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High-energy astrophysics – energies above 100 keV

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Abstract

γ-rays represent the most energetic photons of the electromagnetic spectrum. Astronomy with γ-rays, therefore, allows us to study the most compact, energetic and violent objects in the Universe. These are neutron stars, stellar and massive black holes, supernovae and their remnants. An overview of the history of γ-ray astronomy, the production mechanisms for γ-rays, and an overview of the main results achieved are given.

Introduction

γ-ray astronomy at present ranges from about 100 keV to more than 10 TeV — these are eight orders of magnitude in photon energy. This range is comparable to that from radio to optical astronomy. Thus it is plausible that in γ-ray astronomy we are dealing with a variety of different objects and phenomena. Some of these objects even have their maximum of luminosity at γ-ray energies. It is, therefore impossible to understand the physics of these objects without knowing their γ-ray properties.

γ-rays cannot penetrate the Earth's atmosphere without interaction; the interaction length of rays in air is about 50 $\mathrm{g\,cm^{-2}}$ for photon energies of 10 MeV and shorter at lower and higher energies. Considering the total depth of the atmosphere of 1000 $\mathrm{g\,cm^{-2}}$, it is clear that cosmic γ-rays cannot reach the ground without many interactions in the atmosphere. γ-ray astronomy is separated into two main branches: spaceborne and ground-based. Spaceborne γ-ray astronomy ranges from about 100 keV to typically 50 GeV to 100 GeV. The γ-ray telescopes in this range are carried by balloons or satellites to the top of or outside the Earth's atmosphere. Above 100 GeV the photon fluxes of cosmic sources are so small that reasonable numbers of photons cannot be collected by space telescopes due to their limited detection areas, but cosmic γ-rays can be detected from the ground. At such high energies the primary γ-rays form electromagnetic cascades in the Earth's atmosphere, which propagate through the atmosphere in the direction of the original γ-ray. The secondary electrons and positrons of these cascades

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are observed at ground level by large arrays of large-area optical telescopes via the emitted Čerenkov radiation. Much progress has been achieved during the last decade in this young branch of γ-ray astronomy. However, in this book we restrict the coverage to spaceborne γ-ray astronomy.

Time-line development of γ-ray astronomy from space

The history of γ-ray astronomy from the early 1960s till now is illustrated in Figure 3.1. The first real cosmic γ-ray detections were those made by *Explorer-11* and *OSO-3* in 1961 and 1968 (Kraushaar et al 1965, 1972). Both experiments were designed to measure high-energy γ-rays above 50 MeV. *Explorer-11* detected in total 31, and *OSO-3* 621 cosmic γ-ray photons. The *OSO-3* results already showed clear evidence for γ-ray emission from the Milky Way. The cosmic γ-ray burst phenomenon was discovered at about the same time — namely in 1967 by the network of *Vela* satellites of the US Department of Defense, which were designed to monitor nuclear tests in the atmosphere. This discovery was not made public for several years, and it was in 1973 (Klebesadel et al 1973), that it was first publicized as a new astronomical phenomenon, whose origin remained a puzzle for another 25 years. Also in the 1960s and early 1970s there were several low-energy γ-ray instruments on cis-lunar missions like the *Ranger* (Metzger et al 1964), and especially the *Apollo* missions (Trombka et al 1973). From these measurements a diffuse cosmic background component was discovered, whose energy spectrum showed a bump at photon energies of a few megaelectronvolts, which exceeded the true spectrum by about a factor of ten. Later it was shown that it was actually an artifact caused by instrumental background radiation. This experience emphasizes again the importance of a careful accounting of systematic background sources in the range of γ radiation.

Galactic γ-ray astronomy at high energies took a major step forward with the two satellite missions *SAS-2* and *COS-B* ($>$ 30 MeV and 70 MeV, respectively). Apart from the study of the diffuse galactic γ-ray emission (Mayer-Hasselwander et al 1982), these two missions also provided the first real source detections. The strongest source features were found from the Crab and Vela pulsars and from a source called Geminga, which remained unidentified for another twenty years. Finally in 1992, Geminga was identified as a pulsar as well. These sources can be clearly seen on the *COS-B* and *SAS-2* sky maps. The *COS-B* source catalogue contained in total 25 objects, of which only one (3C 273) was extragalactic (Swanenburg et al 1981).

In the field of cosmic γ-ray line spectroscopy a milestone was achieved by the Germanium spectrometer onboard *HEAO-III* with the first detection of a γ-ray line related to processes of nucleosynthesis, i.e., the creation of new (in this case radioactive) isotopes in astrophysical fusion processes: the 1.809 MeV line from radioactive ^{26}Al which was discovered from the general direction of the galactic centre region (Mahoney et al 1984).

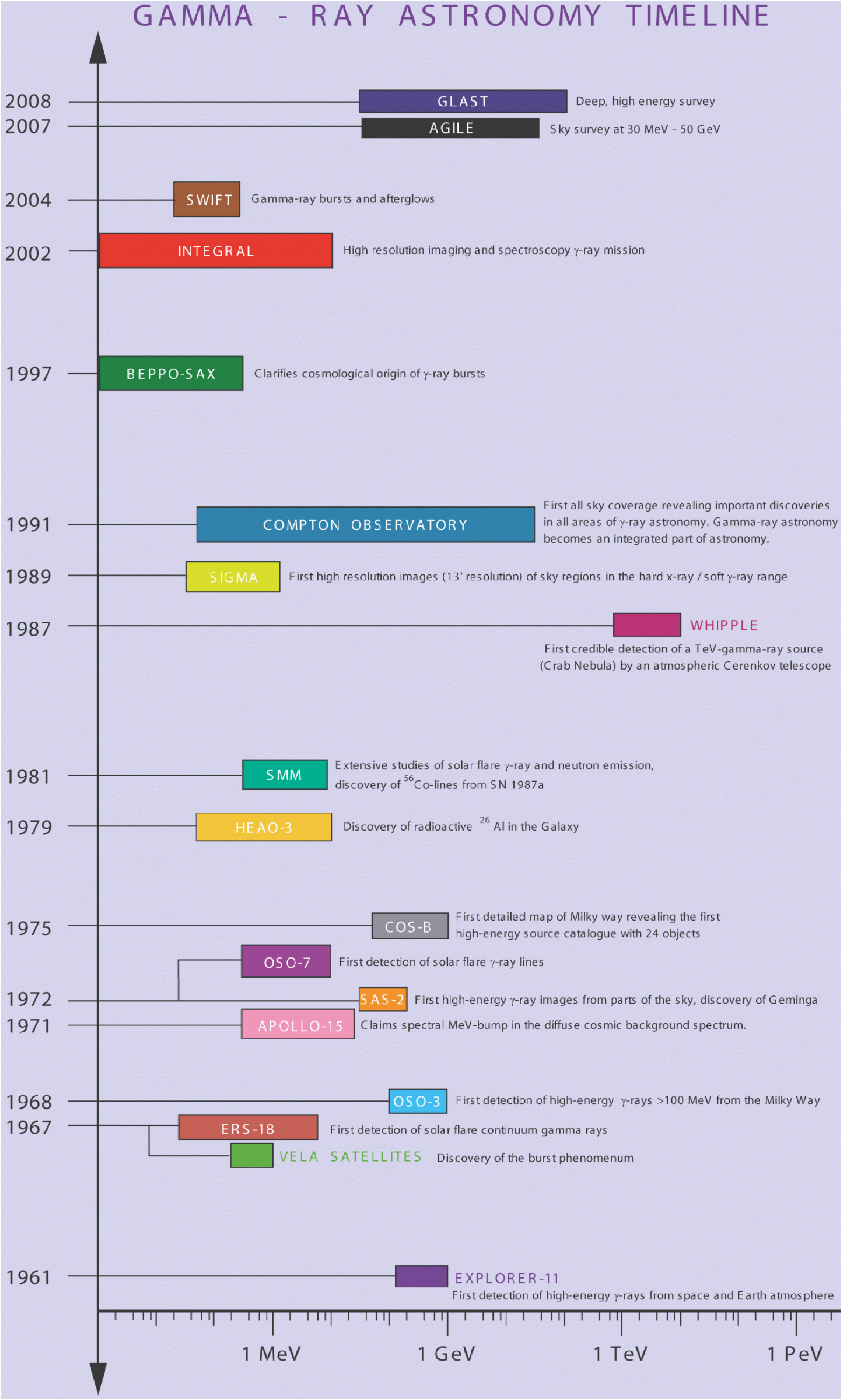

Figure 3.1: The history of observational γ-ray astronomy from the early 1960s until the launch of the *Fermi* Gamma-ray Space Telescope, formerly *GLAST*.

The first γ-ray line measurements from the Sun were made in 1972 by *OSO-7* from the flare of 4 August 1972. Apart from the continuum emission four lines were clearly detected: the annihilation line at 511 keV, the 2.2 MeV neutron capture line, and nuclear interaction lines at 4.4 MeV and 6.1 MeV from excitation of carbon and oxygen nuclei. Pure continuum emission in the γ-ray domain from solar flares up to at least 3.7 MeV had been already detected earlier — in May 1967 — with a scintillation spectrometer on *ERS-18* (Gruber et al 1973). The scintillation γ-ray spectrometer on the *SMM*, which was launched in 1981 and stayed in orbit for nine years, later provided a wealth of information on solar flare γ-ray emission in lines and continuum up to 10 MeV. In addition, however, it also made important studies of cosmic γ-ray lines, e.g., the 511 keV annihilation line and the 1.809 MeV ^{26}Al line from the Galaxy, and, in particular, it succeeded in an impressive detection of nucleosynthetic lines from ^{56}Co decay in SN 1987a in the Large Magellanic Cloud (Leising and Share 1990).

In the 1990s, γ-ray astronomy matured. This "golden epoch" started with the launch of the French telescope SIGMA on board the Russian *GRANAT*. SIGMA allowed imaging in the transition region between X-ray and γ-ray astronomy (mainly around 100 keV) with an unprecedented angular resolution of the order of $10'$. It mainly observed the galactic centre region, where it detected about 30 sources showing a great variety of compact objects, especially systems with stellar black hole candidates (Vargas et al 1997). The wealth of exciting discoveries of the Compton Observatory *CGRO*, which was launched in April 1991 and stayed in orbit for nine years, established the role of γ-ray astronomy as an important branch of astronomy and astrophysics, in general. Thanks to *CGRO*, γ-ray astronomy became an integrated part of astronomy.

The presently known celestial γ-ray sources cover a large variety of different objects, such as the Sun, isolated spin-down pulsars, accreting binaries with stellar neutron stars and black holes, supernovae, supernova remnants, the interstellar medium, normal galaxies, radio galaxies, Seyfert galaxies, quasars and the famous γ-ray burst sources. The question of the origin of the cosmic diffuse background is also of fundamental interest. During the last decade, a few very successful missions with specific scientific objectives followed. The *BeppoSAX* mission — launched in 1997 — succeeded in observing X-ray afterglow emission of a few γ-ray burst sources (Costa et al 1997). The subsequent observations of these objects at optical wavelengths clearly established the extragalactic origin of these sources. The mission *RHESSI*, launched in 2002 and still in operation (Lin et al 2002), is a solar mission, which is mainly devoted to study flares with a spatial resolution of a few seconds of arc and high resolution γ-ray line spectroscopy. The mission *INTEGRAL* (launched also in 2002 and still operating) is devoted to high resolution γ-ray line spectroscopy up to a few megaelectronvolts and to source imaging with an angular resolution of a few minutes of arc in the hard X-ray/soft γ-ray range (around 100 keV).

In the post-*BeppoSAX* era γ-ray burst astronomy has concentrated on the observation of afterglow emission throughout the electromagnetic spectrum. The prime objective of the missions *HETE II* (launch 2000) and *SWIFT* (launch 2004) was to locate the burst positions with high precision within the shortest possible time and to minimize the time-lag between the burst onset and the start of the afterglow observation. Thanks to *SWIFT* the different origins of long and short bursts could be clarified: short bursts come from the coalescence of compact objects like neutron stars and/or black holes, whereas long bursts have their origin in the collapse of very massive stars leading to the formation of a hyper-accreting black hole.

Much progress can be expected in the very near future in the area of high energy γ-ray astronomy (> 50 MeV): in 2007 the *AGILE* mission was launched. It is able to observe sources at a sensitivity level which is comparable to that of EGRET. On 11 June 2008 the *Fermi* Gamma-ray Space Telescope (20 MeV to 100 GeV) was launched. *Fermi* (formerly termed the *GLAST* mission) is about thirty times more sensitive than EGRET and is expected to detect several thousands of new high energy γ-ray sources.

γ-ray production

To produce γ-rays with energies in the 0.1 MeV to few teraelectronvolt regime, sources in thermal equilibrium emitting black body radiation are not sufficient, since unrealistically high temperatures ($> 10^{10}$ K) would be needed. On the other hand, given a relativistic particle population, several well-known mechanisms can give rise to γ-rays that are briefly discussed below. For an extensive review of γ-ray emitting processes see the text books by Hayakawa (1969) or Longair (1992).

Acceleration of charged particles

An electromagnetic field exerts a force on a moving charged particle. The resulting acceleration causes the particle to radiate. The character of the radiation and the name given to it depend on the nature of the accelerating force. If the electron is accelerated in the electrostatic field around a nucleus, the resulting radiation is called bremsstrahlung. It is called cyclotron or synchrotron radiation when the acceleration takes place in a magnetic field for non-relativistic or relativistic electrons. The most common mechanism for the production of relativistic particle populations is Fermi acceleration: in shock fronts particles can gain large momentum by crossing the shock repeatedly. The resulting particle energy spectrum follows a power law and can reach very high energies.

Bremsstrahlung

Bremsstrahlung is emitted during encounters of charged particles, e.g., in ionized plasma. The radiating particle is free, both before and after the deflection. Hence, also the term free-free radiation is commonly used. As the changes in the energy of the charged particle due to the collision are continuous, bremsstrahlung is characterized by a continuous spectrum over a very wide range that extends into γ-rays. Collisions between particles of the same charge-to-mass ratio do not produce bremsstrahlung, at least not in the dipole approximation. Astrophysical plasmas contain electrons with a distribution of velocities. The emission properties of a thermal plasma, with a Maxwellian velocity distribution, give a thermal bremsstrahlung distribution, mainly in the X-ray regime, whereas γ-rays are produced by highly relativistic electrons impinging on ambient protons (electron-proton) or of fast protons with ambient electrons (proton-electron). For a given proton energy, the electron-proton bremsstrahlung decreases for large scattering angles, whereas for proton-electron bremsstrahlung the distribution is almost independent of scattering angle. For the same Lorentz factor γ_{L}, the maximum photon energy for proton-electron bremsstrahlung is about $2\gamma_{\mathrm{L}}$ larger than for the electron-proton bremsstrahlung.

Synchrotron emission

Charged particles moving in a magnetic field experience a constant acceleration, and thus emit electromagnetic radiation. The emitted power goes as $(1/m_0^2)\,\gamma_{\mathrm{L}}^2\,B^2$, where m_0 is the particle rest mass and B the magnetic field strength. Because of the mass dependence, synchrotron losses are much more important for electrons than for protons. For relativistic particles the main emission power is beamed into an angle of order $2/\gamma_{\mathrm{L}}$. Typical observational signatures of synchrotron emission are smooth spectra over a large range of wavelengths without emission lines. The spectra can be approximated by power laws that usually turn over at low and high frequencies. High-energy electrons will lose their energy first, therefore the electron distribution will turn over at the high-energy end of the spectrum. The emission shows strong linear polarization of up to 70 %. A distribution of electrons whose energies are distributed according to a power law with index p will produce a synchrotron spectrum that is also a power law, but with an index $\frac{p-1}{2}$.

Inverse Compton scattering

In an encounter between a high-energy photon and a low-energy electron, the electron receives energy described by Compton scattering. Conversely, high-energy electrons can also up-scatter a low-energy photon to high energies, the so-called inverse Compton effect. The mean energy gained by the photon in one collision is $\Delta E_\gamma \approx \frac{4}{3}\beta^2\,\gamma_{\mathrm{L}}^2\,E_\gamma$. If the electrons have a Lorentz factor of $\gamma_{\mathrm{L}} \approx 10^3$, photons can be up-scattered from the Cosmic Microwave Background, or they can be produced by the electrons themselves via synchrotron radiation in a magnetic field.

Nuclear line emission

Nuclear γ-ray line observations also provide unique opportunities to trace accelerated nuclei. Low-energy ($<$ 100 MeV per nucleon) accelerated particles, interacting with ambient matter produce excited nuclei. They decay promptly via characteristic γ-ray emission into their ground state. If the nuclei are radioactive, they will decay with their characteristic lifetimes in their daughter products emitting delayed nuclear γ-ray lines. Important nuclear γ-ray lines are given in Table 3.1.

Annihilation

The annihilation of a positron and an electron can either occur directly (with both free and bound electrons), producing two photons at 511 keV, or it can form

Table 3.1: Prompt and radioactive nuclear γ-ray lines including the main production and decay channels. From Diehl (2001) and Ramaty et al (1979). (Abbreviations: gs: ground state, *: exited state, SN: Supernovae, N: Novae.)

Isotope	Energy E_γ/keV	Production	Decay	Mean life
^{56}Fe	847	$^{56}\mathrm{Fe(p,p')}^{56}\mathrm{Fe}^*$	$^{56}\mathrm{Fe}^* \rightarrow^{56} \mathrm{Fe_{gs}}$	9.7 ps
^{24}Mg	1369	$^{24}\mathrm{Mg(p,p')}^{24}\mathrm{Mg}^*$	$^{24}\mathrm{Mg}^* \rightarrow^{24} \mathrm{Mg}$	1.8 ps
^{20}Ne	1634	$^{20}\mathrm{Ne(p,p')}^{20}\mathrm{Ne}^*$	$^{20}\mathrm{Ne}^* \rightarrow^{20} \mathrm{Ne_{gs}}$	1.2 ps
^{28}Si	1779	$^{28}\mathrm{Si(p,p')}^{28}\mathrm{Si}^*$	$^{28}\mathrm{Si}^* \rightarrow^{28} \mathrm{Si_{gs}}$	0.7 ps
^{12}C	4438	$^{12}\mathrm{C(p,p')}^{12}\mathrm{C}^*$	$^{12}\mathrm{C}^* \rightarrow^{12} \mathrm{C_{gs}}$	0.06 ps
^{16}O	6129	$^{16}\mathrm{O(p,p')}^{16}\mathrm{O}^*$	$^{16}\mathrm{O}^* \rightarrow^{16} \mathrm{O_{gs}}$	24 ps
^{2}H	2223	$\mathrm{n(p,\gamma)}^2\mathrm{H}$	Radiative n-capture	
^{7}Be	478	N	$^{7}\mathrm{Be} \rightarrow^{7} \mathrm{Li}^*$	77 d
^{56}Ni	1238, 847	SN	$^{56}\mathrm{Ni} \rightarrow^{56} \mathrm{Co} \rightarrow^{56} \mathrm{Fe}^*$	111 d
^{57}Ni	122	SN	$^{57}\mathrm{Ni} \rightarrow^{57} \mathrm{Co} \rightarrow^{57} \mathrm{Fe}^*$	390 d
^{22}Na	1257, 511	N	$^{22}\mathrm{Na} \rightarrow^{22} \mathrm{Ne}^* + \mathrm{e}^+$	3.8 a
^{44}Ti	1156, 68,78	SN	$^{44}\mathrm{Ti} \rightarrow^{44} \mathrm{Sc} \rightarrow^{44} \mathrm{Ca}^*$	89 a
^{26}Al	1809, 511	Star, SN, N	$^{26}\mathrm{Al} \rightarrow^{26} \mathrm{Mg}^* + \mathrm{e}^+$	1.04 Ma
^{60}Fe	1173, 1332	SN	$^{60}\mathrm{Fe} \rightarrow^{60} \mathrm{Co}^*$	2.0 Ma

positronium, either the ortho- or para-states. Para-positronium decays into two photons, producing a line at 511 keV, while ortho-positronium decays into a three-photon continuum below 511 keV. If dark matter, which constitutes most of the mass of galaxies, is made of super-symmetric particles, the centres of galaxies should emit very high-energy γ-rays produced by the self-annihilation of super-symmetric neutralinos.

Particle decay

Relativistic protons which interact with ambient matter or photon fields can produce a π_0 meson that decays into two photons in flight. Given a sufficiently high energy of the primary particles, these photons can reach teraelectronvolt energies and beyond. Neutrinos are also produced through this kind of interaction, mainly via the decay of charged pions. The appearance of the high-energy (> 100 MeV) γ-ray sky is dominated by diffuse emission from the galactic disk originating from π_0 decay following the interaction of high-energy (> 1 GeV per nucleon) protons and nuclei with the interstellar gas.

Overview of the γ-ray sky

γ-ray astronomy has opened a new window to astronomy. The fascinating results obtained so far reveal a Universe of extremes, often far removed from the experiences of classical astronomy. Acceleration and interactions of very energetic particles in environments dominated by extreme magnetic fields, temperatures, and strong gravity can be observed directly through secondary radiation. The γ-

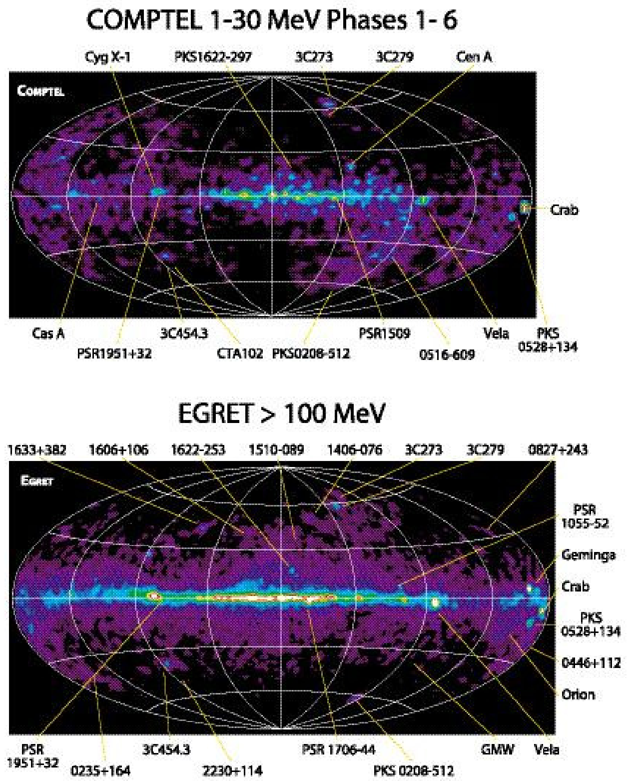

Figure 3.2: COMPTEL and EGRET all-sky maps shown in a galactic coordinate system. The dominant continuum emission along the galactic disk comes from cosmic-ray / gas interactions in interstellar space. Superimposed on the large-scale emission are point-like sources (a few are identified and indicated by their names, but many of the galactic point sources remain unidentified).

ray photons, with their high penetrating power, can leave the production sites more freely than other forms of radiation. The conditions of relativistic physics around black holes and neutron stars, nuclear processes in massive stars exploding as supernovae, and high-energy phenomena on galactic and super-galactic scales can thus be studied and provide insights into phenomena that can not be reproduced in terrestrial laboratories — they can only be observed in nature!

All-sky surveys

Highlights of the *CGRO* mission are the all-sky maps of γ-ray continuum radiation and of spectral line emissions. Figure 3.2 shows the continuum maps of COMPTEL (1 MeV to 30 MeV) and EGRET (above 100 MeV). The dominant galactic continuum emission comes from the interaction of cosmic rays with the gaseous interstellar medium. Superimposed on the large-scale galactic emission are

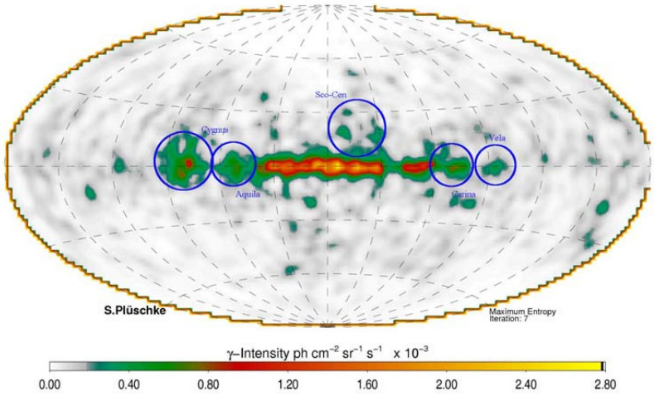

Figure 3.3: Regions of intense 1.809 MeV radiation from radioactive ^{26}Al in this COMPTEL all-sky map indicate the sites of ongoing nucleosynthesis in massive stars and supernova events.

point-like sources, like Crab, Geminga, Vela, and Cygnus. At mid and high latitudes many of the labelled γ-ray sources are identified as active galaxies with nuclei harbouring super massive black holes (AGN). The γ-ray bright AGN are of a type called blazars, which stands for a combination of the AGN type of BL Lac galaxies and to blaze, i.e., shine brilliantly. A different view of the sky is afforded by restricting the energy of the radiation to the narrow band of a γ-ray line. The most prominent line comes from the radioactive isotope ^{26}Al at 1.809 MeV, which is generated in massive stars and in supernova explosions. The ^{26}Al radioactivity is dispersed from the stellar sources into the interstellar medium and, with its half life of $\approx 10^6$ years, maps the production of new nuclei in the Galaxy on this time scale. The COMPTEL ^{26}Al map, displayed in Figure 3.3, shows prominent regions of recent nucleosynthesis in the Galaxy. γ-ray lines from other radioactive isotopes (^{60}Fe, ^{56}Co, ^{57}Co, ^{44}Ti) have also been detected by OSSE and COMPTEL and more recently with the spectrometer on *INTEGRAL*.

Cosmic radioactivity is not only detectable by direct nuclear γ-ray lines but also via positron-electron annihilation, which shows up in a line at 511 keV. The recent sky map from the *INTEGRAL* SPI telescope, shown in Figure 3.4, indicates a strong extended annihilation source from the inner Galaxy (Weidenspointner et al 2008). The one-sided extent of this antimatter emission towards the southern Galaxy (right side of the map) corresponds to a population of binary stars that is similarly off-centre. This observation powerfully suggests that these low mass X-ray binaries are responsible for a major amount of positron production.

γ-ray sources

A functional definition of a γ-ray point source is based on the angular resolution of the telescopes employed: significantly enhanced emission above the surrounding background radiance that conforms spatially to the point spread function of the in-

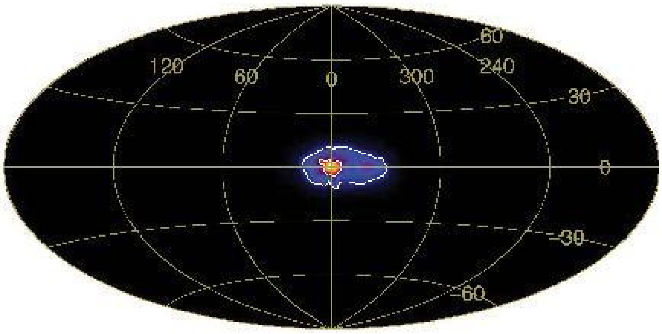

Figure 3.4: A map of the radiance of 511 keV radiation from the annihilation of positrons and electrons in the interstellar medium.

strument can be called an unresolved or point source. The true nature of the source, e.g., as a star-sized object or as a small cloud or supernova remnant, can not yet be discerned clearly with the current γ-ray telescopes. Additional astronomical, spectral, or temporal information has to be introduced to reveal a potential identification. The γ-ray surveys shown in Figure 3.2 were analyzed for point sources by subtracting the diffuse galactic and cosmic background emission and correlating the excess emission with the specific point spread functions. The resulting catalogues of significant sources were published by Schönfelder et al (2000) and Hartman et al (1999) for COMPTEL and EGRET.

A combined all-sky map of the sources detected by COMPTEL and EGRET is shown in Figure 3.5. It contains nearly 300 objects in total. Among the EGRET

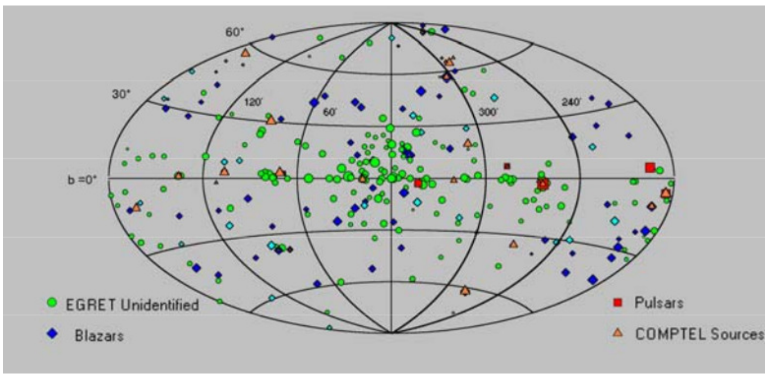

Figure 3.5: A sky map of high-energy point-sources derived from the all-sky surveys of COMPTEL (0.75 MeV to 30 MeV) and EGRET (> 100 MeV). The observations were carried out during the *CGRO* mission from 1991 to 2000.

sources found in the energy range > 100 MeV, seven to ten spin-down pulsars are clearly or tentatively identified by their timing signature as pulsating sources (Kanbach 2002). Nearly one third of all sources ($\approx$ 50 to 70), mostly at high galactic latitudes, are identified as γ-ray blazars (Mukherjee et al 1997). Two thirds of the EGRET sources are still unidentified. Among the COMPTEL sources in the energy range (0.75 to 30) MeV we also find spin-powered pulsars ($\approx$ 4 to 5) and γ-ray blazars ($\approx$ 10), but in addition accretion driven X-ray binaries, a radio galaxy and special γ-ray line sources (supernova remnants and regions of massive star associations).

γ-ray spectroscopy: continuum and nuclear lines

γ-ray spectra carry essential information on the nature of the radiating sources. Aside from wide-band continuum spectra, typically generated in bremsstrahlung, inverse Compton scattering, synchrotron radiation, or π_0 decay, γ-ray lines from nuclear transitions or matter-antimatter annihilation are telltale signatures of the radiating material. Nuclear level transitions can either be excited promptly by reactions of energetic particles or in the course of a radioactive decay chain. To understand the complex line spectra, a de-convolution of the spectra and modelling of the source is often required. Two typical examples are given below: a *RHESSI* solar flare spectrum (see Figure 3.6) and a composite spectrum of the AGN 3C279 (see Figure 3.7). The different processes involved are given in the figure captions.

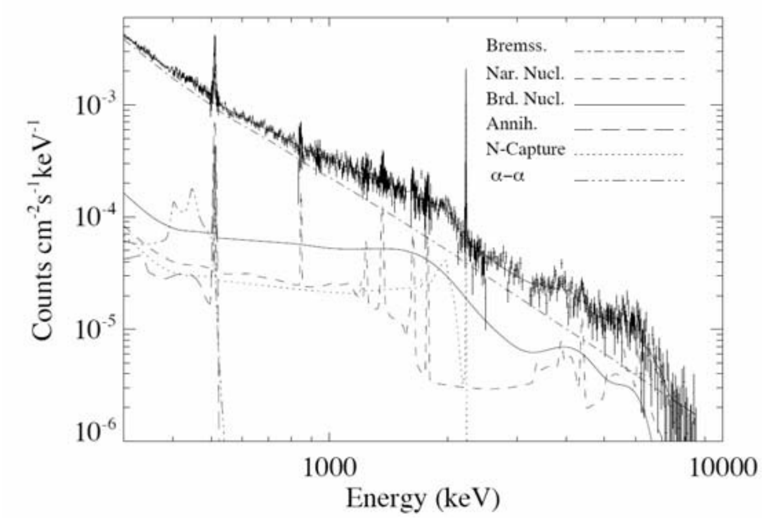

Figure 3.6: Count spectrum of the 23 July 2002 solar flare with fits revealing different components. Brems: non-thermal bremsstrahlung (electron energy); Nar. Nucl: narrow nuclear lines; Brd. Nucl: broad nuclear lines (ion energy and abundance, coronal ambient composition), Annih: annihilation line (positron density), N-Capture: thermal neutron capture (photospheric ^{3}He), $\alpha - \alpha$:^{7}Be and ^{7}Li lines produced in fusion of accelerated α-particles with ambient ^{4}He (from Share et al 2004).

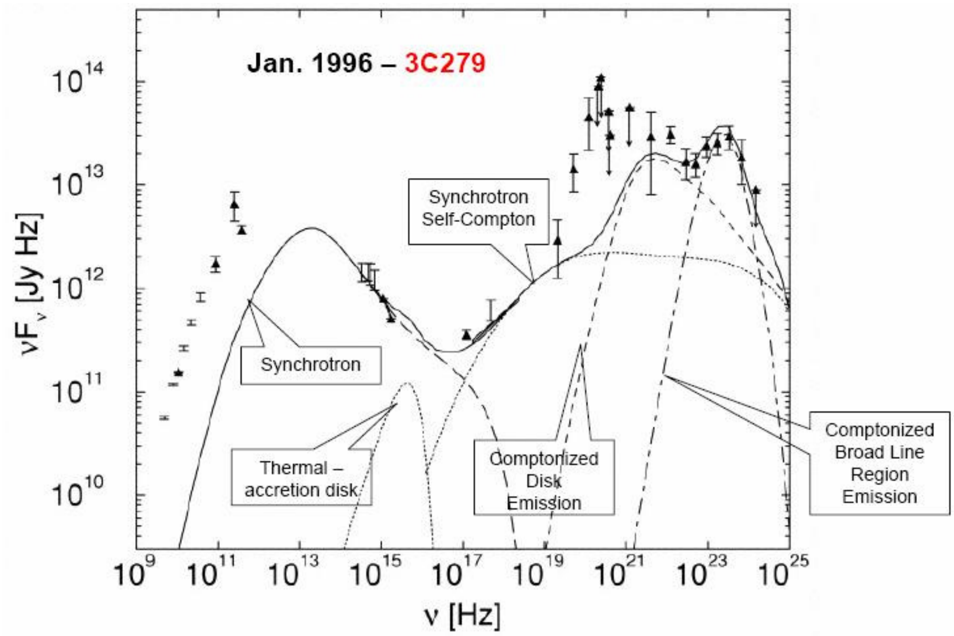

Figure 3.7: Fit to a simultaneously measured broad-band spectrum (from radio to γ-ray frequencies) by electron-induced processes of the quasar 3C279. The total fit (solid line) is the sum of five components. These are from left to right: 1. Synchrotron emission of electrons accelerated along the jet-axis (which is directed towards the observer and which lies perpendicular to the accretion disk around the massive black hole); 2. Thermal emission from the inner part of the accretion disk; 3. Inverse Compton emission produced by relativistic electrons in the jet with their self-generated synchrotron photons (synchrotron-self Compton component); 4. Inverse Compton emission by relativistic electrons in the jet with unscattered disk photons; 5. Inverse Compton emission by relativistic electrons in the jet with disk photons which were scattered into the jet by broad-line clouds.

γ-ray bursts

Since their serendipitous discovery in 1968, γ-ray bursts (GRB) have been intensively researched with space γ- and X-ray telescopes as well as with optical observatories on the ground. The BATSE instrument on *CGRO* provided the first all-sky map of these events. The highly isotropic distribution of GRBs indicated already that they are not of galactic origin. Since the discovery of optical counterparts (prompt emission and afterglows) of GRBs, it is known that most come from cosmological distances. To date the most distant GRB was located at a redshift of $z = 6.29$ (Kawai et al 2006). The currently active GRB space missions (*SWIFT*, *INTEGRAL*, etc.) continue to supply surprising and novel facts about GRB events: we distinguish at least two types of events — long duration (> 2 s) events with soft spectra, and short (< 2 s) hard bursts. The long events are generated in the core collapse of massive stars into a black hole. A fireball directed along a jet with a total energy of $\approx 10^{44}$ J to 10^{45} J is emitted and creates many observed characteristics of these GRBs. The short events could be the result of the merger of two neutron stars in a binary after the orbital momentum has been radiated away in gravitational waves. GRBs are the most powerful, although short lived, explosions known in astronomy. They can be detected across the visible Universe and already serve as important sources for cosmology.

Outlook

The short overview of γ-ray astronomy given in this chapter cannot encompass the richness of high-energy astronomy in all details. However the results testify to the tremendous efforts made in the past; they have stimulated new theories and plans for new γ-ray astronomy missions. In 2002, ESA's *INTEGRAL* mission (≈ 20 keV to several megaelectronvolts) started to observe with several instruments dedicated to imaging and spectroscopy. *INTEGRAL* will probably be operated beyond 2010. In 2007 the small pair-imaging telescope *AGILE* (Italy) was launched and provided the first exciting results of an all-sky survey in 2008, more than a decade after the EGRET survey. The next high-energy mission *Fermi* (15 MeV to 100 GeV), a NASA project with world-wide international participation, was launched in June 2008.

The energy region above the *INTEGRAL* range (> 300 keV) and below the effective onset of *Fermi* (< 100 MeV) is generally considered to be a still under-explored but scientifically very promising spectral range. At these energies detectors based on Compton interactions or low-energy pair-creation telescopes have to be used. This range was investigated by the pioneering COMPTEL instrument on *CGRO* but no follow-up mission with greatly increased sensitivity is currently scheduled. Several proposals for advanced Compton/pair-creation telescopes (0.3 MeV to 50 MeV, Kanbach et al 2005, Greiner et al 2008, Boggs et al 2006) or a focusing kiloelectronvolt telescope based on a crystal Laue lens (Knödlseder et al 2006) are discussed and have been forwarded to the funding agencies. The outlook for a realization of such a mission in the near future is, however, not promising.

For several years, ground based imaging atmospheric Čerenkov telescopes with large collecting mirrors (10 m to 20 m diameter) have covered the γ-ray energy range above ≈ 50 GeV with increasing sensitivity, albeit with rather small fields of view. The observatories HESS (Hoffmann et al 2003), MAGIC (Baixeras et al 2003; Holder et al 2006), and Cangaroo (Kubo et al 2004) have performed the first galactic surveys and found, to date, more than 60 sources in this energy range (e.g., Aharonian et al 2006, for an updated catalog see http://tevcat.uchicago.edu/). The sources include supernova remnants as potential sites of cosmic-ray production, pulsar wind nebulae, and BL Lac type galaxies.

Multi-wavelength observations of high-energy sources using space-based telescopes as well as ground based facilities covering a wide range of the electromagnetic spectrum will be essential for the future of high-energy astrophysics. In the γ-ray range we aim especially to study and understand the non-thermal physics of our cosmic origins, the synthesis of the elements, and the evolution and fate of stars and stellar systems.

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