Institute of Physics

Series in Astronomy and Astrophysics

Very High Energy Gamma-Ray Astronomy

T C Weekes

IoP

Very High Energy Gamma-Ray Astronomy

Series in Astronomy and Astrophysics

The Series in Astronomy and Astrophysics includes books on all aspects of theoretical and experimental astronomy and astrophysics. Books in the series range in level from textbooks and handbooks to more advanced expositions of current research.

Other books in the series

The Physics of Interstellar Dust
E Krügel

Dark Sky, Dark Matter
J M Overduin and P S Wesson

Dust in the Galactic Environment, 2nd Edition
D C B Whittet

An Introduction to the Science of Cosmology
D J Raine and E G Thomas

The Origin and Evolution of the Solar System
M M Woolfson

The Physics of the Interstellar Medium
J E Dyson and D A Williams

Dust and Chemistry in Astronomy
T J Millar and D A Williams (eds)

Observational Astrophysics
R E White (ed)

Stellar Astrophysics
R J Tayler (ed)

Forthcoming titles

Numerical Methods in Astrophysics
P Bodenheimer, G Laughlin, M Rozyczka and H W Yorke

Series in Astronomy and Astrophysics

Very High Energy Gamma-Ray Astronomy

Trevor Weekes

Whipple Observatory, Harvard–Smithsonian Center for Astrophysics, USA

IoP

Institute of Physics Publishing
Bristol and Philadelphia

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Version Date: 20150217

International Standard Book Number-13: 978-1-4200-3319-9 (eBook - PDF)

Visit the Taylor & Francis Web site at
http://www.taylorandfrancis.com

and the CRC Press Web site at
http://www.crcpress.com

To Ann who gave me moral support through four decades of gamma-ray astronomy

Contents

Foreword

Astronomy is a conservative branch of science and astronomers have not always been quick to acknowledge and to welcome new avenues of research for the investigation of cosmic sources. This is particularly true when the new discipline is limited to a small number of, possibly pathological, objects. Radio astronomy was slow to be accepted because it was soon apparent that most stars were not radio sources. In contrast, x-ray astronomy, once the techniques were sufficiently developed, was immediately recognized as a true 'astronomy' since almost every star and galaxy, at some level, was seen to be an x-ray emitter. With the advent of detailed spectral and imaging techniques, it was quickly seen that x-ray astronomers, even if their detectors and observatories were strange, still spoke the language of astronomy.

This is not the case with gamma-ray astronomy. Gamma-ray sources, particularly high energy ones, are as sparse in the cosmos as they are on earth. The telescopes used to detect them are unlike those in any other waveband and there is a complete absence of gamma-ray reflecting optics: the 'telescope' is only as big as the detector! The actual detectors have more in common with particle physics laboratories than astronomical observatories and the practitioners have generally come from the high energy particle physics community. It is small wonder, therefore, that the astronomical community has been reluctant to consider gamma-ray astronomy as a legitimate or useful discipline for astronomical investigation. The fact that the early history of gamma-ray astronomy was muddied by over-enthusiastic interpretation of marginal results did not help.

As the techniques have been developed and detections put on a firm footing, it has become apparent that it is the highest energy photons that are the real tests of source models. The detection of gamma-ray bursts has opened the eyes of the astronomical community to a new dimension, a gamma-ray universe where the energies are fantastic and the lifetimes are fleeting. While it is unlikely that gamma-ray astronomy will ever command the same attention as optical or x-ray astronomy, it has established itself as a discipline that all would-be or practicing astronomers should have some familiarity with.

This monograph attempts to bridge this cultural gap by summarizing the status of gamma-ray astronomy at energies above 30 MeV at a critical point in the development of the discipline: the hiatus between the demise of the Energetic

Gamma Ray Experiment Telescope (EGRET) telescope and the launch of the next generation space telescope, GLAST, as well as the hiatus before the completion of the next generation of imaging atmospheric Cherenkov detectors involving large arrays of telescopes. The present state of knowledge from observations of photons between 30 MeV and 50 TeV is summarized. Some attempt is made to describe the canonical explanations offered by theoretical models but this is still an observation-driven discipline. Although this branch of gamma-ray astronomy has been covered in previous works, this will be one of the first to focus on this energy band and to emphasize the higher energies.

Nothing dates a work more than a description of future developments but upcoming missions and projects are briefly described. In contrast, the early history is timeless and tells much. Each chapter has a brief historical note which describes a key development in that area. The principal processes by which gamma rays are produced and absorbed are well known and are well covered in standard physics texts. The appendix provides a brief summary of the most important processes.

Those who have worked in gamma-ray astronomy over the past four decades know what a wild and sometimes frustrating ride it has been. But I cannot think of a more exciting and exasperating profession nor can I imagine a more interesting time to be an astrophysicist in any discipline. That the discipline of gamma-ray astronomy has come to what it is today is in no small way due to the heroic efforts of those pioneers who more than 40 years ago gambled on there being a gamma-ray universe without even knowing there was an x-ray one. Those of us who followed those early pioneers have had the comfort of walking in their footprints and knowing that there was something to see at the end of the difficult path. Personally I have benefited greatly from the guidance of my early mentors, John Jelley and Neil Porter—physicists with their creativity and persistence are seldom encountered in my experience.

Gamma-ray astronomy has an artificial division at energies of about 100 GeV; below this energy the field thrives in the well-funded laboratories of space astronomy and above it, the work is done with more meagre resources by university groups using ground-based telescopes. Although the astrophysics of the sources does not recognize this energy break point, the two communities have a cultural divide and seldom overlap. In the intervals between operating gamma-ray satellites, the space community does not flock to use the ground-based instruments and equally the guest investigator programs of the space telescopes are not crowded with ground-based gamma-ray astronomers. This artificial divide is inevitably reflected in the subject matter of this monograph in which the two energies regions are often treated as if they were distinct.

In this work I have tried to emphasize the history as I know it. I have tried to be as accurate as possible but some things are a matter of interpretation. Inevitably there is some personal bias for which I have no apologies; it would be a sterile work if it did not reflect some personal opinions.

I am grateful to the many colleagues in the gamma-ray community who have

shared their expertise and enthusiasm with me along the way; I am particularly grateful to members of the VERITAS gamma-ray collaboration who have been the stimulus for much of this work. Several colleagues read sections of the manuscript at various stages of production and made helpful suggestions; errors that remain are my responsibility. These readers included Mike Catanese, Valerie Connaughton, David Fegan, Stephen Fegan, Jerry Fishman, Jim Gaidos, Ken Gibbs, Michael Hillas, Deirdre Horan, Dick Lamb, Pat Moriarty, Simon Swordy and David Thompson. I am also appreciative of the many colleagues who supplied figures, including Michael Briggs, Werner Collmar, Stephen Fegan, Neil Gehrels, Alice Harding, Deirdre Horan, Stan Hunter, Kevin Hurley, John Kildea, Rene Ong, Toru Tanimori, and David Thompson. Irwin Shapiro has been a major supporter of VHE gamma-ray astronomy at the Smithsonian Astrophysical Observatory over the past two decades and I am proud to be a member of his staff. My wife, Ann, has, as always, been supportive and has also provided editorial assistance. I should also acknowledge the role of the funding agencies—but for their tardiness in funding the next generation of detectors I would have been hard put to find the time to put this work together.

Chapter 1

Foundations of gamma-ray astronomy

1.1 Astronomical exploration

Our knowledge of the physical universe beyond the earth comes almost entirely from the electromagnetic radiation received by our eyes or our manmade sensors. The environs of the earth, which we can explore directly, constitutes perhaps 10^{-58} times the volume of the universe. In our lifetime, mankind has seen the extension of the universe that can be physically explored with space probes to the distance of the Solar System's furthest planets. Human exploration thus far is limited to the moon, a tiny step on the cosmic scale. Although it is now feasible to consider unmanned space probes that will reach out to the nearest stars, it is still true that, in the foreseeable future, mankind will be limited to the observation of the radiations from distant sources as the sole means of exploring the distant cosmos.

It is important to emphasize that the astronomers who make a study of these radiations are always passive observers, never experimenters, in the sense that they do not control the experimental environment. This passive role is often a frustration to the high energy physicists who shift their interests into the realm of high energy astrophysics. The inability to control the experimental environment, to repeat the experiment to get better statistics, to vary the process with different input parameters... such limitations seem to make the astronomer powerless and a victim of circumstance.

But astronomers have two powerful weapons at their disposal: the number and variety of sources that they can observe; and the number of ways in which they can observe them. By observing a variety of versions of the same source, they can observe what they can hypothesize to be the same process, at different points in time. Moreover, by observing with the vast panoply of sensors now available, they can see the process in many different 'lights' and thence thoroughly explore the phenomenon. It is thus advantageous to use every conceivable band of the electromagnetic spectrum at its maximum sensitivity.

There is one other advantage that is uniquely available to them as astronomical observers: because they now have tools that permit the observation of sources at great distances they are also looking out at sources separated from them not only in distance but also in time. Thus they can consider the universe surrounding them to be like the layers of an onion; each layer is a chapter in the history of the universe and by comparing the differences in similar objects in adjacent layers they can see the evolution with time. The outermost layer is, of course, the beginning of time, the point when the expansion began and beyond which they have no knowledge. It is one of the outstanding contributions of modern astrophysics that we now have observations that pertain to the very first few seconds of this process. Modern cosmologists have become observational scientists but to continue their work they must use every tool at their disposal to probe these ultimate questions. Radiation that can penetrate great distances is thus of great value in these explorations.

It was inevitable that astronomers would want to explore every decade of the electromagnetic spectrum, no matter how far removed from ordinary terrestrial experience. Prior to the Second World War, the 'visible' band was the only really observational branch of astronomy but it was one that was extraordinarily rewarding since it was tuned to the peak in the spectrum of ordinary stars like our sun, to the transparency of the atmosphere, and to the sensitivity of the most accessible and versatile sensor, the human eye. The Second World War was to produce the radar technology that formed the basis of practical radio astronomy and the rocket technology that enabled x-ray astronomy. We can only speculate what the human perception of the cosmos would be if our human radiation sensors were in a band to which the atmosphere was largely opaque.

Photons are, by any definition, rather dull specimens in the cosmic particle zoo. However, one can argue that their very dullness, their lack of charge, mass, and moment, their infinite lifetime, their appearance as a decay product in many processes, their predictability, all combine to make them a valuable probe of the behavior of more exotic particles and their environs in distant, and therefore difficult to study, regions of the universe. Certainly no one can argue that photon astronomy at low energies (optical, radio and x-ray) has not largely shaped our perception of the physical universe!

1.2 The relativistic universe

Our universe is dominated by objects emitting radiation via thermal processes. The blackbody spectrum dominates, be it from the Big Bang (the cosmic microwave background), from the sun and stars, or from the accretion disks around neutron stars and other massive objects. This is the *ordinary* universe, in the sense that anything on an astronomical scale can be considered ordinary. It is tempting to think of the thermal universe as *THE UNIVERSE* and certainly it accounts for much of what we know about. However, to ignore the largely unseen, non-thermal, *extraordinary*, relativistic universe is to miss a major component and one that is of particular interest to the physicist, particularly the particle physicist. The relativistic universe is pervasive but largely unnoticed and involves physical processes that are difficult, if not impossible, to emulate in terrestrial laboratories. The most obvious local manifestation of this relativistic universe is the cosmic radiation, whose origin, 90 years after its discovery, is still largely a mystery (although it is generally accepted, *but not yet proven*, that much of it is produced in shock waves from galactic supernova explosions). The existence of this steady rain of relativistic particles, whose power-law spectrum confirms its non-thermal origin and whose highest energies extend far beyond that achievable in manmade particle accelerators, attests to the strength and reach of the forces that power this strange relativistic radiation. If thermal processes dominate the *ordinary* universe, then truly relativistic processes illuminate the *extraordinary* universe and must be studied, not just for their contribution to the universe as a whole but as the denizens of unique cosmic laboratories where physics is demonstrated under conditions to which we, terrestrial physicists, can only extrapolate.

The observation of the extraordinary universe is difficult, not least because it is masked by the dominant thermal foreground radiation. In some instances, we can see it directly such as in the relativistic jets emerging from active galactic nuclei (AGN) but, even there, we must subtract the overlying thermal radiation from the host elliptical galaxies. Polarization leads us to identify the processes that emit the radio, optical, and x-ray radiation as synchrotron emission from relativistic particles, probably electrons, but polarization is not unique to synchrotron radiation and the interpretation is not always unambiguous. The hard power-law spectrum of many of the non-thermal emissions immediately suggests the use of the highest radiation detectors to probe such processes. Hence, hard x-ray and gamma-ray astronomical techniques must play an increasingly prominent role among the observational disciplines of choice for the exploration of the relativistic universe.

The development of techniques whereby gamma rays of energy 100 GeV and above can be studied from the ground, using indirect, but sensitive, techniques is relatively new and has opened up a new area of high energy photon astronomy. The exciting results that have come from these studies include the detection of TeV photons from supernova remnants and from the relativistic jets in AGN.

Astronomy at energies up to a few GeV made dramatic progress with the launch of the Compton Gamma Ray Observatory (CGRO) in 1991. Beyond 10 GeV it is difficult to study gamma rays efficiently from space vehicles, both because of the sparse fluxes, which necessitate large collection areas, and the high energies, which make containment within a space telescope a serious problem.

The primary purpose of the astronomy of hard photons is the search for new sources, be they point-like, extended, or diffuse but this new astronomy also opens the door to the investigation of more obscure phenomena in extreme astrophysical environments and processes and even in cosmology and particle physics.

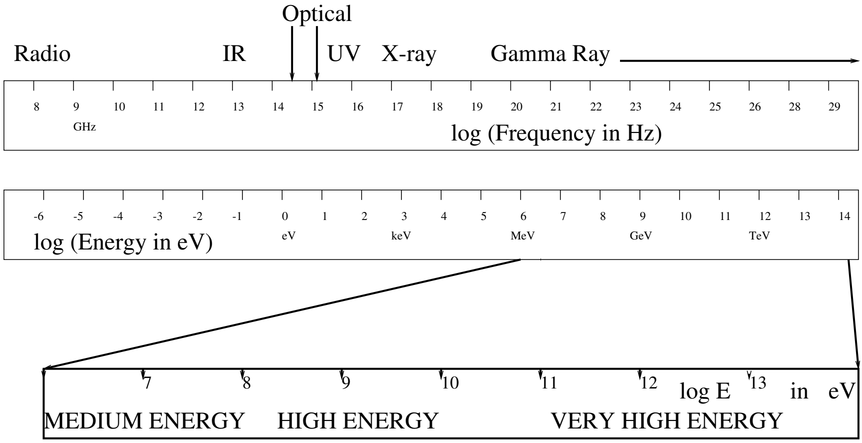

Figure 1.1. Electromagnetic spectrum showing the full extent of the part covered by the generic term, 'gamma rays'. The sub-divisions are defined in the text.

1.3 Definitions

The term 'gamma ray' is a generic one and is used to describe photons of energy from about 100 keV (10^5 eV) to $>$100 EeV (10^{20} eV). A range of 15 decades is more than all the rest of the known electromagnetic spectrum, i.e. from very long wavelength radio to hard x-rays (figure 1.1). A wide variety of detection techniques is, therefore, necessary to cover this huge band. This monograph will concentrate on the somewhat restricted gamma-ray band from 30 MeV to 100 TeV. The choice of this range is easy. It is the energy range where the detection techniques are relatively mature and have the maximum sensitivity; therefore, the best observational results have been obtained in these bands. Previous books [2, 12, 8, 10, 7, 11] have covered the full gamut of 'gamma-ray astronomy' above 100 keV with some loss of emphasis above 100 GeV where there were few results to report. There is, in fact, little in common between the phenomenon of nuclear line emission at MeV energies and the broad emission spectra of AGN at GeV–TeV energies. Hence it can be argued this restricted band of more than six decades (3×10^7 eV to 1×10^{14} eV) deserves a treatment on its own.

Even this band must be divided into two broad bands which are defined here, somewhat arbitrarily: the High Energy (HE) band from 30 MeV to 100 GeV and the Very High Energy (VHE) band from 100 GeV to 100 TeV (table 1.1). The band below 30 MeV (from about 1 to 30 MeV) is often called the Medium Energy (ME) region and that beyond 100 TeV, the Ultra High Energy (UHE) region. These gamma-ray regions are not defined by the physics of their production but by the interaction phenomena and techniques employed in their detection.

Table 1.1. Gamma-ray bands.

Band	Low/medium	High	Very High	Ultra High
Shorthand	LE/ME	HE	VHE	UHE
Range	0.1–30 MeV	30 MeV–100 GeV	100 GeV–100 TeV	>100 TeV
Typical energy	keV–MeV	MeV–GeV	TeV	PeV–EeV
Environment	Space	Space	Ground-based	Ground-based

Below 30 MeV, the Compton process is the dominant interaction process and Compton telescopes are used in their study; these techniques are difficult and inefficient but important because they include the potential study of nuclear lines. They will be only discussed briefly here. The detection techniques in the HE and VHE ranges use the pair-production interaction but in very different ways: HE telescopes identify the electron pair in balloon or satellite-borne detectors, whereas VHE detectors detect the resulting electromagnetic cascade that develops in the earth's atmosphere. As yet there are no credible detections of gamma rays at energies much beyond 50 TeV and hence the upper energy cutoff is a natural one at this time. Furthermore the 'gamma-ray telescope' techniques used beyond these energies are really the same as those used to study charged cosmic rays and, hence, are best studied in that context.

The boundaries of these bands are a matter of personal choice and different authors have defined the regions differently. However, most would agree that the HE region is characterized by observations in the 100 MeV range and the VHE region by observations around 1 TeV. That gamma-ray astronomy is still an observation-dominated discipline is apparent from these definitions.

1.4 The heroic era of gamma-ray astronomy

1.4.1 The early promise

Gamma rays are the highest energy photons in the electromagnetic spectrum and their detection presents unique challenges. On one hand, it is easy to detect gamma rays. The interaction cross sections are large and above a few MeV the pair production interaction, the dominant gamma-ray interaction with matter, is easily recognized. Gamma-ray detectors were already far advanced when the concept of 'gamma-ray astronomy' was first raised in Phillip Morrison's seminal paper in 1958 [9] (see historical note: seminal paper). Indeed it was the expected ease of detection and the early promise of strong sources that led to the large concentration of effort in this field, even before the development of x-ray astronomy. Today the number of known gamma-ray sources is well under a few hundred whereas there are hundreds of thousands of x-ray sources. Why have the two fields developed so differently?

The answer is simple: the detection of cosmic gamma rays was not as easy as expected and the early predictions of fluxes from cosmic sources were hopelessly optimistic.

1.4.2 Peculiarities of gamma-ray telescopes

There are several peculiarities that uniquely pertain to astronomy in the gamma-ray energy regime. These factors make gamma-ray astronomy particularly difficult and have resulted in the relatively slow development of the discipline.

In nearly every band of the electromagnetic spectrum, astronomical telescopes make use of the fact that the cosmic rain of photons can be concentrated by reflection or refraction, so that the dimensions of the actual photon detector are a small fraction of the telescope aperture. How limited would have been our early knowledge of the universe if the optical astronomer had not been aided by the simple refracting telescope which so increased the sensitivity of the human eye! The radio astronomer, the infrared astronomer, even the x-ray astronomer, depends on the ability of a solid surface to reflect and, with suitable geometry, to concentrate the photon signal so that it can be detected above the background by a small detector element.

Above a few MeV, there is no efficient way of reflecting gamma rays and hence the dimensions of the gamma-ray *detector* are effectively the dimensions of the gamma-ray telescope. (As we shall see in the next chapter this is not the case for ground-based VHE telescopes.) In practice, to identify the gamma-ray events from the charged particle background it is necessary to use detectors whose efficiency is often quite low. Hence, at any energy the effective aperture of a space-borne gamma-ray telescope is seldom greater than 1 m^2 and often only a few cm^2, even though the physical size is much larger. The Compton Gamma Ray Observatory was one of the largest and heaviest scientific satellites ever launched; however, its ME and HE telescopes had effective apertures of 5 cm^2 and 1600 cm^2 respectively. Beam concentration is particularly important when the background scales with detector area. This is always the case with gamma-ray detectors which must operate in an environment dominated by charged cosmic rays.

The problem of a small aperture is compounded by the fact that the flux of cosmic gamma rays is always small. At energies of 100 MeV the strongest source (the Vela pulsar) gives a flux of only one photon per minute in telescopes flown to date. With weaker sources, long exposures are necessary and one is still dealing with the statistics of small numbers. Small wonder that gamma-ray astronomers have been frequent pioneers in the development of statistical methods and that early gamma-ray conferences were often dominated by arguments over real statistical significances! As it is to photons in many bands of the electromagnetic spectrum, the earth's atmosphere is opaque to all gamma rays. Even the highest mountain is many radiation lengths below the top of the atmosphere so that it is virtually impossible to consider the direct detection of cosmic gamma rays without the use of a space platform. Large balloons can carry the bulky detectors

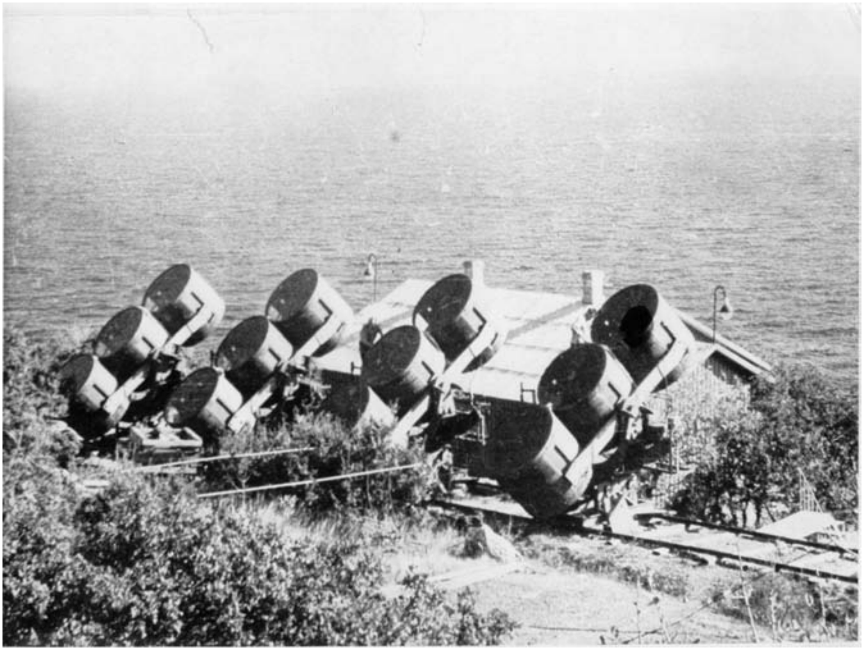

Figure 1.2. The Lebedev Institute experiment that operated in the Crimea, *c*. 1960–64. This was the first major VHE gamma-ray telescope. (Photo: N A Porter.)

to near the top of the atmosphere and much of the pioneering work in the field was done in this way. However, the charged cosmic rays constitute a significant background and limit the sensitivity of such measurements.

The background can take many forms. In deep space it is the primary cosmic radiation itself, mostly protons, heavier nuclei and electrons. This background can be accentuated by secondary interactions in the spacecraft. Careful design and shielding can reduce this effect, as can active anti-coincidence charged-particle shields. However, at low energies induced radioactivity in the detector and its surrounds can be a serious problem. In balloon experiments gamma rays in the secondary cosmic radiation from the cosmic ray interactions in the atmosphere above the detector seriously limit the sensitivity and were the initial reason for the slow development of the field. Huge balloons that carry the telescopes to within a few grams of residual atmosphere are a partial solution but it is still impossible to trust the measurement of absolute diffuse fluxes.

1.4.3 VHE gamma-ray telescopes on the ground

Shortly after the detection of atmospheric Cherenkov radiation (see appendix) from cosmic ray air showers, the phenomenon was utilized to look for point-