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EFFECTS OF MASS AND DISTANCE UNCERTAINTIES ON CALCULATIONS OF FLUX FROM GIANT MOLECULAR CLOUDS

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EFFECTS OF MASS AND DISTANCE UNCERTAINTIES ON CALCULATIONS
OF FLUX FROM GIANT MOLECULAR CLOUDS

By

Matthew Coel

A REPORT

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In Physics

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This report has been approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE in Physics.

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Preface

The Data in Chapter 5 is obtained from the High Altitude Water Cherenkov (HAWC) Gamma-Ray Observatory. It is located near Puebla, Mexico and is utilized by many collaboration research groups internationally.

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Abstract

It is assumed that the distribution of the Milky Way cosmic rays, the cosmic ray ‘sea,’ is even throughout the Galaxy. This assumption can be tested by measuring gamma rays produced from cosmic ray interactions with Giant Molecular Clouds. The gamma ray flux depends on the mass and distance of a given molecular cloud as well as the cosmic ray flux in its vicinity. Thus a predicted gamma ray flux can be compared to actual flux data from a detector. Uncertainties from measuring the mass of and distance to the clouds are taken into account for this prediction. This report also discusses the HAWC water Cherenkov detector and why it is a good resource for this study. HAWC significance maps currently do not show significant flux from Giant Molecular Clouds against the background. A 95% upper limit is calculated for gamma ray and cosmic ray fluxes, which only weakly constrain their possible range.

Chapter 1

Introduction

Cosmic rays (CRs) are charged particles moving in all directions throughout the Galaxy, dominantly atomic nuclei. It is typically assumed that this ‘sea’ of CRs is evenly distributed throughout the Galaxy, not weighted to one section or another. This is because of the Galaxy’s turbulent magnetic fields. This will be described in more detail in Chapter 2. This report will seek to determine if the CR flux observed at Earth is the same as the flux elsewhere in the Galaxy, specifically around Giant Molecular Clouds (GMCs).

In the Milky Way, the space between objects is filled with (mostly) hydrogen molecules, atoms, and ions, an average particle density of 1.5 cm^{-3} (Ferrière, 2001). However there are very cold pockets of dust and gas with particle densities higher

than the surrounding space at upwards of 100 cm^{-3} called molecular clouds (Blitz and Williams, 1999). These clouds are mainly composed of molecular hydrogen, though they also contain other detectable molecules, most notably carbon monoxide, CO, which is used as a marker for molecular clouds.

Molecular clouds are largely composed of the same materials but they can come in a variety of shapes and sizes. Their masses typically range from 10^2 to 10^6 solar masses (Dame et al., 2001). Clouds of 10^4 solar masses and higher are called Giant Molecular Clouds (GMC). Most molecular clouds are found on or near the galactic plane and some can also contain their own CR accelerators, such as supernova remnants (SNRs) and pulsars. Some clouds also contain star forming regions. A typical cloud temperature range is 10-12 K (Ferrière, 2001). This report focuses on three particular GMCs: Taurus, Hercules, and Aquila Rift. More details about these clouds will be presented in chapter 5.

A subtype of molecular clouds is a high/intermediate velocity cloud. These are found above and below the galactic plane and can vary in size. They generally have a low abundance of elements heavier than hydrogen (lower metallicity) (Röhser et al., 2016).

The three clouds studied in this report are passive clouds, meaning they do not have an active, CR-accelerating source inside them. This means gamma rays detected from each cloud are produced in interactions between the cloud and the sea of CRs.

When a high-energy CR proton comes in contact with another proton, an interaction occurs which will be discussed in more detail in the next chapter. This interaction can result in the production of gamma rays. These gamma rays yield information about the initial, impacting CR, which in turn yields information about the CR sea.

Gamma ray flux from a particular molecular cloud can be predicted from its physical properties (specifically its mass and distance from Earth) and the CR flux at the cloud. However, these properties are not absolutely known. There are systematic and statistical uncertainties to both attributes. This report discusses said mass and distance uncertainties, and incorporates the error propagation into gamma ray flux predictions for the three clouds that are studied here. The predictions will be used to determine the High Altitude Water Cherenkov (HAWC) observatory sensitivity to GMCs. The predictions will be compared with measurements to constrain the CR flux near the clouds.

This report is structured as follows: In Chapter 2 CR propagation and spectra are discussed along with the gamma ray production from interactions with molecular clouds. Different telescope and detector types will be discussed in Chapter 3 along with a look at why HAWC is a good detector for this study. Chapter 4 summarizes the methods for determining GMC mass and distance along with their corresponding uncertainties. Chapter 5 compares gamma ray flux predictions for the GMCs with data from the HAWC observatory. In Chapter 6 this study's conclusion is described.

Chapter 2

Gamma Ray Astrophysics

Cosmic Ray Production

The CR ‘sea’ was formed over the Milky Way’s lifespan by CR accelerators, such as supernova remnants (SNRs) and pulsars (Drury, 2012). These highly energetic objects are thought to be the reason Galactic CRs reach energies up to 10^{15} eV.

This energy level is thought to be the upper limit to which Galactic sources can accelerate CRs (Gaisser, 2006). CRs have been detected in the energy range from around 10^9 to 10^{20} eV, with higher fluxes at lower energies (see Figure 2.1). They follow a power-law energy spectrum trend which shows a spectral break around 10^{15} eV called the ‘knee’ followed by a softer spectrum, and another break at around 10^{18}

eV, called the ‘ankle,’ as seen in Figure 2.2. The ‘ankle’ is not well understood but is assumed to denote the onset of extragalactic sources. The spectrum’s ‘knee’ is also not well understood, although it likely denotes the start of the transition from Galactic to extragalactic sources, or a cutoff in the Galactic component of CRs.

Figure 2.1: Cosmic ray energy spectrum showing particle flux vs energy trend. Figure from (Swordy, 2001)

Figure 2.2: Cosmic ray energy spectrum for particles above 10^{13} eV with data from the shown observatories. The flux has been multiplied by $E^{2.6}$ to emphasize the bend at the ‘knee’ and trend toward the ankle. Figure from (Patrignani et al., 2016)

There are several methods for accelerating CRs up to 10^{15} eV, but only first-order Fermi acceleration will be discussed here. Other methods do dramatically increase a moving particle’s energy, but this method increases it to the energy range observed for this report (Grieder, 2010). First-order Fermi acceleration, or diffusive shock acceleration, requires a moving shock front, like what might be the leading supersonic fluid from a supernova (Bell, 2013). An illustration of this can be seen in Figure 2.2.

If a relativistic particle comes to the front from downstream the shock front, toward upstream, it can pass near a charged particle in the stream (Gaisser et al., 2016).

Figure 2.3: Cartoon illustration of shock acceleration from the reference frame of the shock front, moving at speed V_u . The ISM becomes turbulent with the passing on the shock front. A CR follows the path of the arrow as it moves back and forth across the shock front, gaining energy each time it passes back downstream in this reference frame. (credit: Dr. Mark Pulupas space physics illustration) <http://sprg.ssl.berkeley.edu/~pulupa/illustrations/>

If it does, it is affected by the stream's magnetic field, changing direction toward downstream and, on average, gaining kinetic energy proportional to the ratio between the shock's fluid velocity and the speed of light. On its new trajectory it can pass near another charged particle and be deflected back upstream, again with increased energy. This process can continue until the original particle has sufficient energy to escape the front altogether as happens in Figure 2.2. From here the particles continue moving along their path until they encounter another material.

The path a CR takes depends on the magnetic field of the Galaxy, which is approximately $3\mu G$ (Gaisser et al., 2016). The CR will move about the field with a gyroradius dependent on its rigidity. However the magnetic field is not constant everywhere. Events such as pulsar winds, stellar flares, or supernova explosions can ionize the interstellar medium, making the magnetic field turbulent. CRs can be deflected by this turbulence in ‘random’ directions, becoming part of the diffused ‘sea’ of CRs.

Gamma Ray Production

This study does not rely on direct measurements of CRs, but rather gamma rays that are emitted due to CRs interacting with molecular clouds.

When a CR enters a molecular cloud, it can interact with a proton inside. The nature of this interaction is dependent on species of impacting CR, but this report will focus on a proton impactor against a cloud proton. When a high energy proton CR collides with a less energetic proton, some of the kinetic energy is transferred into the creation of charged and/or neutral pions (Miskimen, 2011), where the neutral pion is the focus here. The minimum kinetic energy, E_{min} , required to create a particle this way is given by the relation,

Figure 2.4: Cosmic ray nucleus, N , impacts molecular cloud nucleus, $N(p)$, resulting in their mutual deflection and the creation of charged and neutral pions, along with other particles. The neutral pion, π^0 , decays into two photons. Figure taken from (Ayala Solares, 2017)

$$E_{min} = 2mc^2 \left(1 + \frac{m}{4m_p} \right), \quad (2.1)$$

where m_p is the proton mass and m is the neutral pion's mass (Grieder, 2010). In this case, the E_{min} is about 280 MeV. This interaction is not limited to a single neutral pion. If the energy is about 1 GeV or greater, two neutral pions can be created (Skorodko et al., 2009). After about 10^{-16} seconds, a neutral pion decays into two gamma rays. Sometimes the direction of the gamma rays is Earth-bound where they can be detected. The methods of detection will be discussed in the next chapter.

The rate at which a photon is formed from this interaction is $1.53 \cdot 10^{-25}$ photons (H-atom) $^{-1}$ s $^{-1}$, which assumes the locally measured CR flux and does not distinguish between nucleus or electron (Dermer, 1986). The time dependent part

Figure 2.5: Time a cosmic ray spends in a molecular cloud vs its energy. Two examples of different cloud masses, sizes, and magnetic fields are shown. The dashed lines denote cosmic ray propagation, the dotted lines denote energy loss time for protons, and the solid lines show energy loss time for electrons. The lower curve at corresponding energies is the dominant outcome, less likely to traverse the cloud at lower energy loss time and more likely at lower propagation times. (Gabici, 2013)

relates to the initial CR's energy, seen in Figure 2.5 (Gabici, 2013). In the figure, the dashed curve is CR propagation and the dotted curve is energy loss time. Whichever is below the other is the dominant action for a CR. If the propagation time is shorter, the CR can freely enter and traverse the cloud. If the propagation time is larger, energy loss effects become dominant and the cloud becomes more opaque to the CR. At low energies, the latter case is true, but around 280 MeV and higher the former becomes dominant. Thus at the energy range in which proton CRs are being considered, they are freely able to enter and travel the cloud. If the photon generation rate is multiplied by the energy-dependent propagation time of the initial CR from Figure 2.5, the particle density of the cloud, and the cloud's diameter, the probability of photon creation per area traversed can be calculated.

The integral gamma ray flux, F_γ , from a given molecular cloud has this relationship with its physical properties:

$$F_\gamma \propto \Phi_{CR} \left(\frac{M_5}{d_{kpc}^2} \right) \quad (2.2)$$

where M_5 is the GMC mass in 10^5 solar masses, d_{kpc} is the distance between Earth and the GMC in kiloparsecs, and Φ_{CR} is the integrated CR flux as assumed at the GMC (Aharonian, 2001). For energies above 1 TeV, assuming that the CR flux at the GMC is equal to what has been measured at Earth, the GMC is passive to CRs, and the proportionality is true, one obtains:

$$F_\gamma = 2.85 \cdot 10^{-13} \cdot E^{-1.6} \left(\frac{M_5}{d_{kpc}^2} \right) \text{cm}^{-2}\text{s}^{-1} \quad (2.3)$$

where the E is the minimum energy the flux is integrated over, assumed at 2 TeV (Aharonian, 2001). The constant comes from:

$$F_\gamma \simeq 10^{-7} \cdot \left(\frac{M}{d^2} \right) \cdot q_{-25}(\geq E_\gamma) \text{cm}^{-2}\text{s}^{-1} \quad (2.4)$$

,where the constant comes from energy conversion from the integrated CR flux and

$q_{-25}(\geq E_\gamma)$ is the gamma ray emissivity (Aharonian, 1991):

$$q_{-25}(\geq E_\gamma) = q_\gamma(\geq E_\gamma)(\text{H-atom})^{-1}\text{s}^{-1} \quad (2.5)$$

,and q_{-25} is on the order of 10^{-25} . This emissivity assumes a proton CR flux the same as is measured locally. At $E_\gamma = 2 \text{ TeV}$, $q_\gamma(\geq 2\text{TeV})$ is about $3 \cdot 10^{-31}(\text{H-atom})^{-1}\text{s}^{-1}$. For TeV energies and greater, a parameter is included in the calculation of emissivity that accounts for the cross section of collision between an impacting CR and molecular cloud nucleus resulting in a neutral pion: $q_{-25}(\geq E_\gamma) = 1.45 \cdot 3 \cdot 10^{-6}(\text{H-atom})^{-1}\text{s}^{-1}$. When this is inserted into Equation 2.4 and it is multiplied out, the result is Equation 2.3.

Chapter 3

Detection of Gamma Rays

Telescope Types

There are multiple methods for detecting gamma rays that approach Earth. One is by using satellite-borne detectors in orbit around Earth. A well-known example is the Fermi Large Area Telescope (LAT) (Atwood et al., 2009). It has a large field of view of 2.4 sr and does not collect data directly from an incident gamma ray, but rather from particles that are created. The contacting gamma ray is converted into an electron and positron pair. The LAT then follows the path of the created particles and measures their energies when they reach an internal calorimeter. This reveals both the incoming direction and energy of the initial gamma ray.

Gamma ray observation is not limited to space-based detectors. Ground-based observatories indirectly observe incoming gamma rays via extended air showers.

When an incoming gamma ray greater than 1 TeV impacts a nucleus of the Earth's atmosphere, an electron-positron pair is produced (Grieder, 2010). As these two new particles conserve the energy of the initial gamma ray, they are moving down through the atmosphere as well. As they pass near other atmospheric nuclei, they interact with the nuclei's electric fields, causing them to slow down and emit photons, a process known as bremsstrahlung. The electron, positron, and new photons continue propagating toward Earth, interacting with other nuclei resulting in a cascading shower of particles. This is called an extended air shower (EAS) and this process is seen in Figure 3.1.

One way an EAS is observed is by Cherenkov radiation emitted by its charged component (Grieder, 2010). In a medium, the speed of light, photons, is decreased compared to its vacuum speed based on the index of refraction (n) of the medium. In an EAS, charged particles, namely electrons and positrons, can move at speeds faster than light's in the atmosphere. When this happens, blue light is emitted, which is called Cherenkov radiation. Imaging Air Cherenkov Telescopes (IACTs) situated on the ground can detect this radiation. This type of observatory, for example VERITAS (Holder et al., 2006), H.E.S.S. (Hofmann and H.E.S.S. Collaboration, 2003), FACT (Anderhub et al., 2009), or MAGIC (Guberman et al., 2017), is limited to nighttime

Development of gamma-ray air showers

Figure 3.1: Air shower induced by gamma ray interacting with atmospheric nucleus resulting in a cascade of pair production and bremsstrahlung gamma rays. (credit:Max Planck Institute for Nuclear Physics) <https://www.mpi-hd.mpg.de/hfm/CosmicRay/Showers.html>

with clear skies.

HAWC

Another method of EAS detection is a ground-based observatory which uses water Cherenkov tanks (Smith, 2005). When charged particles reach the water-filled tanks,

they can move faster than light can in water, due to its higher refractive index of 1.33, emitting Cherenkov radiation. Photomultipliers in the tank observe the radiation flash and send the information to internal data acquisition tools.

The High Altitude Water Cherenkov observatory is an example of this detector type. Located on the Sierra Negra mountain in Mexico, HAWC uses 300 water Cherenkov tanks to detect air showers (Abeysekara et al., 2012).

Figure 3.2: Infographic of the HAWC detector, showing an EAS reaching the water Cherenkov tanks. (Credit: HAWC/WIPAC) <https://hawc.wipac.wisc.edu/gallery/view/1695>

This observatory is a good setup to detect air showers originating from gamma rays from GMCs. It has a large field of view of about 2 sr with an angular resolution which becomes better at higher energies, achieving about 0.1 degrees above 10 TeV (Abeysekara et al., 2013). This wide viewing range gives HAWC an advantage in being able to detect gamma ray showers from extended sources, like GMCs, which extend a few degrees in the sky rather than a single point. HAWC is sensitive to energies between 100 GeV-100 TeV. Lastly, since the detectors are in stationary water tanks and are always on, they can detect showers regardless of time of day and can constantly run, giving a near 100% duty cycle.

Chapter 4

Measuring Giant Molecular Cloud Properties

Distance Determination

The distances to the Taurus and Hercules molecular clouds were determined by (Schlafly et al., 2014), where they used a method utilizing light scattering. The method uses the distance to stars behind and in front of the cloud, along with the rate of light extinction in the cloud.

First the distances to stars in the same line of sight as the GMCs were taken from the Pan-STARRS1 survey (Kaiser et al., 2010). This survey used photometry in infrared

and visible ranges to determine the distances.

For each cloud, stars located in front of and behind the cloud were chosen. Stars in the background have their light scattered and reddened as it passes through the cloud (Schlafly et al., 2014). Meanwhile, light from stars in the foreground undergoes less reddening. These stellar bracketed boundaries serve to confine the space where the cloud can be located.

The molecular clouds were modeled as dust screens with an reddening profile as a function of distance. A probability distribution using a background star’s distance and reddening was then made. Markov Chain Monte Carlo (MCMC) sampling was used in conjunction with the probability distribution to determine the cloud’s probable position using the observed amount the background star’s light was reddened. The distance results for the studied clouds are seen in Table 4.1.

Systematic uncertainties were determined to come from the stellar models, photometric calibration, and the dust screen model. Stellar models were used to determine the differences between the apparent and absolute magnitudes of the background and foreground stars. Metallicity is a factor here to which Pan-STARRS1 is insensitive. The distribution of stellar metallicities was modeled by (Schlafly et al., 2014) to compensate. The relative uncertainty on the distance due to uncertainties in the stellar models was determined to be 10%.

The photometric calibration errors are not expected to be dominating factors in overall uncertainties. A 1% distance uncertainty is attributed to this.

The dust screen model assumes that each cloud’s position lies entirely within a set distance for the screen and the extinction rate of light is the same for every cloud. Due to the morphology of a cloud, not every part of it lies within the confines of the model. Different parts of the same cloud can lie at different distances. In addition, the reddening rate, taking into account the background star’s stellar class color, is approximated as a stable, set rate. These assumptions were determined to result in a 10% relative uncertainty. All distance-related errors combined result in a relative uncertainty on the distance of 15%.

While the Taurus and Hercules clouds’ distance uncertainties came from (Schlafly et al., 2014), the Aquila Rift cloud’s is from (Straizys et al., 2003). Although they come from different studies, all three were found using similar stellar light extinction methods. From its study, Aquila Rift’s total distance uncertainty is 24%.

Cloud Name	Mass ($M_{\odot}$)	Distance (kpc)
Aquila Rift	$(1.5 \pm 0.4) \times 10^5$	0.225 ± 0.055
Hercules	$(5.0 \pm 1.3) \times 10^4$	0.200 ± 0.030
Taurus	$(2.0 \pm 0.5) \times 10^4$	0.135 ± 0.020

Table 4.1

Studied Giant Molecular Clouds with their determined masses (Bloemen et al., 1986). Distances for Taurus and Hercules are from (Schlafly et al., 2014) and Aquila Rift is from (Straizys et al., 2003). The attributed uncertainties are also shown.

Mass Determination

The mass values for the studied molecular clouds were determined by (Solomon et al., 1979) from molecular gas intensity experiments. The molecular spectral line intensity is related to column density of CO and by a known gas ratio, to the column density of H_2 . The cloud mass can be calculated from the column densities.

The main component of molecular clouds is molecular hydrogen, H_2 . However the H_2 spectrum is not easily seen, especially in colder clouds (van Dishoeck et al., 1992). So rather than directly observing the most abundant molecule, CO absorption lines are used instead as they are more easily seen. In particular, ^{13}CO is used as a cloud tracer. The most common isotope, ^{12}CO is not used because there is too much of it in molecular clouds and the absorption signal intensity is drowned out (Solomon et al., 1979).

The observed ^{13}CO spectral intensity relates to the column density for that molecule, thus the amount of it present in the molecular cloud (Sanders et al., 1984). Since the abundance of ^{13}C is about 1% of total carbon nuclei, the total CO can be determined. Then the total CO column density can be related to the H_2 column density via the ratio,

$$\frac{CO}{H_2} \approx 10^{-4} \quad (4.1)$$

where (Lacy et al., 1994) measures the ratio and all isotopes are included in the CO (van Dishoeck et al., 1992). The column densities for both H_2 and CO can then be extrapolated throughout the cloud to find the mass, which can be seen in Table 4.1.

Uncertainties in the mass determination largely come from statistical uncertainties for amounts of CO (Bloemen et al., 1986). The systematic uncertainty from calibration for CO detection is around 20% which directly affects the ratio between CO integrated intensity and H_2 column density.

Two smaller sources of uncertainty are GMC temperatures and H_1 data. The temperatures are used for optical depth determination and affect the mass calculation and depend on distances away from and along the galactic plane. 10% mass uncertainty is assumed here. The cloud's mass depends also on the amount of H_1 present, which comes from the ratios of surface densities,

$$\frac{\sigma H_2}{\sigma H_1} \approx 1.35 \quad (4.2)$$

which contributes a mass uncertainty of 10%. The total mass-related errors combined in a 25% mass uncertainty.

Chapter 5

Flux Prediction Comparison

Flux Prediction and HAWC

The diffuse CR flux in the Galaxy is assumed to be the same everywhere. Thus the flux measured locally should match what exists around a GMC. When CRs interact with GMC nuclei, new particles are created, such as neutral pions. Neutral pions decay into photons and this flux can be detected on Earth. The amount of flux is predicted using (eqn. 2.3), which accounts for GMC mass and distance as well as CR flux (Aharonian, 2001). Figure 5.1 shows the calculated fluxes for several GMCs compared to HAWC's flux sensitivity.

Several GMCs fall well below the sensitivity curves, even after 10 years, making them

Figure 5.1: Predicted gamma ray flux from GMCs. The clouds are plotted with respect to their respective declinations above and below the galactic plane. The curves show HAWC's sensitivity to fluxes from extended sources above 2 TeV over time. With more data, HAWC becomes more sensitive to lower fluxes thus making GMC gamma ray detection more likely (Ayala Solares, 2017)

poor choices to study using HAWC. At the time of this writing, HAWC has collected data for nearly three years, meaning that clouds near or above the corresponding curve offer the best chance of being detected. The three GMCs above the 5-year curve fit that description: Aquila Rift, Hercules, Taurus. In addition, these three are passive clouds, meaning they do not contain known CR accelerators and they do not lie directly along the galactic plane, as seen in Figure 5.2. Thus gamma rays created from CR interactions are mainly from the diffuse ‘sea.’ The flux predictions for these

Figure 5.2: Dame survey map (Dame et al., 2001) overlaid with HAWC sensitivity map (Ayala Solares, 2017), all in galactic coordinates. The light blue areas denote regions HAWC is not sensitive to due to its physical location on Earth. The darker bands denote higher sensitivity and hold the three studied GMCs.

three GMCs are now the focus.

However the resulting flux predictions are not exact. In chapter 4 the uncertainties for GMC mass and distance were discussed, with the results shown in Table 4.1 for the three studied GMCs. While the mass uncertainty is greater, 25% compared to 15% for Hercules and Taurus and 24% for Aquila Rift, the distance uncertainty causes the greatest impact as its contribution to the predicted flux is inverse-squared while the mass's is directly proportional. The resulting predicted flux values for Aquila Rift, Hercules, and Taurus can be seen in Table 5.1, along with the flux uncertainties for each.

Cloud Name	Flux ($\frac{\text{photons}}{\text{cm}^2\text{s}^1}$)	Flux Uncertainty ($\frac{\text{photons}}{\text{cm}^2\text{s}^1}$)
Aquila Rift	2.79×10^{-12}	$\pm 1.2 \times 10^{-12}$
Hercules	1.18×10^{-12}	$\pm 4.6 \times 10^{-13}$
Taurus	1.03×10^{-12}	$\pm 4.0 \times 10^{-13}$

Table 5.1

Studied Giant Molecular Clouds with their calculated fluxes and flux uncertainties using (eqn 2.3).

Figure 5.3: Predicted gamma ray flux from 3 studied GMCs with uncertainties included

Shown in Figure 5.3 is the flux for these three GMCs plotted along with their respective uncertainties. This implies that Aquila Rift is most likely to be visible to HAWC as even its uncertainty range largely lies within current sensitivity predictions.

Next the predicted flux for the three GMCs were tested against HAWC measurements.

Figure 5.4: HAWC significance map along Galactic plane. The background is smoothed with a 0.5 degree diameter disk and a point spread function is used for the sources. Contours show ISM boundaries from (Dame et al., 2001). Figure shown from (Ayala Solares et al., 2017)

Figure 5.4 shows a significance map of HAWC’s sky. The contours are boundaries for ISM from (Dame et al., 2001). The sources HAWC sees mainly lie along the Galactic plane. In Figures 5.5, 5.6, and 5.7 the ISM contours for the three GMCs are focused on. No significant excess is seen within the cloud boundaries themselves.

As HAWC does not see significant emission from the GMCs, upper limits on the gamma ray flux from the three GMCs can be determined. The difference between the HAWC data and estimated background is divided by the square root of the background like in Figures 5.8, 5.9, 5.10. These figures show each cloud’s excess detection against the fraction of PMTs reconstructing shower events. None of these

Figure 5.5: HAWC significance map for the Aquila Rift molecular cloud. The background is smoothed with a 0.5 degree diameter disk and a point spread function is used for the sources (Ayala Solares et al., 2017)

clouds show a notable excess above the background. Without a significant excess seen in the three GMCs, a flux upper limit was instead determined. Figure 5.11 shows the three clouds' predicted fluxes compared with calculated 95% upper limits. These limits are not very constraining and they leave a wide range of possible gamma ray fluxes.

Since the gamma ray flux upper limit has been calculated, the same can be done for the CR flux near each cloud. Since the predicted gamma ray flux is directly proportional to the CR flux, their upper limits are related as well:

Figure 5.6: HAWC significance map for the Hercules molecular cloud. The background is smoothed with a 0.5 degree diameter disk and a point spread function is used for the sources (Ayala Solares et al., 2017)

$$ULF_{\gamma} = k \cdot UL_{\Phi_{CR}} \cdot \left(\frac{M}{d^2} \right) \quad (5.1)$$

where the ‘UL’ denotes an upper limit for gamma rays and CRs respectively, and ‘k’ is the constant from (eqn. 2.3). The ratio between a GMC’s predicted gamma ray flux and flux upper limit is the same as the surrounding CR sea’s assumed flux and

Figure 5.7: HAWC significance map for the Taurus molecular cloud. The background is smoothed with a 0.5 degree diameter disk and a point spread function is used for the sources (Ayala Solares et al., 2017)

flux upper limit:

$$\left(\frac{UL_{F_\gamma}}{F_\gamma} \right) = \left(\frac{UL_{\Phi_{CR}}}{\Phi_{CR}} \right) \quad (5.2)$$

where the calculated results are seen in Figure 5.12. The upper limits on the CR flux near the three clouds are larger than the CR flux measured at Earth and thus not

Figure 5.8: Excess plot for the Aquila Rift GMC. N' is HAWC data and $\langle N' \rangle$ is the estimated background. 'f' is the fraction of PMTs that reconstructed a gamma ray shower from the cloud. The different fractions correlate to different energies, a smaller fraction relating to smaller energy. This shows that no matter how many PMTs were triggered, there is no significant excess (Ayala Solares et al., 2017)

Figure 5.9: Excess plot for the Hercules GMC. N' is HAWC data and $\langle N' \rangle$ is the estimated background. 'f' is the fraction of PMTs that reconstructed a gamma ray shower from the cloud. The different fractions correlate to different energies, a smaller fraction relating to smaller energy. This shows that no matter how many PMTs were triggered, there is no significant excess (Ayala Solares et al., 2017)

very constraining.

Figure 5.10: Excess plot for the Taurus GMC. N' is HAWC data and $\langle N' \rangle$ is the estimated background. ‘f’ is the fraction of PMTS that reconstructed a gamma ray shower from the cloud. The different fractions correlate to different energies, a smaller fraction relating to smaller energy. This shows that no matter how many PMTs were triggered, there is no significant excess (Ayala Solares et al., 2017)

Figure 5.11: Flux 95% predicted upper limits for GMCs. The uncertainties are those from Figure 5.3 (Ayala Solares et al., 2017)

Figure 5.12: Flux ratios for GMCs compared with measured cosmic ray flux (Ayala Solares et al., 2017)

Chapter 6

Conclusion

The goal of this study was to probe the ‘sea’ of Galactic diffuse CRs. In chapter 2 the diffusive shock acceleration mechanism for CR acceleration was described. The interaction between an accelerated CR and a Giant Molecular Cloud was detailed, resulting in the creation of a gamma ray. This gamma ray flux is predicted from Equation 2.3 which uses properties of the clouds and the assumed CR flux.

The HAWC detector, as described in chapter 3, is able to detect gamma ray-induced air showers at the high energies these gamma rays have as they reach Earth. This means measurements by HAWC can be compared against the predicted gamma ray flux.

In chapters 4 and 5 the uncertainties in Giant Molecular Clouds’ masses and distances

were taken into account when finding the uncertainty range of predicted gamma ray fluxes and how they compare to HAWC’s sensitivity. It was determined that despite the upper end of the uncertainty range being within HAWC’s sensitivity to the flux, the data maps do not show a high significance toward detection and no discernable excess was found. Instead, upper limits were calculated for CR flux, which do not place tight constraints on the possible range of CR flux.

In the end, no certain conclusion was reached regarding whether or not the CR ‘sea’ is evenly distributed throughout the Galaxy. Aquila Rift offers the best constraint for the three studied clouds from Figure 5.12, with an upper limit of twice the locally measured CR flux. As HAWC continues operating and detecting these gamma ray showers, as seen in Figure 5.3, over time it will become more sensitive to smaller fluxes, thus more able to be compared against the predicted flux. It is also possible that not all uncertainties are accounted for, like for instance in the assumed CR flux part of Equation 2.3. The uncertainty range may yet be much larger than what was shown in this report.

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