Chapter I

INTRODUCTION

The study of the extragalactic background radiation is important to our understanding of the structure and the evolution of the Universe. In fact, the study of the background radiation has played an important role in the history of astronomy and has been referred to as the oldest problem in cosmology. Dating back to the mid-eighteenth century, the question "Why is the sky dark at night?" known as Olbers' paradox, has played a crucial role in the development of cosmology. The paradox is as follows: "In a Universe consisting of unbounded space populated endlessly with luminous stars, a line of sight in any direction from the eye, extended into the depths of space, eventually intercepts the surface of a star. Visible stars should therefore cover the entire night sky without any separating gaps. Hence, the riddle of cosmic darkness: Why is the sky dark at night?" (Harrison 1990).

The background radiation is a unique source of information in cases where the source is truly diffuse in nature or consists of the integrated emission from numerous unresolved sources. Cosmology and astrophysical studies relating to the distribution and evolution of galaxies and the large-scale structure of the Universe draw heavily upon the nature of the extragalactic radiation across the entire electromagnetic spectrum. For example, the blackbody spectrum of the cosmic microwave background radiation is predicted in the Big-Bang theory. Precise measurements of the microwave background radiation has been key to the general acceptance of the Big-Bang theory of cosmology.

In the context of gamma rays, the extragalactic background is particularly important because of the transparency of the universe to gamma rays. To illustrate the transparency of gamma rays, consider a 2 MeV gamma-ray traveling across the Universe at critical density ($\sim 10^{-29}$ g/cm^3). The mass-attenuation coefficient for a 2 MeV photon in hydrogen is 0.025 cm^2/g. Assuming the age of the Universe to be 15×10^9 years, the 2 MeV photon traverses 0.15 g/cm^2 of material or equivalently only 0.4% of a mean free path. This illustrates the power of gamma rays as probes of the early Universe. More detailed calculations that incorporate the effects of photon-photon annihilation and Compton scattering by intergalactic electrons show that the Universe becomes opaque to 1–100 MeV gamma rays above redshifts of 100 (Stecker 1974). In a similar fashion, the Galactic center is opaque to visible light, ultraviolet and X radiation but is transparent to gamma rays. Thus one is able to observe high energy processes at the Galactic center with little loss of information due to scattering.

The dominant feature of the gamma-ray sky is the narrow band of intense radiation that lies along the Galactic plane. The gamma-ray intensity rapidly decreases as we move away from the Galactic plane. The Galactic plane emission is strongest in the inner 100° wide band about the Galactic center. The width of the emission along the plane varies with energy, it is about ~5–10° wide between 1–10 MeV (Strong 1996), and decreases to ~2–5° above 100 MeV (Hunter et al. 1997). This emission is usually referred to as the diffuse galactic emission. Superimposed on the diffuse Galactic emission is the isotropic diffuse extragalactic radiation. Besides the diffuse emissions there are numerous gamma-ray point sources distributed mostly along the galactic plane (e.g., pulsars, Black-hole candidates, X-ray binaries) that constitute the Galactic sources. The sky is also populated more uniformly with extragalactic point sources (e.g., AGNs, BL Lacs). In addition, there are gamma rays from transient sources like gamma-ray bursts or solar flares.

The diffuse Galactic gamma-ray emission is usually associated with the production of gamma rays in the interactions of primarily cosmic-ray protons and electrons with the interstellar medium. The emission above ~100 MeV is dominated by π^0 decay, resulting from interactions between cosmic-ray protons and nuclei of interstellar gas. For the emission below ~100 MeV, the bremsstrahlung losses of lower energy electrons (E_e <100 MeV) and the inverse-Compton radiation due to the scattering of interstellar photon radiation by the higher energy electrons (E_e >100 MeV) become increasingly important.

The existence of antimatter in the Universe can be investigated through its distinct annihilation signature, i.e., π^0-decays produced in proton-antiproton annihilations and the 0.511 MeV emission from electron-positron annihilations. The importance of gamma-ray astronomy as a probe of this annihilation radiation is evident. The steady-state theory of cosmology requires a spontaneous and continuous creation of *new* matter. Antiparticles are also created to conserve the baryon and lepton numbers. Earlier satellites (e.g., Ranger, OSO-3) measured gamma-ray intensities significantly lower than the predictions for the annihilation radiation by the steady state theory (Fichtel and Kniffen 1974; Gould and Burbidge 1967). The gamma ray measurements contributed to the dismissal of the steady-state theory of cosmology.

The properties of the cosmic diffuse gamma (CDG) radiation are not measured as well as those of the X-ray diffuse radiation. The difficulties in measuring the diffuse gamma radiation vary with energy. At lower energies (0.5–10 MeV), the major difficulty is the intense instrumental background. The instrumental background is created both in the surrounding material and in the detector itself. At higher energies (>100 MeV) the diffuse Galactic emission is intense, so it is important to accurately separate the Galactic diffuse radiation from the extragalactic diffuse emission.

The CDG radiation is assumed to be isotropic in space and constant in time. Hence, there are no unique spatial or temporal variations to distinguish the CDG radiation from the background radiation. Background radiation here refers to all non-cosmic sources of gamma radiation. The CDG measurement is usually made by first subtracting all of the background sources (including the instrumental background and atmospheric photons) and then attributing the residual flux to the CDG radiation. This often results in the subtraction of comparably sized numbers yielding values with relatively large errors.

The striking feature of the CDG spectrum in the MeV range, measured prior to COMPTEL, was an apparent flattening between 1 and 10 MeV. A simple power law extrapolation from the X-ray regime showed the presence of an excess, dubbed the *MeV bump*, in the 1–10 MeV range. The spectrum above 10 MeV seemed to join smoothly with the CDG measurements above 50 MeV. The measurement of this excess was tentative with different amounts of excess reported in measurements by different groups.

Some of the arguments for the validity of the bump were: (1) the presence of the flattening in the MeV region was present since its earliest detection (Arnold et al. 1962;

Metzger et al. 1964; Vette et al. 1970; Vedrenne et al. 1971; Golenetski et al. 1971); (2) the CDG measurements by numerous groups (Schönfelder, Graml, and Penningsfeld 1980; Trombka et al. 1977; White et al. 1977), using different types of detectors (omnidirectional spectrometers, Compton telescopes), showed the presence of an excess at some level; (3) the excess was seen with detectors in interplanetary space, low-Earth orbits and balloon payloads; (4) the existence of a theoretical framework in which the MeV bump was expected in the CDG spectrum (Stecker 1971; 1985).

Some of the arguments against the existence of the bump were: (1) as early as 1972 it was realized that cosmic-ray induced radioactivity was an important source of background in the MeV region (Fishman 1972); (2) refinements in the data analysis showed many of the original measurements were too high (Trombka et al. 1973; Vette et al. 1970) because of the background due to induced activity, consequently the level of the MeV bump had reduced since the early detections; (3) since the higher levels for the excess in earlier measurements were attributed to incomplete background correction, many suspected this to be the case even for the later measurements; (4) the neutron-induced background was particularly difficult to estimate since it mimics gamma-ray events.

Although widely accepted, the shape and the intensity of the CDG spectrum in the 1 to 10 MeV range was considered controversial. Most of the measurements of the CDG spectrum prior to COMPTEL were performed in the 70's and ended by the early 80's. This was the status of the MeV CDG spectrum for the next 15 years before the COMPTEL instrument.

Notwithstanding the controversial nature of the data, there were attempts to interpret the CDG spectrum in the MeV energy range. There were detailed models involving either π^0 production by cosmic-ray interactions with intergalactic gas or matter-antimatter annihilation at early epochs in the Universe (Stecker 1971). Other models to account for the MeV bump included inverse Compton scattering by relativistic electrons, nuclear lines produced in the supernovae, nonthermal bremsstrahlung by electrons in intergalactic space and relativistic thermal bremsstrahlung from a hot MeV plasma residing in the intergalactic space. Many of these earlier models for the CDG radiation have been reviewed by others (see for example Fichtel, Simpson, and Thompson 1978; Fichtel and Trombka 1981; Silk 1973).

Active galaxies were also postulated to be possible contributors to the high-energy diffuse radiation (Bignami et al. 1979). At X-ray energies around a few keV, the results of the Einstein Deep Survey (Giacconi et al. 1993) and Rosat Deep Observations (Hasinger et al. 1993; Shanks et al. 1991) show that a significant fraction of the diffuse radiation is due to unresolved sources. Before the launch of the *Compton* Observatory, high-energy gamma-ray emission was detected from only one nearby quasar 3C 273. Now there are over 60 AGNs detected by the EGRET instrument. Active galaxies are now considered a likely source of the extragalactic diffuse radiation between 10 and 500 keV and above 100 MeV.

Diffuse radiation, in the MeV energy range, is predicted in the context of a baryon-symmetric Universe, where the Universe separated into regions of matter and antimatter at early epochs. The presence of the MeV bump, where the gamma rays arise from matter-antimatter annihilations (Stecker 1978, 1985), was considered to be the experimental evidence for the existence of cosmological antimatter. Therefore, the CDG radiation at MeV energies has ramifications for both cosmology and particle physics since it addresses a fundamental question: Is the Universe baryon-symmetric or baryon-asymmetric?

With important cosmological interpretations drawn from these studies, it has become important to improve the credibility of the experimental results in the MeV range. The measurement of the CDG spectrum in the 1 to 30 MeV range is the subject of this thesis.

With the launch of the Imaging Compton telescope COMPTEL, there were expectations to make precise measurements of the CDG spectrum in the MeV energy range. Although COMPTEL is primarily an imaging detector, it is well suited to measure with greater precision and accuracy the CDG flux mainly because of its large detection area, low-background, wide field-of-view (~1.5 sr) and long exposure times. However, COMPTEL is the first Compton telescope exploring the MeV energy range from a satellite platform, the nature of the background in orbit is different than the environment at the top of the atmosphere. The response of COMPTEL to neutrons (Morris et al. 1995) also showed that the neutron-induced background is an important background component. As a result, there was no prior available analysis procedure defined within the COMPTEL collaboration for making the CDG measurement.

The difficulties in measuring the CDG spectrum with medium-energy gamma-ray detectors, such as COMPTEL is unique due to the intense instrumental background. The intimate relationship between the medium-energy gamma rays and nuclear de-excitations ensures that the telescope itself becomes a bright source of background, especially when it operates in regions of intense high energy particle fluxes. For the EGRET instrument, operating at higher energies (>100 MeV), the instrumental background is more than an order of magnitude lower than the intensity of the CDG radiation (Sreekumar et al. 1998). The FIRAS instrument aboard the COBE satellite uses a differential technique by comparing the blackbody spectrum from the sky to an internal blackbody source to measure the microwave background radiation (Mather et al. 1990).

The goal of this thesis is to describe measurements of the cosmic diffuse gamma-ray (CDG) spectrum from 800 keV to 30 MeV with the COMPTEL instrument. Some of the new key elements in the CDG analysis include the use of the time-of-flight measurement to improve the signal-to-background ratio, devising a unique method to eliminate atmospheric photons from the COMPTEL data, using the charged-particle detector rates as measures of the prompt background, and employing Monte Carlo simulations to determine the absolute COMPTEL response to the diffuse isotropic radiation and to determine the dataspace characteristics of background events from the decay of long-lived radioactive isotopes.

The CDG spectrum is constructed by measuring the count rate of gamma rays from high galactic latitudes during periods when the Earth is outside the COMPTEL field-of-view. The instrumental counts contains contributions from the prompt and delayed background components. Special data selections are applied to suppress them. Above 4.2 MeV, in the absence of long-lived background, the count rates are extrapolated to zero cosmic-ray intensity to eliminate the prompt background and arrive at the CDG count rates. The prompt background is produced primarily by the interactions of neutrons and protons with the spacecraft. The delayed emission from long-lived radioactivity, present only below 4.2 MeV, is determined by fitting the energy spectrum. Their contributions are then subtracted from the data. Below 4.2 MeV, the long-lived background corrected counts are extrapolated to zero cosmic-ray intensity to determine the CDG count rate. The CDG flux is determined by deconvolving the resultant count spectrum with the computed instrument response for an isotropic diffuse source having a power-law distribution in energy. These COMPTEL CDG flux values in the 1 to 10 MeV range are about 5–10 times lower than those of the pre-COMPTEL estimates. The measurements show no evidence for a MeV bump in the 1 to 10 MeV range. The CDG spectrum in the 1 to 30 MeV range is well described by a power-law photon spectrum with an index of -2.4 ± 0.2.

This thesis consists of four major parts. The introductory chapters include the instrument description and the instrument response. A general overview of the instrumental background and the technique developed to remove the atmospheric contribution from celestial observations is presented.

Following these introductory sections is a detailed discussion of the instrumental background. The distribution of events in time-of-flight space is examined. The energy spectrum and its overall behavior is discussed followed by a discussion of the long-lived background component. The veto-rate measurements used to compute the prompt background are introduced.

In the third part, the CDG analysis method is explained. Because of the complex nature of the background the analysis procedure varies with energy. The analysis technique for each energy range is discussed individually. Calculations of the systematic errors are shown.

In the fourth part, I present the CDG spectrum. An explanation for the MeV bump in earlier measurements is discussed. The popular models used to explain the CDG emission and the implication of the COMPTEL measurements are also discussed.