COOL GAS IN THE MAGELLANIC STREAM

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Received 2008 September 12; accepted 2008 December 19; published 2009 January 13

ABSTRACT

We present the first direct detection of cold atomic gas in the Magellanic Stream, through 21 cm line absorption toward a background radio source, J0119—6809, using the Australia Telescope Compact Array. Two absorption components were identified at heliocentric velocities 218.6 km s\(^{-1}\) and 227.0 km s\(^{-1}\), with optical depths of \(\tau \approx 0.02\). The corresponding H\(\text{i}\) emission region has a column density in excess of \(2 \times 10^{20} \text{ cm}^{-2}\). The inferred spin temperature of the emitting gas is \(\approx 70 \text{ K}\). We failed to find cool gas in observations of three other radio continuum sources. Although we have definitively detected cool gas in the Stream, its spin temperature is higher than similar components in the LMC, SMC, and Bridge, and its contribution to the total H\(\text{i}\) density is probably lower. No corresponding \(^{12}\text{CO}(J = 1 \rightarrow 0)\) or dust appears to be associated with the cool gas, suggesting that the cloud is not forming stars.

Key words: galaxies: formation – galaxies: interactions – Magellanic Clouds – radio continuum: galaxies – radio lines: galaxies

1. INTRODUCTION

The Magellanic System consists of the LMC, SMC, the Magellanic Bridge, which links the two, the Leading Arm, and the Magellanic Stream—a ribbon of gas stretching behind the Magellanic Clouds for \(\approx 100^\circ\) across the sky. Metallicity measurements (Gibson et al. 2000; Lu et al. 1998) confirm the Stream is a low-metallicity environment, less than the Galaxy, M31 and M33, similar to the present day SMC (0.1 solar) and LMC (0.3 solar), but possibly higher than the Magellanic Bridge (Lehner et al. 2008). The formation and evolution of the Stream continues to be a contentious issue within the Magellanic community. The two dominant theories involve ram pressure stripping of LMC or SMC gas on their last passage through the LMC, SMC, and Bridge, and its contribution to the total H\(\text{i}\) density is probably lower. No corresponding \(^{12}\text{CO}(J = 1 \rightarrow 0)\) or dust appears to be associated with the cool gas, suggesting that the cloud is not forming stars.

The presence of cool atomic gas in the Magellanic Stream is often accompanied by molecular cloud condensations, the precursor to star formation. H\(\text{i}\) at 21 cm absorption and emission spectroscopy of the Clouds and Bridge have confirmed the existence of such cold atomic gas (Marx-Zimmer et al. 2000; Dickey et al. 2000; Kobulnicky & Dickey 1999). The detection of CO adjacent to dense H\(\text{i}\) cloudlets in the Bridge (Muller et al. 2003) confirms that molecular cloud formation can occur in relatively tenuous, low-metallicity environments. However, few studies have investigated the presence of cool gas in the Magellanic Stream (Mebold et al. 1991). While the presence of such gas would not in itself indicate the presence of molecular clouds and star formation, it is still a significant step in determining the Stream’s star-forming potential and the degree of fragmentation and collapse of its gas clouds.

The fine-structure lines of C and O (and, to a lesser extent, N, S, and Si) provide the bulk of the cooling and improve the efficiency of star formation in the interstellar medium (ISM). Consequently, the ISM of metal-poor environments such as the Magellanic Stream will experience lower cooling rates, resulting in higher warm–cool gas ratios. Marx-Zimmer et al. (2000) showed that for the LMC the distribution and abundance of cool gas was determined by the local ISM conditions.

Given the apparent absence of dense gas and further dynamical perturbations, the ability for cool clouds to form in the Stream is markedly reduced, unless pressure confinement is significant (Santomigrovic et al. 2002). The warm–cool gas phase mixture is not only dependent on the gas pressure and heavy element abundance, but also on the dust-to-gas ratio and the strength of the interstellar UV radiation field (Wolfire et al. 1995). A lower dust-to-gas ratio reduces shielding of molecules from photodissociation by the intense radiation field, allowing photodissociation fronts to penetrate deeper into clouds (Bot et al. 2007). Wolfire et al. (1995) showed that the range of pressures over which the two-phase medium is possible is narrower and the pressures in that range are higher. The higher pressure results in fewer cool phase regions in equilibrium and may explain the lower cool gas abundance in the SMC and Magellanic Stream. Richter et al. (2001) detected H\(\text{2}\) in the Stream toward the Seyfert galaxy Fairall 9 and suggested that for a Stream lifetime of about 2 Gyr, H\(\text{2}\) could form in situ in small compact cloudlets. Braine et al. (2001) suggest for typical H\(\text{i}\) number densities only a few million years are required to transfer 20% of atomic gas to molecular H\(\text{2}\). Alternatively, Richter et al. (2001) suggest that molecular gas could have survived intact during the host galaxy stripping process; however, Braine et al. (2001) conclude this to be impossible, stating molecular gas in tidal streams is formed from condensing atomic gas and not pre-existing stripped clouds.

The presence of cool atomic and molecular gas would have major implications for the fate of the Stream. Current estimates...
of the mass of the Stream, \( \sim 1.9 \times 10^8 M_\odot \) (Putman et al. 2003), only consider the neutral atomic hydrogen which is not abundant enough for gravitational collapse and the formation of a tidal dwarf galaxy (Braine et al. 2001). Recent numerical simulations (Recchi et al. 2007; Duc & Mirabel 1998) show that tails produced by tidal interaction are subject to fragmentation which may lead to star formation.

In this Letter, we present the successful detection of cool atomic gas in the Magellanic Stream with the Australia Telescope Compact Array (ATCA), and the result of a follow-up search for the \( ^{12}\text{CO} (J = 1 \rightarrow 0) \) transition within the cool cloud with the Mopra telescope. In Section 2, we describe the emission and absorption observations and selection criteria for the four background continuum sources, and in Section 3, we present the results of our investigations and discuss the implications of our results for theories of Magellanic Stream evolution.

### 2. OBSERVATIONS

The H75 configuration of the ATCA was used to observe a 250 deg\(^2\) field of the Magellanic Stream centered on 1420 MHz. The observations were made in the period 2005 July 24–26, 27–30, and August 1–2. The field was sampled with 2618 separate pointings of the ATCA which were grouped into 17 regions, each containing 154 pointing centers. An integration time of 20 s per pointing was used, and each pointing center was visited approximately six times across a 10 hr observing day. The total integration time was therefore 120 s (2 minutes) per day, per pointing. A bandwidth of 4 MHz (corresponding to a velocity range of 840 km s\(^{-1}\)) was used, which was divided into 1024 channels per baseline for each of two polarizations. After Hanning smoothing the velocity resolution was 1.649 km s\(^{-1}\). The rms sensitivity and angular resolution were 0.23 K and 7.4 × 6.2 arcmin\(^2\), respectively.

The primary calibrator PKS B1934–638 was observed as a flux standard at the beginning of each observing day for ~15 minutes and had an assumed flux density of 14.9 Jy at 1420 MHz. PKS B0252–712, used for the secondary (phase) calibrator (5.72 Jy at 1420 MHz), was visited for 5 minutes at the commencement of each observing session and revisited once per hour. Stray-radiation corrected Galactic All Sky Survey (GASS) data (N. McClure-Griffiths et al. 2009, in preparation) were regridded to the same spatial and velocity dimensions as the ATCA data, and the two sets combined in the Fourier plane.

Following the identification of four radio sources in the background of relatively high column density Stream clouds (listed in Table 1), a follow-up search for the 21 cm line in absorption was performed with the ATCA. Two 12 hr observation runs were made on 2007 February 7 and 8 using the 6A km array configuration. The correlator was configured to give a total bandwidth of 4 MHz over 1024 channels, resulting in a velocity resolution of 0.8 km s\(^{-1}\). Only targets with column densities greater than \( \sim 1.5 \times 10^{20} \text{cm}^{-2} \) directly in front of background continuum sources with flux greater than 300 mJy were selected (Figure 1). Two sources were observed daily, each for 30 minutes at 70 minute intervals. At the beginning of both days the primary calibrator PKS B1934–638 was observed for 10 minutes, and before each source a secondary phase calibrator (PKS B0008–421 or PKS B0252–712) was tracked for 5 minutes. All data were reduced following standard procedures using the MIRIAD reduction package. The cleaned maps have a typical rms of 7.5 mJy beam\(^{-1}\) per channel. Three objects (J0053–4914, J0110–6727, J0119–6809) are consistent with point sources at the resolution of our maps (~6 arcsec). J0154–6800 is slightly resolved. Nevertheless, optical depth and spin temperature limits are still obtainable.

The UNSW-MOPS 3 mm spectrometer was used on the Mopra telescope to search for any molecular material that might be associated with the cool absorbing H I. The UNSW-MOPS was configured in the narrow-band mode to perform dual-polarization position-switching observations of the \( ^{12}\text{CO} (J = 1 \rightarrow 0) \) transition at 115.271 GHz. A single pointing at the position of J0119–6809 was observed for 60 hr over the period 2007 October 1–2, 5–6, 8–10. The narrow-band mode configuration provides 138 MHz bandwidth over 4096 channels, resulting in a 360.45 km s\(^{-1}\) velocity range with a resolution of 0.088 km s\(^{-1}\). At the beginning of each session the calibrator was checked using the standard source M17 and showed that the system was stable to within 10% for the entire observing run. Every ~75 minutes, the telescope pointing was recalibrated by observing nearby SiO maser sources RDor and UMon. Pointing corrections were repeated until errors less than 6 arcsec were achieved. During each session system temperatures varied between approximately 420 and 800 K; however, only data obtained with \( T_{\text{sys}} \) less than 700 K were reduced. Data were bandpass-corrected, calibrated, and smoothed over five channels using the ASAP package, resulting in a 3σ brightness temperature of 36 mK and 0.44 km s\(^{-1}\) velocity resolution.

### 3. SPECTRAL ANALYSIS

A 21 cm absorption line was detected toward the continuum source J0119–6809. This is the first detection of cold atomic hydrogen in the Magellanic Stream. From the spectrum shown in Figure 2, it is clear that the velocities of the absorption features at around 220 km s\(^{-1}\) are in good agreement with the emission spectrum velocities which range from 200 to 250 km s\(^{-1}\). This indicates the absorption arises from the same cloud. Two components are clearly identifiable in the absorption spectrum at 218.6 km s\(^{-1}\) and 227.0 km s\(^{-1}\) (Figure 2). A sum of two Gaussians was fitted to the spectrum, and the fit components listed in Table 2. A single Gaussian fit results in residuals that are too large compared with noise.

Upper limits on the H I optical depths were obtained for the three sources without observable H I absorption, and these are

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**Table 1**

| Object       | R.A. (12h00) | Decl. (12h00) | Flux Density (mJy) | \( N_{\text{HI}} \) (10\(^{20}\) cm\(^{-2}\)) | 3σ τ | \( T_B \) (K) | 3σ \( T_i \) |
|--------------|-------------|--------------|--------------------|---------------------------------------------|------|--------|--------|
| J0053–4914   | 00 53 52.1  | -49 14 03    | 743                | 2.2                                         | <0.016 | 5.30   | >330   |
| J0110–6727   | 01 10 46.7  | -67 27 56    | 358                | 3.2                                         | <0.083 | 7.46   | >85    |
| J0119–6809   | 01 19 41.8  | -68 09 34    | 659                | 2.3                                         | -see Table 2- |        |        |
| J0154–6800   | 01 54 24.8  | -68 00 41    | 355                | 2.4                                         | <0.054 | 5.02   | >90    |

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\(^4\) The Australia Telescope Compact Array is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO.
listed in Table 1. Table 1 also lists the relevant source information. Although not representative of a physical temperature (since both the warm and cool components are present in any one channel), spin temperature \( T_s \) provides a means of estimating the temperature of the Stream’s cold absorbing gas. Mebold et al. (1991) use the emission brightness temperature and maximum optical depth of associated emission/absorption components to determine an upper limit for the cloud temperatures Table 1. For the central velocity \( (v_0) \) of each component, the spin temperature is defined:

\[
T_s(v_0) = \frac{T_B(v_0)}{(1 - e^{-\tau(v_0)})}
\]  

(1)

where \( T_B \) is the brightness temperature of the emission, and \( \tau \) is the optical depth of the absorption feature. The calculated spin temperatures for components 1 and 2 are 79 ± 9 K and 68 ± 6 K, respectively (Table 2). These temperatures are low, and are an indication of the presence of at least some cool gas in the Stream. Nevertheless, the temperatures are higher than similar measurements in the Magellanic Bridge (20–40 K) by Kobulnicky & Dickey (1999), the LMC (30–40 K) by Mebold et al. (1997), and the SMC (20–50 K) by Dickey et al. (2000). The column density of the surrounding warm H\(_i\) is similar to the column densities of the warm neutral envelope measured by Kobulnicky & Dickey (1999) \((N_{\text{H}i} \geq 10^{20} \text{ cm}^{-2})\). Due to possible turbulent motions and warm gas components, the temperature deduced from linewidth alone is much higher than the spin temperature.

Table 2

| Peak | \( v_0 \) (km s\(^{-1}\)) | Height \((1 - e^{-\tau})\) (km s\(^{-1}\)) | FWHM (km s\(^{-1}\)) | \( T_B \) (K) | \( \tau \) | \( T_s(v_0) \) (K) |
|------|-------------------|-----------------|-----------------|--------|------|-----------------|
| 1    | 218.6             | 0.043 ± 0.005   | 4.19            | 3.38   | 0.044 | 79 ± 9          |
| 2    | 227.0             | 0.051 ± 0.005   | 5.03            | 3.49   | 0.052 | 68 ± 6          |

Initial observations of molecular gas in the Bridge by Smoker et al. (2000) failed to detect \(^{12}\)CO\((J = 1 \rightarrow 0)\) down to
we successfully detected cool atomic hydrogen with a spin temperature of ~70 K at the location J0119–6809. A follow-up search for molecular gas with the Mopra telescope failed to make a detection down to the resolution limit implying star formation could not be occurring in this region of the Stream. Only high H I column density clouds (2 × 10^{20} cm^{-2}) were chosen for this investigation. Most Stream Clouds are much more tenuous than this, leading us to conclude that star formation is not presently an active process in the Magellanic Stream.

We thank Naomi McClure-Griffiths for access to the preliminary GASS data used in Figure 1. D.M. thanks Annie Hughes for very helpful discussions.

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