk roughly 500 Myr ago. From a momentum-conservation argument, they deduce an initial velocity of 220 km s^{-1} after separation for MS IV. Additional drag from the ambient halo medium modifies the orbit to give the current radial velocity of -140 km s^{-1} with respect to the local standard of rest at a distance $d \sim 20$ kpc. The transverse velocity is unspecified but must be large ($\sim$340 km s^{-1}) because even a total velocity of $\sim$300 km s^{-1} implies that the orbital energy has diminished by 10^{54} ergs since separation. The dissipated energy heats the cloud, which has thermal energy $E_c = 3/2 M_c/m_p k T_c \approx 10^{51}$ ergs at 20 kpc—roughly 0.1% of the input energy; the cloud must therefore evaporate. However, as the analysis below shows, if we adopt lower bounds on the velocity and age of MS IV, $V_c = 220$ km s^{-1} and $t = 500$ Myr, we obtain an upper limit on the gas density at 50 kpc that is lower than that required to give the drag in the Moore & Davis (1994) model.

In addition to the short evaporation timescale, it is difficult to accept the smaller distance to MS IV because at 50 kpc the cloud temperature, mass, and size put it approximately in virial equilibrium, which naturally explains its centrally condensed appearance. At 20 kpc, the cloud should be unbound and rapidly expanding unless confined by a strong external pressure.

The parameters of the halo gas at either distance are rather uncertain. Following current galaxy formation models (e.g., White & Frenk 1991), we assume that the gas is in quasi-hydrostatic equilibrium in the Galactic potential. The estimated temperature of the halo $T_h = 2.9 \times 10^6$ K for an isothermal halo with rotation speed $V_0 = 220$ km s^{-1}. This implies that the sound speed $c_h = 200$ km s^{-1}. Halo gas at this distance may rotate with velocities on the order of 10–20 km s^{-1}, leading to a small reduction in its temperature or density. The rotation would have little influence on the Stream-gas interaction, since gas rotation would be aligned with the disk while the Stream travels on a nearly polar orbit.

Previously, the density of halo gas has been estimated by Moore & Davis (1994) using a drag model to account for the kinematics of the Stream clouds. Matching the kinematics of the Stream requires a gas particle density $n_h \sim 10^{-4}$ cm^{-3} at a distance of approximately 50 kpc. As noted above, this approach neglects the energy input into the cloud as it snowplows though the halo medium.[1] As we will show below, heating dominates drag and cloud survival against evaporation sets a much stronger limit on the halo gas density. This argument is similar to that posed by Cowie & McKee (1976) in constraining the density of ionized gas in the intergalactic medium based on the timescale for conductive evaporation of neutral clouds.

2.1. *Energy Input and Mass Loss*

In its rest frame, the total instantaneous internal energy of the cloud is $E_c = T + W$, where T is the total thermal energy and W is the potential energy. The rate of change in energy is determined by energy input and loss:

$$\frac{dE_c}{dt} = \rho_h v_h A\left(\frac{1}{2}v_h^2 + \frac{5}{2}c_h^2\right) - \Lambda n_h n_c V - \dot{M}\left(\frac{1}{2}u^2 + \frac{5}{2}\Delta c^2\right) + \dot{W}. \quad (1)$$

The first term on the right-hand side gives the energy input through the projected surface area $A = \pi R_c^2$ of the cloud's leading edge from halo gas with density ρ_h, streaming velocity v_h, and sound speed c_h, the second term gives the inelastic cooling rate with reaction rate Λ in the volume V at the cloud surface where halo gas at density n_h mixes with cloud material at mean density n_c, the third term gives the cooling from cloud mass loss at surface velocity u and change in enthalpy $5\Delta c^2/2$, where Δc^2 is the change in the square of the cloud sound speed, and the last term gives the rate of change of the potential energy.[2]

In a steady state, $\dot{E}_c \approx 0$ (e.g., Cowie & McKee 1977). As we discuss below, the protons carry roughly two-thirds of the incident energy: all of the energy of bulk flow and half of the enthalpy, which is of the same order. However, at these energies ($\sim$100 eV), proton collisions with cloud H I are dominated by charge transfer: inelastic losses are negligible.[3] Therefore, neglecting $\dot{W}$ heating, we obtain the steady state mass-loss rate

$$\dot{M} = \frac{\rho_h v_h A[v_h^2/2 + 5c_h^2/2]}{u^2/2 + 5\Delta c^2/2}. \quad (2)$$

The mass-loss rate is equal to the accretion rate times the ratio of specific energy input to specific energy outflow. The outflow velocity $u \sim v_e$, the surface escape velocity of the cloud in the tidal field. A typical cloud is loosely bound so that $v_e \sim v_{\mathrm{therm}}$, the thermal velocity of the cloud. The change in enthalpy is of the same order. For MS IV, this implies that the evaporated mass leaves the cloud with $u \sim 10$ km s^{-1} and $T \sim 2 \times 10^4$ K. Figure 1 shows the mass-loss rate for various combinations of relative velocity and ambient gas density. For the minimum relative velocity $v_h = 220$ km s^{-1} and age $t = 500$ Myr defined above, $n_h < 10^{-5}$ cm^{-3} in order for the cloud to survive.

Mass loss is not spherically symmetric as in the evaporation of cold clouds embedded in a hot, diffuse medium (Cowie & Mckee 1977; Balbus & Mckee 1982; Draine & Giuliani 1984). Here the halo gas strongly heats the cloud at the leading edge, causing outflow along this surface and ablation of material from the poles (C. Murali 1999, in preparation); the interaction is analogous to that of comets with the solar wind, also referred to as a *mass-loaded flow* (Biermann, Brosowski, & Schmidt 1967; Wallis & Ong 1975; Galeev, Cravens, & Gombosi 1985).

[1] Although clouds have been modeled as blunt objects (e.g., Benjamin & Danly 1997), the boundary conditions are different. The no-slip and no-penetration boundary conditions are not applicable, since the cloud is permeable. Magnetic fields do not prevent penetration and shear stress because of charge transfer.

[2] Since $W = \int d\boldsymbol{r}\rho\Phi$, $\dot{W} = \int d\boldsymbol{r}(\dot{\rho}\Phi + \rho\dot{\Phi})$. Generally, when the cloud loses mass, $\dot{\rho} < 0$ and $\dot{\Phi} > 0$ while $\rho > 0$ and $\Phi < 0$, so that $\dot{W} > 0$.

[3] Charge transfer at these relative velocities redistributes particle momentum and energy, rather than creating photons (Janev et al. 1987).

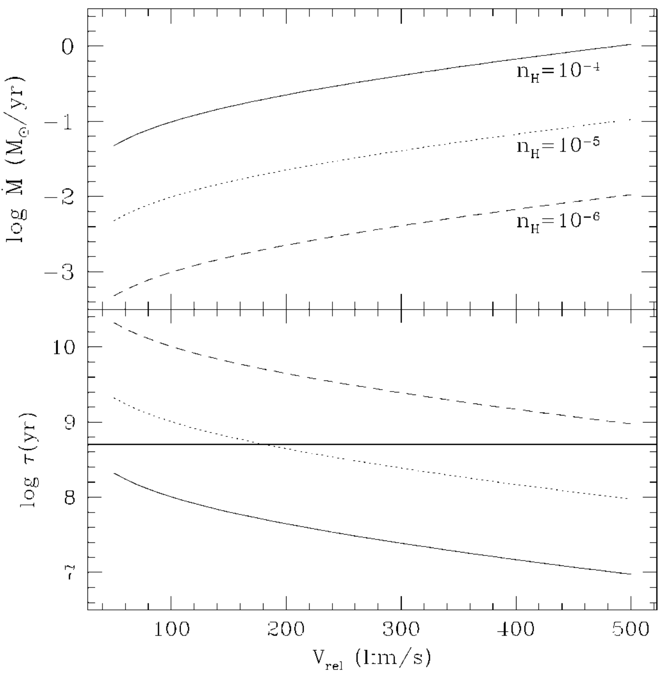

FIG. 1.—Cloud mass-loss rates (*top*) and corresponding lifetimes (*bottom*) as a function of relative velocity for different halo densities. The horizontal line in the lower panel shows the 500 Myr cutoff. Lifetimes shorter than this are unlikely.

Since the flow of halo gas is roughly supersonic, a bow shock may form; however, the shock will be very weak and approximately at or interior to the leading edge of the cloud because of cooling from mass loading (Wallis & Ong 1975). Nevertheless, the morphology may be detectable through sensitive X-ray or EUV observations.

2.2. *Accretion and Drag*

Accretion of mass and momentum has only a small effect on the cloud even though energy accretion is significant. The mass accretion rate

$$\dot{M}_{\rm acc} = \rho_h v_h A, \qquad (3)$$

while the momentum accretion rate

$$\dot{P}_{\rm acc} = \rho_h v_h^2 A. \qquad (4)$$

Note that momentum transfer from accretion is equivalent to drag with drag coefficient $C_D = 2$. At $v_h = 220$ km s^{-1} and $n_h = 10^{-4}$ cm^{-3}, the mass accretion rate $\dot{M} = 9.0 \times 10^{-4}\ M_\odot$ yr^{-1}. For an accretion time of 5×10^8 yr and neglecting mass loss, the cloud accretes $\sim 5 \times 10^5\ M_\odot$—roughly 5% of its initial mass. Momentum transfer through accretion reduces the velocity by roughly 10 km s^{-1}. For $n_h < 10^{-5}$ cm^{-3}, changes in mass and momentum are entirely negligible.

2.3. *Thermalization and Cooling*

Collisions between incident protons and electrons in the inflowing halo gas and target H I in the cloud thermalize the flow and lead to some excitation and radiative cooling. Estimates of the relevant rates can be obtained by considering the cross sections or reaction rates for collisions between the incident and target particles given their densities and typical relative velocity. Because the halo gas is so diffuse, H^+-e^- scattering is unimportant: H-H^+ and H-e^- collisions dominate.

Momentum transfer through charge exchange between protons and neutral hydrogen atoms thermalizes the halo gas flow at the leading edge of the cloud. Recent plasma calculations by Krstić & Schultz (1998) give momentum transfer cross sections $\sigma_{\rm mt}$ at the appropriate energies using the standard method of partial wave expansions to determine scattering amplitudes (e.g., Landau & Lifschitz 1977). For relative velocities $v_h \sim 200$ km s^{-1} or relative energies ∼100 eV, $\sigma_{\rm mt} \sim 10^{-15}$ to 10^{-16} cm^{-2}. Thus the mean-free path into the cloud $\lambda = 1/n_c\sigma_{\rm mt} \sim 10^{16}$ cm for $n_c \sim 0.25$ cm^{-3}.

Cooling does little to balance the energy input into the cloud. Janev et al. (1987) provides a compendium of thermal reaction rates $\langle \sigma v_{\rm rel} \rangle$ as a function of relative energy for excitation, ionization, and recombination (inelastic processes) in a wide range of atomic, electronic, and ionic collisions. Examining these rates shows that radiation arises purely from collisions between electrons in the inflowing halo gas and neutral hydrogen atoms in the cloud. For H-H^+ collisions in a hydrogen plasma at $T = 10^4$ K = 1 eV with $v_h = 200$ km s^{-1}, the reaction rate for any inelastic excitation from ground state is less than 3×10^{-11} cm^3 s^{-1} (Janev et al. 1987, pp. 115–136), which is entirely negligible. Thus, since the halo gas is so diffuse and energy transfer between electrons and protons is minimal, all the proton energy (roughly two-thirds of the total) in the bulk flow heats the cloud; only electron-neutral collisions can produce radiation.

For ground-state excitation and ionization by electrons under these conditions, reaction rates are below 5×10^{-8} cm^3 s^{-1} (Janev et al. 1997, pp. 18–31). Recombination rates are considerably lower: $\langle \sigma v_{\rm rel} \rangle < 10^{-13}$ cm^3 s^{-1} (Janev et al. 1987, pp. 32–33) and cannot be important even after thermalization to the outflow temperature of 1 eV. Thus, for densities of incident particles $n_h \sim 10^{-4}$ cm^{-3} and target particles $n_c \sim 0.25$ cm^{-3} with mean relative velocity of order the electron thermal velocity v_e, which is given by the mean energy 100 eV, the energy lost to inelastic processes

$$\Lambda n_h n_c V = n_h N_c \sum_i \langle \sigma v_{\rm rel} \rangle_i h\bar{\nu} A < 10^{36}\ {\rm ergs\ s^{-1}}, \qquad (5)$$

where $V = A\lambda$ and $N_c = n_c\lambda$, the neutral column density in the mixing layer. The sum over i includes the dominant processes: excitation from $n = 1 \rightarrow n = 2(s, p)$ and from $n = 1 \rightarrow n = 3$ and ionization from $n = 1$ (Janev et al. 1987, pp. 18–27) at a temperature of 100 eV. We take $h\bar{\nu} = 10$ eV and ignore electron cooling (which reduces the amount of radiation produced) over the mean-free path of the protons in the cloud; therefore, the loss rate is an upper limit. After cooling, electrons drop to the thermal velocity of the outflowing gas; the combination of velocity and density are too low to permit any additional inelastic cooling. While the radiation rate is substantial, it is considerably lower than the total rate of energy input into the cloud, which is of order 10^{38} ergs s^{-1}. Although Weiner & Williams (1996) propose that Hα from the leading edge of MS IV can be produced collisionally when $n_h \sim 10^{-4}$ cm^{-3}, the rate estimated here is considerably lower than measured. This in turn suggests that escaping UV photons from the Galactic disk produce the Hα emission through ionization and recombination (Bland-Hawthorn & Maloney 1999) or possibly through fluorescence.

3. EVOLUTION OF HALO GAS

In current scenarios of galaxy formation, gas in galactic halos should cool interior to some radius r_c which increases with time (e.g., White & Rees 1978; Mo & Miralda-Escudé 1996). For circular velocity $V_0 = 220$ km s^{-1}, $r_c \approx 250$ kpc at the current time. However, given the lack of evidence for cooling flows, it is expected that gas within r_c is heated into a constant entropy core (Mo & Miralda-Escudé 1996; Pen 1999), so that, for $r < r_c$, the halo gas density

$$\rho_h(r) = \rho_h(r_c)\left[1 - \frac{4}{5}\ln\left(\frac{r}{r_c}\right)\right]^{3/2}, \tag{6}$$

where $\rho_h(r_c) = f_g V_0^2/4\pi G r_c^2$ and f_g is the fraction of the total halo mass density in gas. If f_g equals the universal baryon fraction, then $f_g \sim 0.05$ for $\Omega_m = 1$ and $f_g \sim 0.15$ for $\Omega_m = 0.3$, where Ω_m denotes the ratio of total mass density to closure density of the universe. The constraint on the density derived here suggests that $f_g \lesssim 5 \times 10^{-3}$. Within the context of this density model, this discrepancy with the universal fraction leads to the possibility that a considerable amount of gas has cooled and formed stars or dark matter (Mo & Miralda-Escudé 1996) or has been expelled by strong heating (e.g., Field & Perronod 1977; Pen 1999). Ultimately, however, it is not clear that this model properly describes the gas distribution in galactic halos.

4. SUMMARY

We have reexamined the interaction of the Magellanic Stream with ambient gas at large distances in the Galactic halo. Our analysis shows that heating dominates over drag. Therefore, because of their high relative velocities, clouds are prone to evaporation if the ambient gas density is too large. In particular, the requirement that MS IV survives for 500 Myr at 220 km s $^{-1}$ imposes the limit on the density of halo gas at 50 kpc: $n_h < 10^{-5}$ cm $^{-3}$. This upper limit is roughly an order of magnitude lower than the density determined from the drag model of Moore & Davis (1994) and does not concur with current models of the gas distribution in galactic halos.

I am grateful to Mineo Kimura, Hiro Tawara, Predrag Krstić, Neal Katz, Gary Ferland, and Ira Wasserman for discussion, numerous helpful suggestions, and providing data. I am also indebted to the referee for very constructive criticism. This work was supported by NSERC.

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