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AN Hα SURVEY OF THE SMALL MAGELLANIC CLOUD WITH WISCONSIN Hα MAPPER

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Abstract

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1. INTRODUCTION

The Small Magellanic Cloud (SMC) is a nearby dwarf irregular galaxy with a gas rich interstellar medium (ISM). As a member of a three galaxy system, the Large Magellanic Cloud, Small Magellanic Cloud, and the Milky Way, the SMC has undergone interactions which have resulted in an extended envolope of neutral gas(Gardiner et al. 1994; Gardiner & Noguchi 1996; Besla et al. 2007). The extent of the HI evelope has been thoroughly studied (Hindman et al. 1963; Stanimirovic et al. 1999; Bruens et al. 2005; Kalberla et al. 2005; Nidever et al. 2010), with the total neutral gas mass measured at 4.0 x 10^8 M_{sun} Bruens et al. (2005). However, studies of the ionized portion of the gas have been primarily limited to HII regions, supernovae remnants, and large filamentary structures(Le Coarer et al. 1993).

As is apparent from our own Milky Way's warm ionized medium (WIM), ionized gas is pervasive beyond the denser structures observed in a galaxy (HII regions/supernovae remnants/filaments) (Hill et al. 2012). In the Milky Way, the WIM has a filling factor of ∼30% (Reynolds 1977; Berkhuijsen 1998; Berkhuijsen et al. 2006), with emission visible in every direction. It is pervasive throughout the galaxy, which lends insight into the source of ionizing photons that power the WIM. Miller & Cox (1993), Dove & Shull (1994), and Dove et al. (2000) suggest that radiation from early-type stars leaked through the cold H I clouds where they formed, ionizing a warm neutral medium throughout the galaxy. McKee & Ostriker (1977) proposed that, instead of a warm medium ionized by young stars, the WIM could be the result of the surfaces of neutral clouds embedded in a hot medium. However, it is difficult to get a complete census of possible ionizing sources into the MW due to our location. Galaxies like the SMC give us a chance to explore these scenarios while having a thorough overview of the structure of a galaxy and the collective sources of ionization.

Magellanic irregular galaxies are similarly expected to have a high ionization fraction of their interstellar gas. However, few studies have been conducted investigating the WIM (referred to as diffuse ionized gas (DIG) outside the MW) in dwarf galaxies. There are a limited number of studies of the DIG which used aperture photometry to measure Hα emission (Hunter & Gallagher 1990, 1992; Hunter et al. 1993). Hunter (1990) found that 15%-20% of Hα emission in dwarf irregular galaxies is from the diffuse ionized medium. Unlike the Milky Way, constraining the filling factor and densities of Hα emitting gas in these galaxies is difficult, so the total ionization fraction of the galaxies could not be determined. Using assumptions of the properties of the DIG, they suggest that diffuse material is the dominant form of ionized gas in dwarf irregulars. However, these surveys focused more on the bright structures within the galaxies than the faint portion of the DIG. This restriction to brighter structures is due to the difficulty in detecting the DIG in dwarf irregulars. The prior studies listed were at the detection limit of their telescopes. Hunter (1993) took deep Hα images of 51 irregular and amorphous galaxies, detecting emission down to a few Rayleighs for the more nearby galaxies. The COS/UVES Absorption Survey by Fox et al. (2013) pushed the limit much lower, detecting ionized gas associated with the Magellanic Cloudss at much lower column densities (∼10%). However they were limited to 69 AGN's located near the Magellanic System and along the Stream. WHAM is able to probe fainter gas than Hunter (1993), down to a few mR, and cover the entire SMC region. A study of the nearby Magellanic Bridge revealed that diffuse ionized gas should trace the neutral component, and may extend several degrees beyond the neutral boundaries. Additionally, the study suggested an upper boundary of 50% ionization of the gas within the Bridge systemBarger et al. (2013). If similar conditions exist within the SMC, then a large fraction of the gas has gone undetected by previous studies.

To determine if the SMC has a similar high ionization fraction as predicted by the Bridge study, we present an Hα emission survey of the SMC using the Wisconsin Hα Mapper (WHAM) observatory. Section 2 includes a description of the WHAM and the Hα observations. Section 3 covers the data reduction process, which includes the velocity calibration and the removal of atmospheric line. We present the non-extinction corrected Hα intensity map of the SMC in Section 4 and discuss the differences and similarities of the Hα and H I emission. In Section 5, we compare the behaviors of the Hα and H I gas, including their emission levels and velocity distributions. We investigate the total mass of the SMC by addressing the distribution of neutral and ionized gas in Section 6. We list our major conclusions in Section 7.

2. OBSERVATIONS

The WHAM facility was specifically designed to study faint optical emission lines from diffuse sources. Hα emission is produced through a recombination of an electron with a proton. The intensity of the line is dependent on the integrated electron density squared, also known as the Emission Measure. As a result, these lines are very weak in low-density ionized gas and an instrument with high sensitivity is necessary to observe them. Previous studies listed in Section 1 detected Hα with lower limit emission measures of 0.1-0.41 R. However, these studies were limited to the central star region of the SMC. WHAM is sensitive down to about 20 mR, limited primarily by foreground atmospheric lines. WHAM is specialized to detect faint, optical emission from diffuse ionized sources with a sensitivity of a few hundredths of a Rayleigh. The spectrometer, described in detail by Haffner et al. (2003), consists of a dual-etalon Fabry-Perot spectrometer that produces a 200 km s−1 wide spectrum with 12 km s−1 velocity resolution from light integrated over a 1○ beam.

WHAM is composed of a dual-etalon Fabry-Perot spectrometer with a 0.6 m siderostat. In WHAM's normal spectral mode, it has a 1° field of view on the sky and a 12 km/s spectral resolution. This setup produces a spectrum that reflects the integrated emission within the beam and not of individual sources such as stars. WHAM's spectral resolution is well-matched to the typical Hα lines from diffuse ionized gas, which typically have FWHM of $\geq$ 20 km/s. A 30-second exposure can achieve a signal-to-noise of 20 for a 0.5 R line with a width of 20 km/s.

Observations of the SMC were taken from October 1st, 2010, and Januart 5th, 2011 by Kat Barger and Alex Hill. We fully sampled the Hα emission of the SMC with WHAM at an angular resolution of 1° and a velocity resolution of 12 km s^{-1} over the local standard of rest (LSR) velocity range 50 to 250 km s^{-1} from (l , b) = (289.5° , − 35.0°) to (315.1°, − 55.3°).

Observations are grouped into "blocks" of 30–50 Nyquist sampled pointings of the entire SMC at 0.5° spacings. These observations were taken at Cerro Tololo Inter-American Observatory. Each single observation had an exposure time of 30 s, with total observation times of a single block ranging from 15-30 minutes. Keeping exposure times short reduces the variations observed in atmopsheric lines.

2.1. *Data Reduction*

To reduce the data, we used the ring-summing and flatfielding procedures described in Haffner et al. (2003). After the data was ring summed, we callibrated the Hα velocities using atmopsheric lines, subtracted the atmospheric emission, and callibrated the night to night tramission variations to normalize the data.

2.2. *Velocity Callibration*

The spectra are inittialy pre-processed, ring-summed, and flat fielded. This leaves the spectra in 2 km s-1 bins over a 200 km s^{-1} window. The OH line at v_{geo} = +272.77 km s^{-1} dominates the edge of the velocity window. We use the OH line in combination with an estimated velocity shift based on the velocity window tune. This velocity offset is then added to the spectra. Due to the velocity frame not including the entire OH line, there is some uncertianty over the corrected velocity. However, by comparing the estimated velocity from the spectrometer tune with the expected velocity from the OH line, we reduce our uncertianty.

2.3. *Removing Atmospheric Emission*

The bright OH line contaminates the spectra at +260 vgeo +290 km s−1. As a result, this line does occasionally overlap with the Hα emission features close to SMC velocities. Fainter atmospheric emission is present below $\sim$ 0.1 R at all velocities in this survey. The removal of both the bright and faint atmospheric lines is crucial for detecting the faint Hα emission between the Magellanic Clouds. To remove the atmospheric contamination, we must remove the background continuum, the bright atmospheric lines, and the faint atmispheric lines.

2.3.1. *Background Subtraction*

The background continuum emission can be assumed to be flat over all velocities. The baselines are well behaved over the velocity range of this survey, except when contaminated by emission from bright foreground stars. When a foreground star is present, the spectra becomes distorted and creates an elevated, non-linear background with absorption lines. Beams that contain stars with $m_V < 6$ ($\sim$ 9%) within a 0.55 radius are excluded from this survey to minimize this foreground contamination and are replaced with an average of the uncontaminated observations within 1°.

2.3.2. *Bright Atmospheric Line Subtraction*

The strength of the bright and faint atmospheric lines vary differently throughout the night and over an entire year. The OH line (Meriwether 1989) is produced from interactions between solar radiation and Earth's upper atmosphere and will vary in strength with the direction and the time of the observation. For this reason, the OH line at v_{geo} = +272.44 km s^{-1} is always fitted seperately from the faint atmospheric lines. We removed these lines by fitting a single Gaussian profile convolved with the instrument profile. Two effects alter the shape bright atmospheric lines: (1) The precision in aligning the dual-etalon transmission functions (spectrometer "tuning") can result in very slight night-to-night variations in the instrument profile at a level only detectable in narrow, bright lines. (2) A geocoronal "ghost"—due to an incomplete suppression of a geocoronal line at vgeo = −2.3 km s^{-1} from a neighboring order in the high-resolution etalon (see Haffner et al. 2003)—lies underneath the OH line at vgeo = +272.44

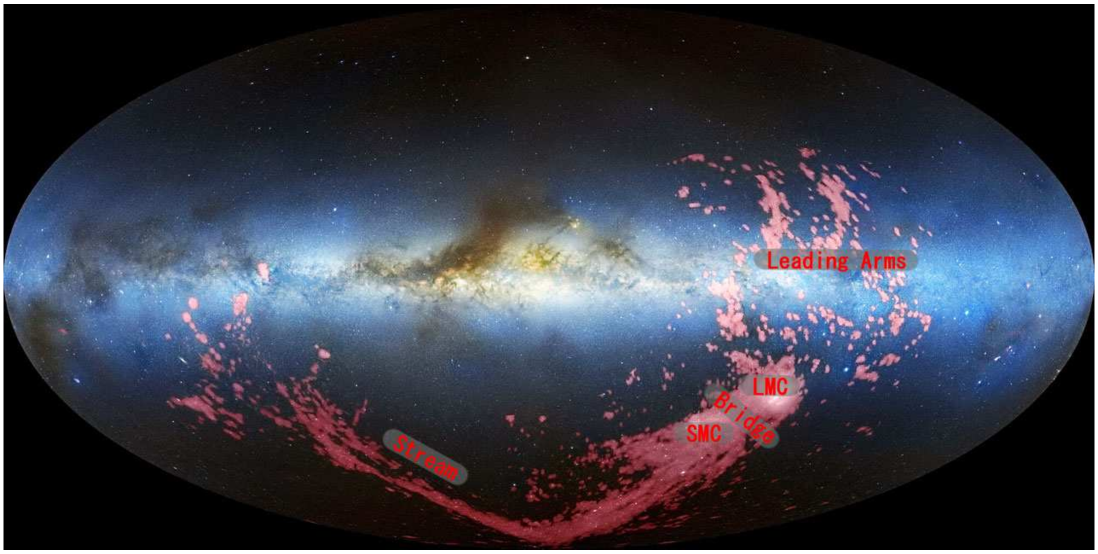

Figure 1. Placeholder figure

km s^{-1}. However, due to the velocity window only containing a portion of the OH line, it is difficult to perfectly fit, especially when SMC emmision may lie underneath the OH line. Removal of some higher velocity SMC emission is unavoidable. To try and minimize removal of SMC emission, we assign a width of 10 km s^{-1}to the gaussian to prevent inclusion of lower velocity emission not attributed to the OH line.

2.3.3. *Faint Atmopsheric Line Subtraction*

While the OH line dominates, faint atmospheric lines are present throughout the entire spectrum. The strength of these faint atmospheric lines changes primarily with airmass. To create a synthetic atmopsheric model, we observed two directions faint in Hα emission multiple times over 10 days to create an average spectrum with a high signal-to-noise ratio. This averaged spectrum consists of numerous 30- and 60-second ob- servations, totaling 4.5 hours of integrated exposure time, towards (l,b) = (60.0, −67.0) and (89.0, −71.0). These are "faint" directions that appear to have no strong Hα emission, so that we can identify atmopsheric lines. These faint lines are characterised in Hausen et al. (2002) and Haffner et al. (2003), with similar characteristics for the faint atmospheric lines near Hα in the northern hemisphere observed towards the Lockman Window. We removed the faint atmospheric lines from the SMC observations by scaling the synthetic atmospheric template to match the atmospheric contamination. This accounts for changes in the flux due to airmass and daily fluctuations. We then subtract the scaled atmospheric template from the observation.

3. THE SMC SURVEY

3.1. *Analysis*

We measure the total Hα emission to estimate the total ionized gas mass of the Magellanic System. We calculate the mass of the ionized gas as $\mathrm{M_{H+} = 1.4 m_H n_e D^2 \Omega L_{H+}}$, where Ω is the solid angle, D is the distance from the Sun, mH is mass of a hydrogen atom, and the factor of 1.4 accounts for helium. The integral of the square of the electron density over the path length of ionized gas is the emission measure (EM), which determines the strength of the Hα emission. The emission measure in its basic form is EM=$\int n_e^2 dl$, however for Hα emission the emission measure can be written as

$$EM = 2.75(\frac{T}{10^4 K})^{0.924}(\frac{I_{H\alpha}}{R})cm^{-6}pc$$

If we then assume that the electron density is a constant, you can rewrite the equation to solve for the line of sight depth.

$$L_{H^+} = 2.75(\frac{T}{10^4 K})^{0.924}(\frac{I_{H\alpha}}{R})(\frac{n_e}{cm^{-3}})^{-2}pc$$

The emission measure can be used to solve for the mass in the beam. From Hill et al. 2009, we can then take into account the 1° beam size and write the mass equation as

$$(\frac{M_{H^+}}{M_{sun}})_{beam} = 8.26(\frac{D}{kpc})^2(\frac{EM}{pc*cm^{-6}})(\frac{n_e}{cm^{-3}})^{-1}$$

where D is the estimated distance in kiloparsecs. The distance to any section of the Stream is uncertain and is very likely not constant along its length. Due to the variation in D, the calculation of the mass of the Stream will be integrated over varying distances. However, we will still be able to obtain an upper and lower limit for the total mass of ionized gas in the Stream based on the estimated range of distances.

4. DISCUSSION AND CONCLUSIONS

4.1. *Future Work*

Regions of the continious SMC gas envelope that were not covered in this survey will be included in the forthcoming Magellanic Stream Survey.

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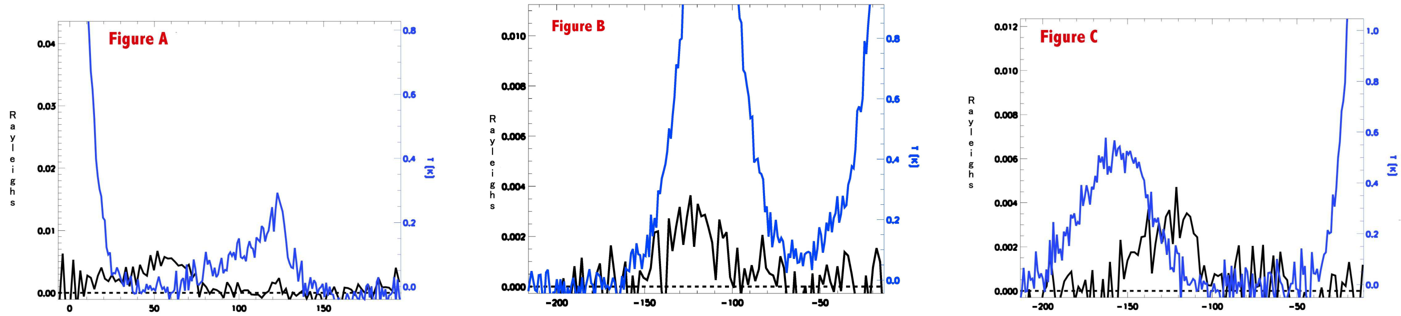

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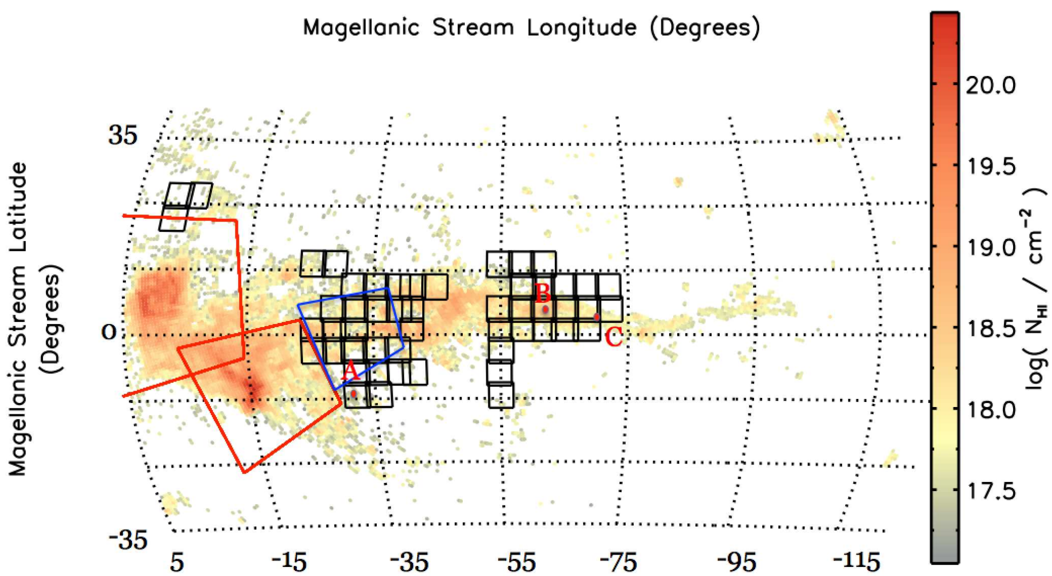

Figure 3. Placeholder

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