Chapter 1

Introduction and Background

1.1 Introduction

The idea of looking at the sky as seen in deep underground muons might seem to be a good idea at first glance. After all, the past several decades of astronomy have produced cascades of new discoveries as astronomers have used exotic equipment to look into new windows on the universe. From radio waves to gamma rays, the electromagnetic spectrum has produced results that Hubble's generation would never have guessed. Now, even graviton astronomy is being taken seriously, with several large interferometers under construction. So, why not look with muons?

The answer to this simple question seems to limit any ideas of a great new way to look at the universe. The problem is that nearly all the muons seen on or in the earth are the produced when high energy hadronic cosmic rays collide with earth's atmosphere at high altitudes. These collisions produce π and K mesons, some of which decay into muons. However, these hadronic parents (mostly protons) are charged particles, and our galaxy possesses a non-uniform magnetic field of several microgauss. Thus, the primary cosmic rays are deflected repeatedly as they travel through this field on their journey to the earth. The direction from which they arrive bears no relation to that from which they originated. Therefore, unlike puzzling out the structure of a star from its photon emission, the cosmic rays cannot be used to discover the directions of sources of origin.

Contrary to expectations, there have been repeated reports of muons associated with sources (see Section 1.3). These claimed sources, the binary pulsars Cyg X-3 and Her X-1, are of such an extreme nature that one expects the unexpected from such objects. However, there were also many null results from other experiments that failed to confirm the initial detections. The MACRO (Monopole, Astrophysics, and Cosmic Ray Observatory) detector is well suited to look for such signals, but has not seen them to date. One troubling facet of the old analyses is that none of the underground experiments in question have been able to detect the one astronomical source that should be seen in muons: the shadow of the moon. The moon blocks out the cosmic rays coming from its direction, and is close enough to the earth that scattering of the primaries by magnetic fields is not a problem. Since MACRO has been in full operation for an extended length of time, it has gathered the statistics necessary to see the shadow of the moon (see Chapter 4). This verification of MACRO's ability to see an astronomical object allows a new search of the sky for more interesting astrophysical sources of muons to be performed with more confidence on a larger set of data.

1.2 Cosmic Ray Muons

Nearly all muons observed on the Earth are the end products of the high-energy interactions between hadronic cosmic rays and the earth's atmosphere[1]. These cosmic rays are mostly protons, but all nuclei up to and including uranium have been observed[2]. When a cosmic ray reaches the earth, it will collide with a nucleus from the earth's atmosphere. This results in a complicated interaction that produces a cascade of secondary particles. Prominent among these particles are charged π and K mesons. Some of these mesons decay before they can interact with another air nucleus. The branching ratio favors decay into muons.

A small fraction of the cosmic ray induced muons come from gamma ray parents. A gamma ray interacting in the atmosphere will also induce a cascade of lower energy particles. Muons can be pair-produced in such an interaction. However, this interaction has a much lower probability to produce muons than a hadronic interaction. For muons energetic enough to be seen by MACRO ($\gtrsim$1.2 TeV), the flux of muons produced by gamma rays has been shown to be reduced by a factor of 10^5 from the parent flux of gammas[3]. When compared to hadronic showers of similar energy, electromagnetic showers produce fifty times fewer muons[4]. Given the fluxes of ultra-high energy gamma rays observed by early air shower experiments (Section 1.3), it would take MACRO decades to observe this muon flux.

An even smaller part of the muons come from weak interactions of muon neutrinos with nearby matter. Due to the tiny cross section of this interaction, muons from neutrinos compose less than one part in a million of the muons MACRO sees. This flux has been measured in MACRO by looking for muons travelling upwards from below the detector[5]. Such muons can only come from neutrino interactions in the rock below MACRO.

Muons are the most penetrating of all non-neutrino particles created in an atmospheric cascade. A mere meter of earth will halt most of the electrons produced by the shower, so any underground experiment will only see the muons. Air shower arrays use this fact to discriminate between electromagnetic and hadronic showers. To do this, scintillation counters are buried just underneath the surface array. Particles that trigger the buried counters are muons, but both muons and electrons trigger the surface counters. Thus, the relative abundance of muons compared to electrons in the shower can be measured, revealing the origin of the shower to be hadronic or electromagnetic. Electromagnetic showers are seen to be "muon poor"[6].

1.3 History of Muon Astronomy

Despite the fundamental problem of an apparently directionless signal, the first hints that there might be something to the field of muon astronomy came between 1975 and 1985. Several surface air shower arrays saw some evidence for Ultra-High-Energy (UHE - above 20 TeV) gamma rays from the directions of point sources. Cyg X-3 was one, as were other X-ray binaries, Her X-1 and 1E2259+59. None of these detections was particularly strong[6,7], and they have not been confirmed by modern gamma ray experiments.

While UHE gamma rays from such sources would not be too surprising, several of these detections were not muon-poor, as one would expect from a gamma-ray induced shower. The Kiel result[8] was the first of these and showed modulation of the signal by Cyg X-3's 4.8 hour orbital period. Haverah Park's observations a year later confirmed this result, although only in the modulation of the signal[9], not with any DC excess. The CYGNUS experiment reported a similar result for Her X-1, modulated by the pulsar's 1.24 second period but with a low significance for a simple DC excess[10].

Adding to the mystery, two underground experiments also reported muons attributed to Cyg X-3. The Soudan 1[11,12] and Nusex[13] experiments both saw muon signals from Cyg X-3 modulated by the 4.8 hour period.

These results fueled a burst of speculation as to their possible cause. The parents of most muons are charged, long-lived hadrons whose arrival directions do not point back to their sources due to deflections in the galactic magnetic field. Aside from the tremendous flux of neutrinos needed to produce any noticeable signal, the zenith angle distribution of the muons observed ruled out this explanation[14]. Gamma rays seem the obvious choice. However, there were too many muons to be explained by pair production from the known gamma ray fluxes, even if one stretched the standard model to extremes[3]. With straightforward ideas ruled out, exotic theories started to appear. Several authors postulated new, long-lived neutral particles that interact hadronically[15,16]. These were named "Cygnets" after their supposed source. Others suggested that UHE gamma rays might start interacting like hadrons instead of photons[17,18,19], or that some neutrinos might interact strongly[20]. These theories involved major departures from the standard model.

No more UHE gammas have been detected coming from the sources in question[21], severely constraining the possibility of a gamma ray source for the muons.

Additionally, recent results from the HERA collider support the standard model in the case of high energy photon interactions[22]. Furthermore, no astrophysical sources in general and Cyg X-3 in particular have been seen again in muons by any underground group other than the Soudan collaboration. Frejus[23], IMB[24], Homestake[25], and Kamiokande[26] have all given null results. Neither did previous studies using MACRO[27,28,29] find any muon signal. On the other hand, the Soudan 2 group has seen an astrophysical muon signal on another occasion. It was a burst of muons from Cyg X-3 coincident with a large radio burst in January 1991[30] (see Chapter 7).

1.4 The Goals of this Analysis

This analysis will examine the sky once more using the muons seen by the MACRO detector. MACRO has recorded an order of magnitude more muons since the last such search, improving the sensitivity of this analysis. Furthermore, MACRO will demonstrate its ability to see a nearby astronomical object, the moon, and to detect small fluctuations in the muon signal by looking for seasonal variations in the absolute muon rate. These two results are simple tests of the functionality of MACRO as a muon telescope. An experiment must be able to find such expected effects before it can make a statement, either pro or con, about any unexpected effects. No other underground experiment has seen the shadow of the moon, and the Soudan experiments have seen neither signal.

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