

Cannibalization of Dwarf Galaxies by the Milky Way

Distance to the Leading Arm of the Magellanic System

Jacqueline Antwi-Danso¹ and Kat Barger^{1,2}

¹Department of Physics & Astronomy, Texas Christian University, Fort Worth, TX 76129, USA

²Department of Physics, University of Notre Dame, IN 46556, USA

Background

Galaxies form stars from clouds of gas and dust. In the absence of a source of replenishment, large galaxies – like the Milky Way (MW) – deplete their gas reservoirs in a few billion years, far shorter than their lifetimes. Chemical evolution models suggest that the Galaxy has survived by accreting low metallicity gas from the intergalactic medium and dwarf galaxies. Tidal interactions between two dwarf galaxies near the MW, the Large and Small Magellanic Clouds (LMC and SMC), have caused large quantities of gas to be flung into the halo of the MW. Much of this tidal debris, known as the Magellanic System (M_{sys}), is currently headed towards the disk of the MW, spearheaded by the Leading Arm (LA). Estimates for the amount of gas contained in the M_{sys} suggest that it could raise the present star formation rate (SFR) of the Galaxy¹. Unfortunately, its position predisposes it to ionizing radiation from the MW halo and extragalactic background (EGB), hindering gas accretion. The LA, however, appears to have already survived the trip to the disk as its morphology indicates interaction with the interstellar medium (ISM) of the Galaxy. The exact amount of gas that this structure contains is uncertain because of weak constraints in its distance. We made an emission-line study of the H α ionization in the LA and compared the observed with models of the anticipated ionizing flux from the MW and EGB. Based on this, our current best estimate for the distance to the LA at 80° from the LMC is $d \leq 14.8$ kpc from the Sun.

Observations and Reduction

We collected our observations using the Wisconsin H α Mapper Telescope (WHAM) at the Cerro Tololo Inter-American Observatory (CTIO) in Chile. It is currently the best instrument available for detecting faint emission from diffuse ionized sources due to its high-throughput dual Fabry-Perot spectrometer combined with a 0.6-meter objective lens². We made seven pointed H α observations positioned at 75 – 90° from the LMC and SMC and reduced the data with the same On-Off target procedure used in Barger et al. 2015 and the standard WHAM pipeline³. We ignore collisional sources of ionization and photoionization from the Magellanic Clouds (MCs) and propose that if the MW and EGB cause most of the photoionization, then the rate of ionization of the gas is proportional to the rate of recombination of the protons and electrons. The strength of the H α emission will then be proportional to the ionizing flux because the H α transition line arises from recombination. Since our Universe is made of mostly hydrogen, the number of “free” electrons will be approximately equal to that of ionized hydrogen atoms, hence:

$$\phi_{\text{LC}} = 2.1 \times 10^5 \left(\frac{I_{\text{H}\alpha}}{0.1\text{R}} \right) \left(\frac{T_e}{10^4\text{K}} \right)^{0.094} \text{ photons cm}^{-2} \text{ s}^{-1}. \quad (1)$$

We assumed that the gas is optically thick and that $T_e=10^4$ K since H α emission peaks at this temperature.

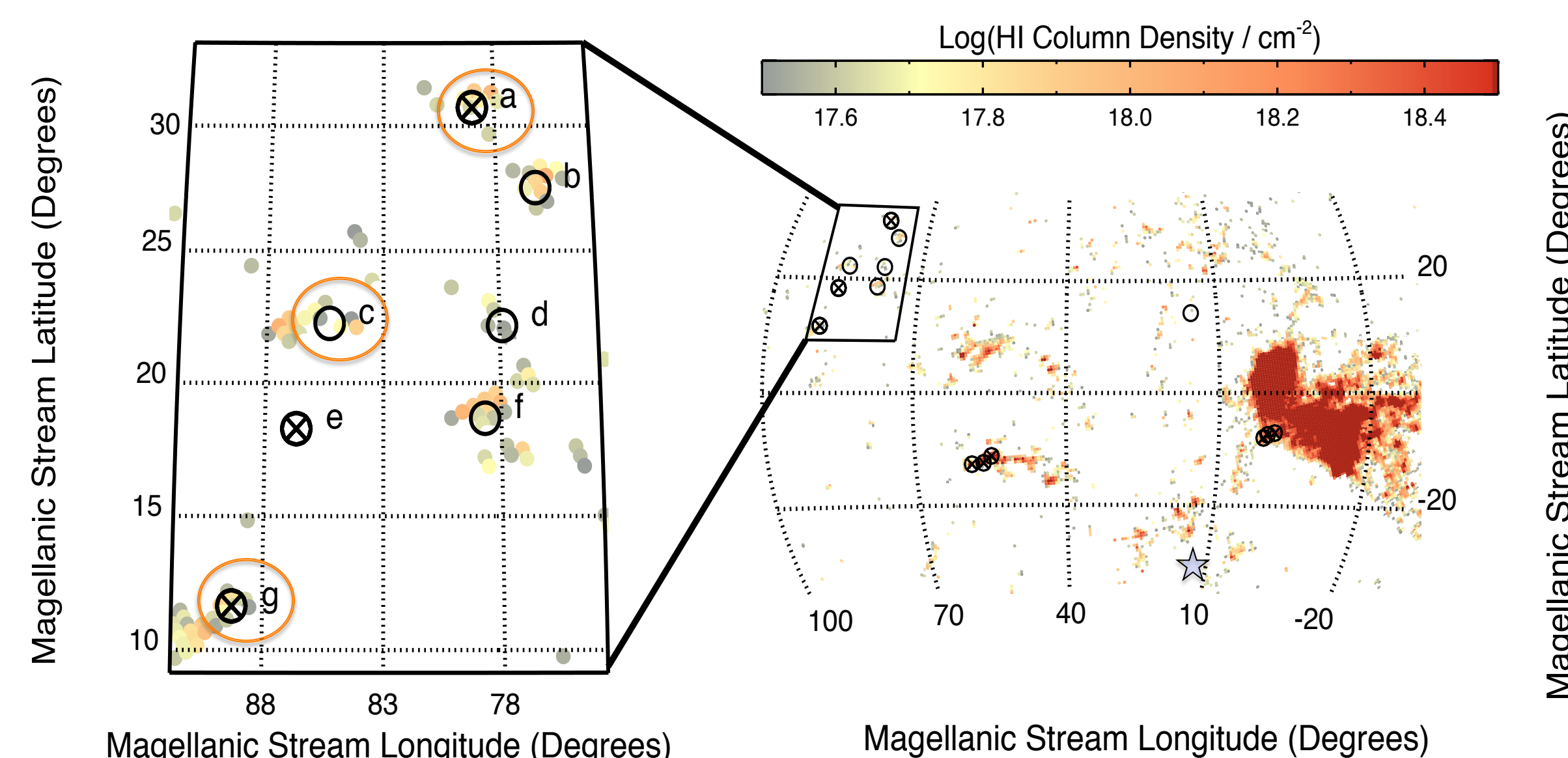


Fig 2. – Locations of H α observations in the LA. Detections are open circles and non-detections are cross-filled circles. The seven WHAM observations presented in this study lie within the black rectangle and are labeled (a-g). Locations with HST/COS observations by Fox et al. 2014 are marked with orange circles. The star marks the location of an O6V star observed by Casetti-Dinescu et al. 2014.

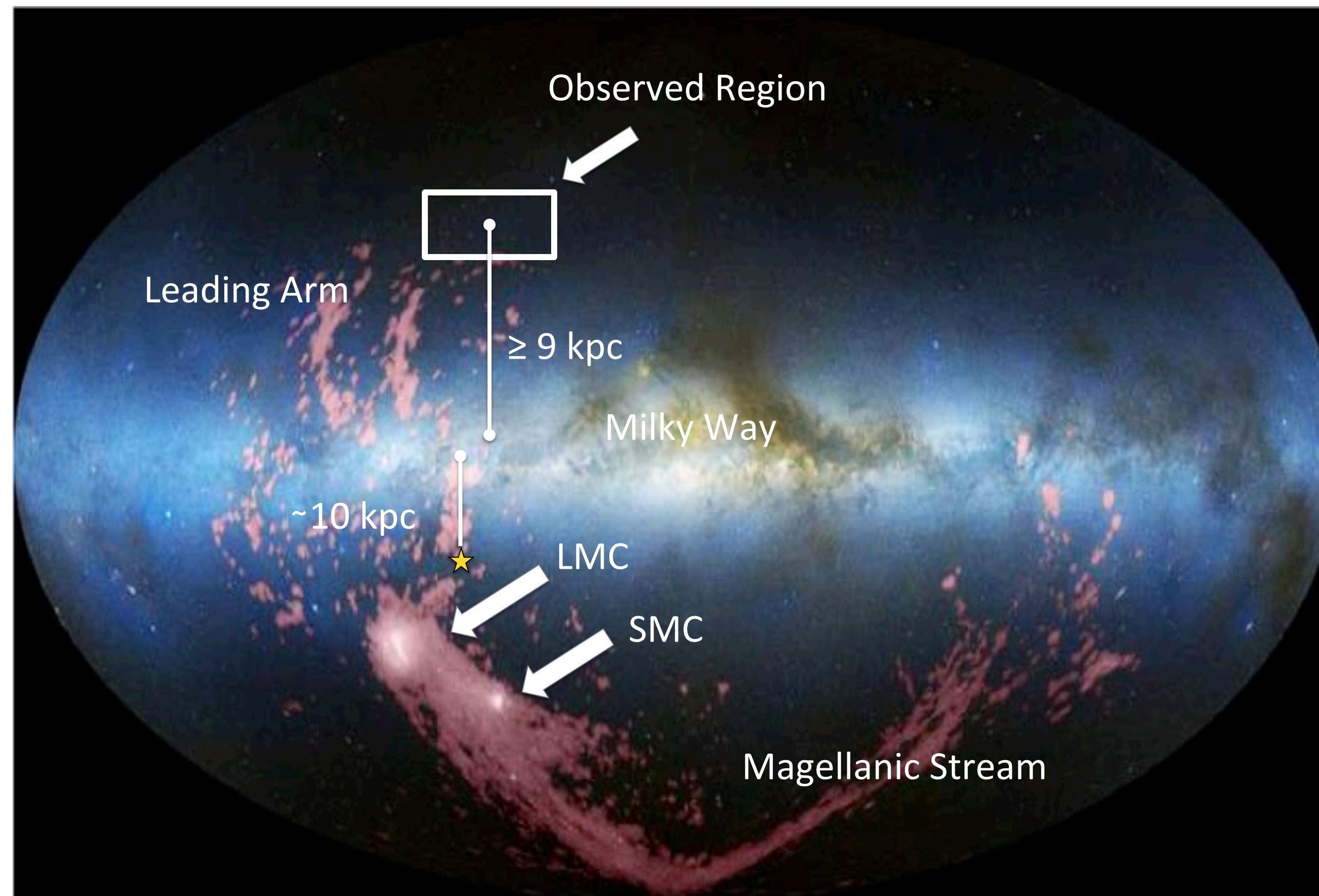


Fig 1. Map of the 21cm HI emission in the Magellanic System noting distances above and below the Galactic plane of our observed region and the O6V star. Photo credit: Nidever, et al. 2010, NRAO/AUI/NSF and Meilinger, Leiden-Argentine-Bonn Survey, Parkes Observatory, Westerbork Observatory, Arecibo Observatory.

Error Analysis

To determine the H α intensity, we modeled the emission as a Gaussian convolved with the WHAM instrument profile. Since the LA H α emission is faint and diffuse, this behooves us to employ statistical methods that ensure that our uncertainties are reported to a high degree of accuracy. Of the seven sightlines, four exceeded a 3σ detection. We determined the best fit by minimizing the χ^2 with the goodness-of-fit technique, using the IDL MPFIT routines. To calculate the systematic uncertainties in our intensity values, we created a three-dimensional best $\chi^2 \pm 1$ volume and found the location of the minimum value in the volume, which corresponds to the location of the best χ^2 value for the data set. Using this location as an index, we created a similar intensity volume and calculated the differences between the value at that location in the volume and the maximum and minimum values in the volume. These represent the upper and lower systematic uncertainties respectively.

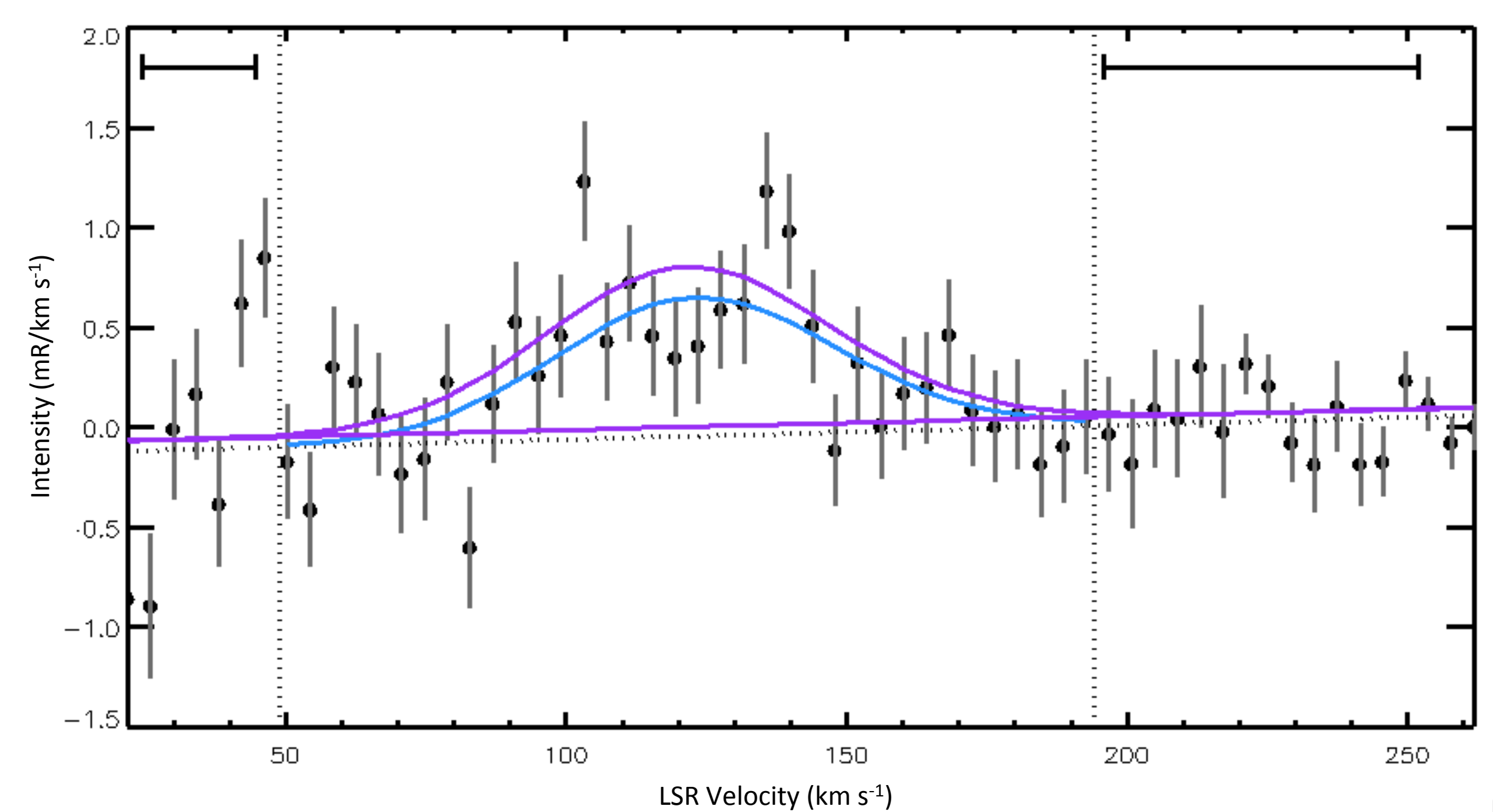


Fig 3. – Data fitting using modified IDL MPFIT routines. The blue line is the “best guess” fit of the data set. The fit with the best χ^2 and its corresponding background are plotted in purple.

Results

Since the strength of the H α emission is directly proportional to the rate of recombination, H α emission traces all the warm ionized gas in the Leading Arm. Figure 4 shows the Fox et al. 2005 model for the ionizing flux of the MW combined with the Haardt & Madau 2001 model for the EGB as a function of distance from the Galactic center. The ionizing flux is most intense at the center because that is where most star formation takes place. This plot is two dimensional for illustration purposes, but is adequate for describing this region in three-dimensional space because the ionizing flux contributions from the MW and EGB are symmetric. We took the calculated H α intensities and their corresponding statistical errors and calculated the ionizing flux needed to reproduce the H α emission through photoionization alone using Equation 1. We then compared this value with MW and EGB models of the ionizing flux in Figure to determine the distance that best matched the anticipated flux at the Galactic longitude and latitude of our observations. From this, our best estimate for the distance to the Leading Arm at the location of our observations is 18.1^{+3} kpc from the Sun. This represents a minimum value for what the distance could be, as we are ignoring the ionizing contribution of the Magellanic Clouds and sources of collisional ionization. Therefore, we find that this part of the LA is ≥ 14.8 kpc from the Sun at a Galactic height of ≥ 9 kpc. Casetti-Dinescu et al. 2014 find the O6V star formed in the LA to be 40 kpc⁴ from the Sun. Using the reported coordinates of the star, we found it to be at a Galactic height of ~ 10 kpc; hence our study is consistent with their results.

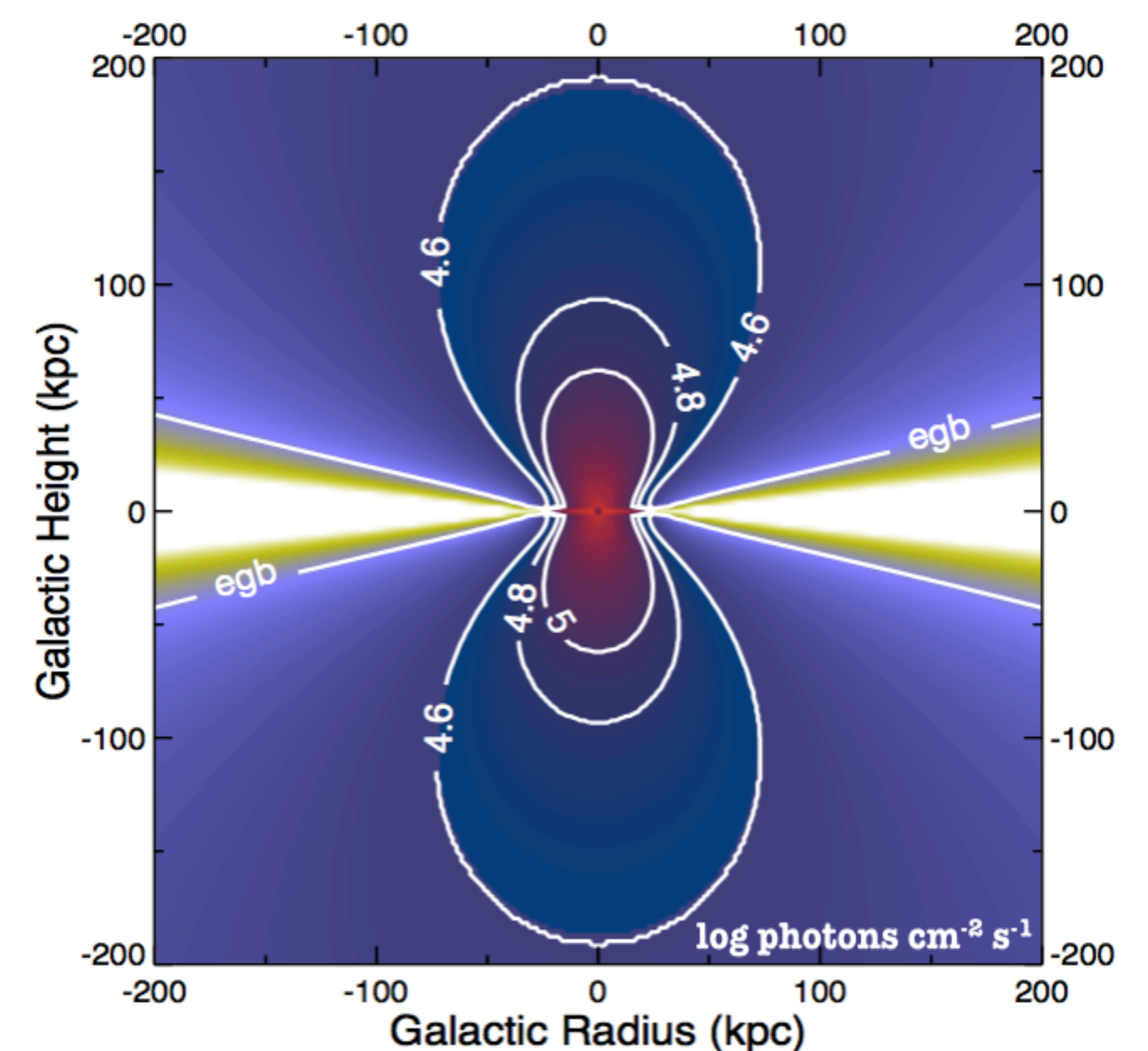


Fig 4. – Ionizing radiation field of the Galaxy^{5,6} and the EGB⁷. The plot shows a 400 x 400 kpc slice through the center of the Galaxy. The numbers on the contour lines give the logarithm of the flux in units of photons cm⁻² s⁻¹. The ionizing contribution of the EGB has a constant value of 3.22×10^4 photons cm⁻² s⁻¹ (Haardt & Madau 2001, Bland-Hawthorn et al. 1991, 2001) .

Contact

Jacqueline Antwi-Danso

Department of Physics and Astronomy, Texas Christian University

✉ Email: j.a.danso@tcu.edu

🌐 Website: www.tcu.digication.com/jacqueline_antwidanso

☎ Phone: (817)-703-2418

References

1. Fox et al. 2014
2. Reynolds et al. 1998
3. Haffner et al. 2003
4. Casetti-Dinescu et al. 2014
5. Fox et al. 2005
6. Bland-Hawthorn et al. 1999, 2001
7. Haardt & Madau 2001

Acknowledgements

The National Science Foundation supported WHAM through AST 1108911 and the TCU REU through grant number NSF PHY-1358770. K. A. Barger is further supported through NSF Astronomy and Astrophysical Postdoctoral Fellowship award AST 1203059.