HIGH-RESOLUTION OBSERVATIONS OF THE MAGELLANIC STREAM

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ABSTRACT

The Magellanic Stream consists of a stream of gas stretching from the Magellanic Clouds, which extends well into the northern hemisphere. Except for small regions, existing observations of neutral hydrogen (HI) in the Magellanic Stream have only been made at relatively low angular resolution (~14 arcmin or larger). In this paper, we present our initial study of the Magellanic Stream at higher resolution using the Australia Telescope Compact Array (ATCA)\(^{1}\). To overcome the “short-spacing” problem inherent with interferometer observations, we combine our data with recent Parkes data to allow the first detailed HI study of the important region at the head of the Stream, where it peels away from the Magellanic Bridge and Small Magellanic Cloud. Over a region of area 140 deg\(^2\), we are able to fully image all structures with spatial scales in the range 0.1 to 2 kpc. In this paper, we present a preliminary analysis of the morphology of the gas distribution.

INTRODUCTION

The redistribution of neutral atomic gas through intergalactic space, by gravitational interactions between galaxies, has long been observed in the form of bridges and tidal tails. The debris produced in these interactions may form new dwarf galaxies, variously known as tidal dwarf or proto-galaxies, which later collapse to form stars. Star-forming regions and molecular clouds have been discovered in the tidal tails of a number of interacting galaxies, for example NGC 3077 a member of the M81 triplet [1], supporting this mode of galaxy formation.

The Large and Small Magellanic Clouds (LMC and SMC) are gas-rich dwarf galaxies that form an interacting system with the Milky Way, enabling investigations of galaxy interaction and, potentially, galaxy formation at our very doorstep. Three gaseous features, the Magellanic Bridge, the Magellanic Stream and the Leading Arm (LA), are the stunning products of this three-way interaction [2]. These gaseous features are connected, and their morphology and velocity field contains important information on the orbital and interaction history of the Clouds. The Magellanic Bridge is a high column density gas stream connecting the stellar bodies of the SMC and LMC. The Leading Arm [3] protrudes from the Bridge and the LMC and leads the space motion of the clouds. Both features exhibit clumpy and filamentary gas morphology. Perhaps the most magnificent of the three, the Magellanic Stream, is a coherent structure emanating from the Bridge and the SMC and extends 100º across the sky, into the northern hemisphere. The gas complexes associated with the Stream make up a large fraction of the high-velocity HI concentrations known as High-Velocity Clouds (HVCs). HVCs do not fit into classical models of Galactic rotation and fall in the velocity range |\(v_{lsr}\)| = 90 – 400 km s\(^{-1}\) (see [4]).

The Stream was first described in [5] and has more recently been investigated by the 21-cm multibeam receiver on the Parkes 64-m telescope [2, 6, 7, 8]. Assuming a distance of 55 kpc, the total mass of the Stream is 4.9 x 10\(^8\) solar masses [8]. The filamentary web at the head of the Stream probably represents freshly-stripped material. Although details of the mechanism driving this gas remain uncertain, huge amounts of gas are emerging from this interface region [8]. The distribution of the gas in this region is very different to that of the Stream, forming a complex web in position-velocity space. The gas appears to be confined to two narrow filaments, although isolated clouds extend over 20º from either side of the

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main Stream. The narrow filaments may also form a helix-like structure, possibly representing the orbital history of the Magellanic Clouds [2].

The formation and evolution of the Magellanic Stream is crucial to understanding the formation and evolution of the Milky Way and Local Group. The gas still contained within the Magellanic System will accrete onto the Milky Way on timescales of a few Gyr and will largely drive the future evolution of the Milky Way and its satellite population. However, simple questions such as whether the Magellanic Stream is mainly formed by tidal forces, or whether ram-pressure forces are significant, are surprisingly difficult to answer as they depend on the details of the dark matter distribution of the component galaxies and the gas density in the outer Galactic halo. The discovery of the Leading Arm [3] suggested that tidal forces are the dominant mechanism responsible for the formation of the Stream. However, OVI absorption and Hα emission have been detected in the Stream, indicating an interaction with the Galactic halo [9,10]. The absence of stars in the Stream does not necessarily eliminate tidal models. Some best-fitting tidal models predict the Stream to be almost purely gaseous due to the compactness of the stellar disk of the SMC relative to the tidal radius [11].

In this paper, we present the first observational study of a large region (140 deg²) at the head of the Stream at a resolution better than that provided by the Parkes telescope. This was achieved through a mosaic of 924 pointings with the Australia Telescope Compact Array (ATCA), combined with recent Parkes observations from [8]. The Parkes data “fills in” the short baselines missing from the ATCA observations. This paper presents the initial results from this survey. Future papers will present data from a wider region and at higher still angular resolution.

**OBSERVATIONS**

The H75 configuration of the ATCA was used to observe a 250 deg² field of the Magellanic Stream and Interface Region in the 21-cm line of neutral Hydrogen. The observations were made in the period 2005 July 24-26, 27-30 and August 1-2. The field was further separated into 17 regions, each containing 154 pointing centres. An integration time of 20 sec per pointing was used, and each pointing centre was visited ~6 times across a 10 hour observing day. The total integration time was therefore 120 sec (2 min) per day, per pointing. An example of the sampling in the uv-plane is shown in Figure 1.
for the central pointing (no. 77) of region 7. 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 polarisations. The observing frequency was centred on 1420 MHz. The resulting velocity resolution is 1.649 km s\(^{-1}\), after Hanning smoothing. The rms sensitivity is 0.1 K, and the angular resolution is 7.4 x 6.2 arcmin\(^2\). The primary calibrator PKS 1934-638 was observed as a flux standard at the beginning of each observing day for ~15 min and had an assumed flux density of 14.9 Jy at 1420 MHz. PKS 0252-712, used for the secondary (phase) calibrator (5.72 Jy at 1420 MHz), was also visited at the commencement of each observing session, for 5 min and revisited once per hour.

The processing and reduction of the ATCA visibility data, and construction of the final image cube was performed in the MIRIAD data reduction package. The data were processed in a standard manner with deconvolution of the line cubes being performed using the maximum-entropy algorithm MOSMEM.

Generally, interferometers provide high spatial resolution imaging for small-scale structure, whereas single dishes are used to image large-scale structures. However even the most compact interferometer configurations suffer from the “short-spacing problem” arising from the fact that the shortest interferometer baseline determines the large spatial scales able to be imaged. The baseline projections of a 2-D array of an Earth-tracking interferometer (such as the H75 ATCA configuration) onto the u-v plane, traces a series of non-concentric ellipses. Each baseline traces a different ellipse producing an ensemble of ellipses (known as the “Sampling Function”) indicating the spatial frequencies measured by the array [12]. While the mosaicing process effectively reduces the shortest projected baseline by around half the diameter of an individual antenna, the u-v plane still suffers if significant large-scale structure is present [13]. Consequently, imaging of the ATCA data alone results in many of the commonly observed artefacts, including negative “bowls” around emission regions and negative and positive sidelobes ([13] and references therein).

Parkes observations of the Magellanic Stream are particularly useful for combining with the ATCA data to supply the missing short-spacing data. The diameter of the Parkes telescope significantly exceeds the shortest ATCA baseline available of 30.6 m. Previous observations [7, 8] used the inner seven beams of the 21-cm multibeam facility of the Parkes telescope to make narrow-band observations of the entire Magellanic System. This data was therefore regridded to the same spatial and velocity dimensions as the ATCA data and Hanning-smoothed to the same velocity resolution using the REGRID task. The two data sets were then combined using the task IMMERGE, which scales the Parkes data by comparing real and imaginary parts of the ATCA and Parkes data in an annulus of the Fourier plane which is common to both. The two data sets were then added linearly so the combined amplitude-spatial frequency response curve returns to a Gaussian form, with equal width to that of the ATCA data.

RESULTS

Fig. 2 is an image, in RA-Declination coordinates of the combined data cube showing the column density of the HI emission in the observed region, over a velocity range 156 to 245 km s\(^{-1}\). Filaments, clumps, and diffuse clouds dominate the region. The SMC is clearly visible in the bottom right corner of Fig. 2 (RA 1\(^{h}\) 20\(^{m}\), Dec -72\(^{\circ}\) 24\(^{\prime}\), J2000) with the highest column densities being around 7.4 x 10\(^{19}\) atoms cm\(^{-2}\), a factor of ~300 times higher than the faintest regions visible in this figure. Although a velocity analysis of the gas surrounding the Stream has not been done, the structure of the emission in Fig. 2 appears to support findings [8] that high-velocity gas is currently leaving the SMC and Bridge. It is evident from Fig. 2 that less gas is being pulled from the eastern edge of the SMC.

There is no clear border from which the Magellanic Stream can be separated from the Interface Region. Reference [8] defines the border by the gap near (l, b) = (300\(^{\circ}\), -61\(^{\circ}\)) or (RA, Dec) = (01\(^{h}\) 02\(^{m}\), Dec -56\(^{\circ}\) 04\(^{\prime}\)) (J2000). This lies slightly to the north of the region presented here, meaning that the entire region presented here corresponds to the Interface Region (plus some of the Bridge and the SMC). However, much of the ‘downstream’ structure is already visible here, with a clear separation of the Stream into two main filaments starting at a common position near (RA, DEC) = (01\(^{h}\) 50\(^{m}\), Dec -69\(^{\circ}\) 20\(^{\prime}\)) (J2000). The main filaments then run north in Fig.2 at RA 01\(^{h}\) 10\(^{m}\) and 01\(^{h}\) 50\(^{m}\) (J2000). The filaments are separated by ~5\(^{\circ}\) and both point in the direction of the South Galactic Pole, which lies north (in the celestial sense) of the region presented here. The HI column density has been estimated to be N\(_{\text{H}}\) = 1–2.5x10\(^{20}\) cm\(^{-2}\) at the beginning of the Stream, decreasing to N\(_{\text{H}}\) = 1.5–3x10\(^{19}\) cm\(^{-2}\) in the more diffuse filaments [2]. The general tendency is for the filaments to become smoother and more tenuous to the
north. The main filaments appear to have a tenuous filamentary connection at Dec -65°. This connection gives the outflow a ‘bubble-like’ appearance. This is probably unrelated to the helical morphology previously hypothesised [2] for the Stream, as the data presented here only represents ~10% of its length. Again, a velocity analysis may elucidate the origin of this structure.

Many compact, high column-density clouds are observed at the head of the Stream, near the SMC. Whether these clouds are formed in-situ by fragmentation in large-scale shocks, or whether they are pulled off the SMC in this form and later evaporate due to internal pressure, low self-gravity and tidal stretching, remains to be seen from detailed studies. Numerical simulations [10] suggest an extraordinarily wide range of distances of the clouds in this region of between 30 and 80 kpc. However, noticeably absent in Fig.2 are the head-tail structures observed [7, 14] in many of the clouds in the Stream. This absence may indicate the short time available for interaction with the Galactic halo for these clouds, unlike for other clouds in the Stream [15]. Some clouds in Fig.2 are well-separated from the main Stream – e.g. at RA 00h 41m, Dec -62° 27' (J2000). These clouds are diffuse and appear to be part of the much larger Interface region defined in [8].

Fig. 2. HI column density map of Region 1 from the ATCA survey of the Magellanic Stream. The velocity range encompassed here is \( v_{\text{LSR}} = 156\text{--}245 \text{ km s}^{-1} \).
CONCLUSION

A preliminary analysis of the morphology of the gas in the Interface Region has been presented. The combined interferometer and single-dish data set has enabled a study of the large-scale features of the Magellanic Stream gas at the highest resolution to date. The bifurcation of the main filament is visible from the beginning of the Stream, as well as compact high-density clouds and a ‘bubble-like’ structure to the gas flowing from the SMC and Magellanic Bridge. Further analyses will be conducted to investigate the morphology and dynamics of this gas and the entire observed Stream.

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