ISAS - INTERNATIONAL SCHOOL FOR ADVANCED STUDIES

GAMMA–RAY EMISSION FROM COSMIC POINT–LIKE SOURCES

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Chapter 1

Introduction

γ–ray astronomy is viewing the Universe through the most energetic part of the electromagnetic spectrum extending above a few $10^5 eV$ up to $10^{15-16} eV$ or even higher up to $10^{18} eV$ if recently observed neutral particles from the direction of Cyg X–3 are photons.

The first discussions concerning γ–ray astronomy started at least since 1950s (see e.g. Morrison, 1958), while the first observations were carried out on balloons in 1960s (see e.g. Fazio, 1967) although without positive results. However the big interest to this subject was strongly stimulated by discoveries of point–like X–ray sources in early 1960s. indeed the first certain detection of extraterrestrial γ–rays came from a satellite OSO–3 (Kraushaar *et al.*, 1972), which observed γ–rays with energies above 50MeV from the direction of the Galactic disk. The most important results were collected by the satellites SAS–2 (started in 1972) and COS B (started in 1975). Analysis of these observations reported discovery of at least 24 point–like sources close to the Galactic plane (Swannenburg *et al.*, 1981) and 15 features at higher Galactic latitudes probably extragalactic origin (Young and Yu, 1988).

Because of the rectilinear propagation of γ–rays and the nature of their production processes, γ–ray astronomy provides an excellent new opportunity to gain insight into the nature of the Universe. The γ–ray observations permit a direct study of the largest transfers of energy in astrophysical processes including, acceleration of particles, distribution of matter and cosmic rays, explosions, gravitational accretion onto compact objects, processes of nucleosynthesis and matter–antimatter annihilation.

Another attractive feature of γ–ray astronomy is that the Universe is largely transparent to γ–rays. The optical depth in the medium with parameters typical for our Galaxy (dimension, density of background photons and matter, magnetic field), is much lower than 1 for most of the photon energies (see Tab. 1.1).

For example, we can observe the Galactic center in MeV and GeV photons which is impossibile in the optical or low energy X–ray region.

photon energy (eV)	absorption process	optical depth
$5 \times 10^4 - 5 \times 10^7$	Compton scattering	2×10^{-2}
$5 \times 10^8 - 10^{11}$	e^+e^- pair production in a medium	2×10^{-3}
$5 \times 10^{11} - 5 \times 10^{13}$	e^+e^- pair production on optical photons	2×10^{-3}
2×10^{15}	e^+e^- pair production on relic photons	1.4
2×10^{16}	e^+e^- pair production on relic photons	0.78
2×10^{17}	e^+e^- pair production on relic photons	0.14

Table 1.1: *The optical depth for γ-ray photons in the Galaxy for following parameters: the Galactic dimension $\sim 10kpc$, the concentration of gas $1particle/cm^3$, the energy density of optical and relic photons $1eV/cm^3$ and $0.3eV/cm^3$, respectively (from Dogiel and Ginzburg, 1989).*

One of the biggest disadvantages of γ–ray astronomy is the impossibility of performing observations from the ground level at MeV and GeV photon energies (for which photon fluxes are the highest), since such γ–ray photons are absorbed by the Earth atmosphere.

The observations must be done in high–altitude balloons flights or from satellites with long exposure time because of very low γ–ray fluxes compared to cosmic particle radiation. The detection of γ–ray photons above $10^{11}eV$ is possible indirectly from the ground by analysies od the secondary radiation (particles, Charenkov radiation) induced by such energetic photons in the Earths atmosphere. However the real need of γ–ray astronomy is an essential improvement in experimental techniques at least one order of magnitude in sensitivity and angular resolution in comparison to SAS 2 and COS B detectors. Planned in the near future experiments (GRO, Hercules, etc...) will achieve such parameters which could be a turning–point in this subject.

Since the whole topic of γ–ray astronomy is too large, I will concentrate in this thesis on the observations and interpretation of γ–ray emission from point–like sources. Our hopes on the big progress in this topic are connected with launching γ–ray detectors on the board of GRO satellite in 1990.

The thesis is organized in the following way:

In chapter 2 I have described the techniques applied in the detection of γ–rays at different energies. Also a short general description of observational results is added.

In chapter 3, specific mechanisms of γ–ray production are analyzed. I have concentrated on practical applications of γ–ray emission mechanisms in modeling sources without detailed description of the basic formulae which can be found in many books or review articles (see e.g. Blumenthal and Gould, 1970; Stecker, 1971; Rybicki and Lightman, 1979).

In chapter 4, the more detailed results of γ–ray observations of the best known Galactic sources are described in the following sequence: Galactic Center, γ–ray bursts, Cyg X–1, Geminga, Crab Nebula and Pulsar, Cyg X–3. Each review is preceded by a general introduction since it is impossible to analyse γ–ray emission from them without any knowledge about their structure observed in other wavelengths of electromagnetic spectrum. Also proposed models and mechanisms applied to these sources are reviewed. Because of the limited volume of this thesis I missed a few very interesting sources from viewpoint of γ–ray observations like: our Sun, supernova SN1987a or SS433.

Chapter 5 is organized similar to chapter 4 but describes extragalactic γ–ray objects that in this thesis are represented by quasar 3C 273, Seyfert galaxy NGC 4151 and radio galaxy Cen A.

In chapter 6, I have tryed to show perspectives of γ–ray astronomy concentrating on future experiments planned or under studies.

At the end, short summary and conclusion are included.

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Chapter 2

Observations of γ–rays from cosmic sources

2.1 Introduction

The observations of γ-rays from cosmic sources have been performed by completely different techniques than those ones applied to lower photon energyies.

Usually, the γ-ray interval from $10^5 - 10^{16} eV$ (or maybe even further?) is divided on a few smaller ranges, depending on physical processes applied in detection of high energy photons. To detect photons in the low energy range (from $10^5 - 10^7 eV$), the photoelectric effect and Compton process are useful. In the high energy range ($10^7 - 10^{10} eV$) , the production of e^+e^- pairs by γ–ray photons in the field of heavy particles is applied. At energies above $10^{11} eV$, the intensities of photon fluxes from cosmic objects are so small that detection in the outer space is practically impossible. However photons with such energies produce showers of secondary particles in the Earth atmosphere. The Cherenkov radiation emitted by these relativistic particles can be detected on a clear night. If the energy of the primary photon is $> 10^{14} eV$, the secondary particles from γ–ray sources can be detected directly at the ground level. However the problem is how to distinguish showers initiated by photons from those ones initiated by charged particles. It is widely believed that this is possible by investigating some characteristic parameters of the air showers (e.g. muon contents, age parameter, etc...).

In this chapter we shortly review different techniques (and their limitations) applied to detection of γ–ray photons in above mentioned energy ranges. (for more detailed review see, e.g. Bertsch *et al*, 1988; Hillier, 1984; Weeks, 1988). Also, the main observational results will be presented. The perspectives of future development of γ–ray detectors will be reviewed in chapter 6.

2.2 Low energy γ-ray range

The energy losses of γ–ray photons by ionization in cristal scintillatars and semiconductors is widely used to derive γ–ray spectra in 100keV–10MeV energy range. The energy resolution of these detectors depends on the number of photons (in scintillators) or electron–hole pairs (in semiconductors) produced per unit energy absorbed in the detector. Usually, two kinds of materials are used. NaI(Tl) in scintillation detectors and Ge(HP) in semiconductor detectors. However to obtain high–resolution measurements, the cooling of the detector to low temperatures is necessary (liquid and solid cryogens, mechanical refrigerators or passive radiative cooling were applied).

In the outer space, the basic problem for the detector observing γ–ray source concerns the rejection of cosmic particle background or at least good knowledge about background influence on the measured result. The major background component is due to charged particle interactions with the γ–ray detector. To eliminate it, anticoincidence shielding of the detector (high Z–material) by plastic scintillatar (low Z–material) is applied. Also γ–ray background caused by emission of radioactive nuclei (from planetary surface, atmosphere, spacecraft, etc..) or γ–ray emission induced in the detector by charged particles, must be taken into account in derivating the photon flux from the source.

In long time working detectors, influence of the energetic neutrons and protons on the Ge (HP) semiconductors (called radiation damage) is very strong. This process can reduce significantly the detector energy resolution.

The above detectors (applying ionization measurements) are not able to localize the γ–ray source in space. The information about arrival direction of photons can be obtained by using active or passive collimators, pinhole arrays or coded aperture and triangulation method. The first method was applied in the OSSE detector on Gamma Ray Observatory satellite. The field of view of the detector was limited to $3.8° \times 11.4°$ throughout the 0.05–10MeV energy range. For details see, Kniffen et al., (1988). The triangulation method was applied on the detectors looking for γ–ray burst sources. The precision of the source localization depends on the number of the satellites and on the relative distances between them and on the precision of measurements of time delay between sygnals from different satellites. The third method applies the pinhole array. However since the γ–ray fluxes are very low, a system of holes randomly distributed is usually used (see, e.g. Dicke, 1968). For practical application in observations of this last method, see e.g. McConnell et al. (1987).

In the upper part of the low energy γ–ray range, the Compton interaction process dominates. The detector using this process can determine the arrival direction of photon by direction measurements of the scattered electron. In many cases, segmentation of the detector or measurements of time delay between upper and lower parts of detector are useful in derivation of the localization of the photon arrival in the sky. In general, Compton detectors are specially useful in measurements of the continuum γ–ray spectrum or broad spectral features (but not sharp lines).

A few γ–ray sources in the MeV were recognized, in spite of the poor angular resolution and low sensitivity of detectors in low energy γ–ray region. In the case of solar flares, γ–ray lines (0.511MeV from e^+e^- annihilation, 2.223 MeV from neutron capture and 4.438 MeV and 6.129 MeV from deexcitations of nuclear levels in ^{12}C and ^{16}O, respectively) were first discovered by Chupp *et al.*, (1973). The variable 0.511MeV annihilation line was observed from the direction of the Galactic Center and redshifted 0.511MeV line was detected in a few percent of γ–ray bursts.

A number of γ–ray lines were expected from nucleosynthesis in supernova explosion (see, e.g. Clayton *et al.*, 1969). Recently, chain of decays $^{56}Ni \rightarrow ^{56}Co \rightarrow ^{56}Fe$ (0.847MeV and 1.238MeV lines) was confirmed in observations of the supernova SN 1987a (Tueller *et al.*, 1988). Also 1.809MeV line from ^{26}Al decay (produced during explosive nucleosynthesis) was observed from the general direction of the Galactic Center.

The observation of two emission lines close to 1.5MeV and 1.2MeV was reported by Lamb *et al.* (1983) from the peculiar source SS 433. They recognized them as a blue and redshifted emission line of ^{24}Mg and estimated total power on $2 \times 10^{37} erg/s$. However this observation was not confirmed by Norman and Bodansky (1983) and Geldzahler *et al.* (1989).

The continuum emission of low energy γ–rays is often connected with line emission (e.g. Solar flares, the Galactic Center, γ–ray bursts). In the case of Solar flares first observations were made by Peterson and Winckler (1959). This emission was probably originated in bremsstrahlung process of relativistic electrons (below 1MeV) and by Doppler–broadened unresolved nuclear lines (above 1MeV). Strong MeV photon fluxes were also observed from pulsars (e.g. Crab, Vela, etc ..) and black hole candidates like Cyg X–1.

For review of γ–ray observations from the Galactic Center, Crab pulsar, Cyg X–1 and γ–ray bursts, see chapter 4.

Also some extragalactic sources were reported as MeV γ–ray emitters. Two of them (NGC 4151 and Cen A) are discussed in chapter 5. Moreover, the observed shape of difussive extragalactic emission with bump in MeV range (Schönfelder *et al.*, 1980; Trombka *et al.*, 1977) suggests that most of the extragalactic sources should emit a significant part of their power in low energy γ–ray photons.

2.3 High energy γ–ray range

To detect the γ–ray photons in high energy energy region ($10^7 - 10^{10-11}eV$), the production of e^+e^- pairs by photon in the strong field of a particle is applied. The probability of this interaction increases with energy from the threshold at $2m_ec^2$ up to about 100MeV and than is approximately constant. So, the best efficiency of the observation of γ–ray sources in this energy range seems to be its higher energy part. However the number of emitted photons by source strongly decreases with energy and make observations above $\sim 10^{10}eV$ practically impossible by present detectors on the satellites.

From the directions of motion of the e^+e^- pairs, it is possible to determine the arrival directions of primary photon. The uncertainty of this method is much poor in comparison to the observations in lower wavelengths (accept for low γ–ray region). For example, the accuracy of 4° at 30MeV, to 1.5° at 10^2MeV , to 0.2° at 10^3MeV can be achieved (Bertsch *et al.*, 1988). The advantage of this method is that e^+e^- pairs provide a unique signature in the detector and permits a clear identification of γ–ray photons avoiding the background difficulties.

To detect e^+e^- pairs, the spark chamber telescope emerged as the most promissing approach. It was applied in the γ–ray telescopes of the two pioneering experiments, SAS 2 and COS B and will be also launched in the near future missions: GRO (EGRET telescope) and GAMMA–1 satellites. For details of the above instruments see, e.g. Kniffen, *et al.* (1974) , Akimov *et al.* (1987).

Because of the very big charged particle background, (about 10^4 more particles than photon), the anticoincidence system rejecting charged particles is very important. If not, the instrument will not have time to observe γ–rays and data collection system will be overwhelmed. The parameters of the spark chamber are a compromise in order to achieve the best sensitivity (minimum distance between wires in spark chamber telescope) and the best angular resolution (for wider spacing wires). In the bottom part of the telescope was placed the directional Cherenkov counter and in the center plastic scintillator in order to distinguish photons between upcoming charged particles (which do not intersect anticoincidence scintillator) and to restrict the angle of acceptance for photons directions. The energy of photon is measured by scintillator crystals with thickness of a few radiation lengths (e.g. Cs(Tl) or NaI(Tl)) or calorimeters (e.g. GAMMA–1 telescope). The analysis of the data from this kind of instruments is particularly difficult, since up to now, it is impossible to do this work completely automatically. So, in practice, every event should be reviewed by well trained analytists and scientists knowledgeable of the specific aspects of the work.

The main observations in this energy range were done by SAS 2 (energy region 35–200MeV) and COS B (energy region 70–5000MeV) satellites. SAS

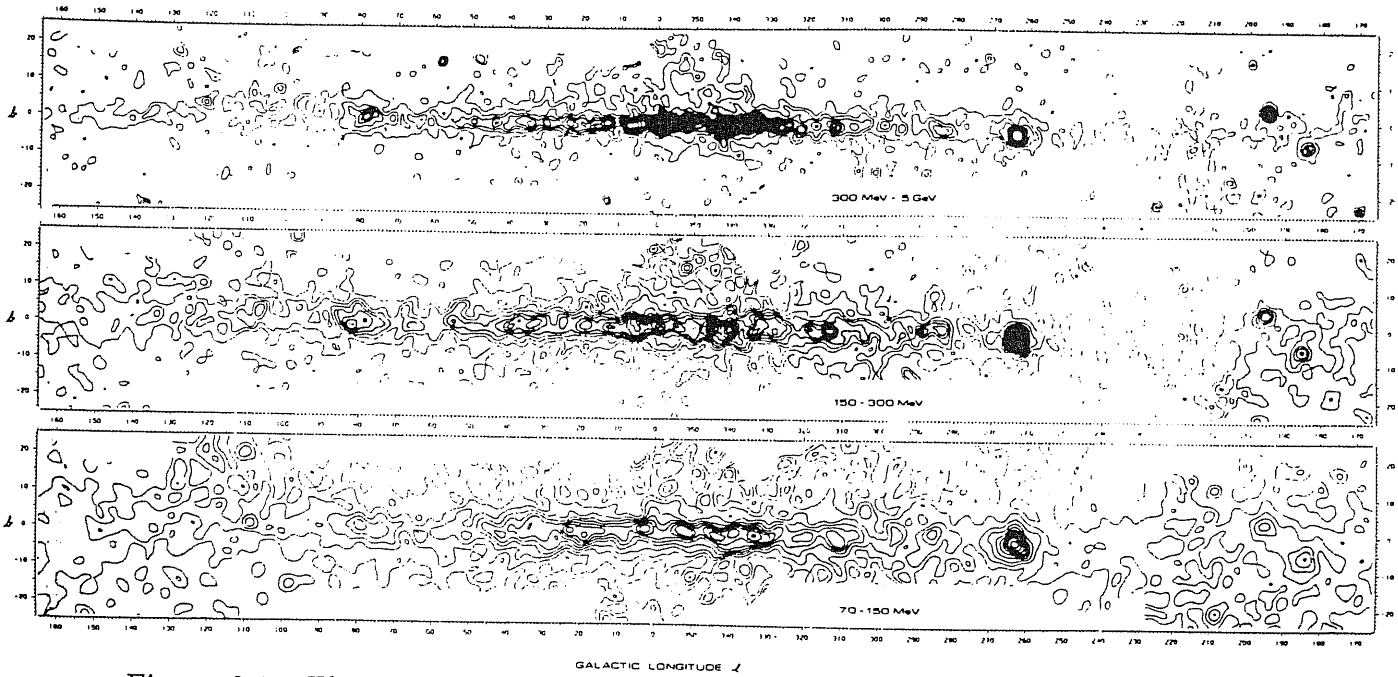

Figure 2.1: *The counters of COS B γ–ray intensity from our Galaxy in 3 energy ranges (from, Mayer–Hasselwander, 1982)*

2 have monitored about half of the sky, although the number of registed photons was not very big ($\sim$ 8000 events) because of unexpected electronic damage. COS B satellite collected much more photons ($\sim 10^5$ events). However these last observations were mainly limited to the Galactic plane with only a few extensions to the higher latitudes. For display of the COS B results in the Galactic coordinates see, Figure 2.1.

The statistical analysis of the COS B results has shown the existence of 24 point–like sources included in "2CG catallogue" (see, Swannenburg *et al.*, 1981). Some of these excesses were identified with known objects like the Crab and Vela pulsars, Cyg X–3 (seen by SAS 2 but not confirmed by COS B) and the quasar 3C 273. The second biggest peak (2CG195+04), called "Geminga", was not surely identified at other wavelengths. Another peak (2CG353+16) was connected with the ρ *Ohp* dark cloud. For more detailed discussion of the Crab pulsar, Cyg X–3, Geminga (see, chapter 4) and 3C 273 (see, chapter 5). The possible excesses in SAS 2 results were analysed by Houston and Wolfendale (1983) and Young and Yu (1988).

It is not completely sure if all reported excesses observed in γ–rays are really point sources. For example, the reanalysis of γ–ray data in connection with new observations of distribution of matter can explain 3 excesses (2CG 036+01, 2CG065+00 and 2CG095+04) as caused by cosmic rays irradiated gas cloud (Bignami *et al.*, 1984).

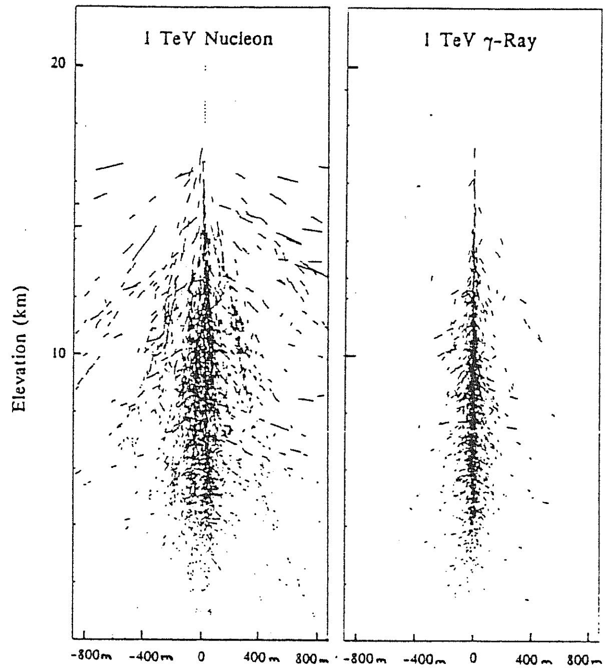

Figure 2.2: *Monte Carlo simulations of air showers induced by 1TeV nucleon and γ–ray photon (from Hillas, 1985)*

2.4 Very high energy γ–ray range

The Very High Energy (VHE) photon range (called also TeV range), extending from $\sim 10^{10}eV$ up to $\sim 10^{14}eV$, was defined by the atmospheric Cherenkov technique applied to observations in this energies. Such energetic photons are able to produce an electromagnetic cascade in the atmosphere that should have different features from the air showers induced by protons. Proton induced showers have: greater muon contents, longer time spread, bigger fluctuations and lateral distribution and different UV photon character (for more detailed description see, Lamb (1989) and references therein). However the above parameters have only statistical significance and even if detection techniques can be maximally optimized, the γ–ray photons cannot be uniquely identified. For the numerically simulated view of the showers initiated by photon and protons see, Fig. 2.2.

Because of the large energy of the primaries, the secondary particles are strongly beamed and maintain photons (or particles) directionality. The Cherenkov radiation (in the range of detection from 3500–5000Å) emitted by these secondary particles (electrons and muons with energy above 21 MeV and 4 GeV, respectively) is collimated in the cone of the about 100m in size on the Earth. A typical shower light pulse has a duration of 3–5ns so if the detector's sensitive time is limited to a few ns, the Cherenkov light dominates the background night–sky light.

The atmospheric γ–ray telescope consists from two main elements, mirrors and photo–tubes. Mirror (or system of mirrors), usually with diameter $1 \div 10m$, concentrates the Cherenkov light on photo–tubes which measure their intensity (for details of some working telescopes see e.g. Appendix in review by Weeks, 1989).

In practise, to obtain useful information, experimenters rely on numerical simulations of both γ–ray and hadronic showers and distributions of the Cherenkov light caused by them. The features of photon–particle interaction in TeV energy range are well known from accelerator experiments so characteristic parameters of distribution of the Cherenkov light were calculated in many papers: lateral distribution (e.g. Paterson and Hillas, 1983), pulse width (e.g. Hillas, 1987), effectiveness of imaging (Plyasheshnikov and Bignami, 1985).

The main difficulties in the observations of VHE γ–ray sources are connected with their variability which makes the comparisons of results from different experiments very difficult. On the opposite, the existence of periodicities in a source emission allows to reduce influence of the background cosmic radiation. The results of positive observations of γ–ray sources ($> 0.1TeV$) are collected in Table 2.1.

Specially interesting results have been obtained in recent observations of Her X–1 (Resvanis *et al.*, 1988; Lamb *et al.*, 1988; Dingus *et al.*, 1988). The strong TeV excess from this source was detected although primary particles seem not to be photons because the signals have similar features to the background cosmic ray events (e.g. muon contents). It is particularly surprising that the parameters of TeV photons observed from cosmic sources do not agree with data obtained from particle accelerators in this same energy range.

Contradictory observations in TeV photon range were reported from: PSR 0950, PSR 1133, Geminga, M31 and Galactic plane. For more detailed discussion of the Crab Nebula and pulsar, Cyg X–3 and Geminga see chapter 4 and Cen A see chapter 5.

2.5 Ultra high energy γ–ray range

The secondary particles of an electromagnetic cascade (air shower) initiated by photon with energy $> 10^{14}eV$ can be detected directly at the sea–level or mountain altitudes. Such observations can be carried out day and night independently on the weather. This is a big advantage in comparison to Cherenkov observations which need moonless and clean sky. The air shower, initiated by primary with energy $> 10^{15}eV$, consists of a disk of secondary particles with diameter of $\sim$ 200 meters (at the sea–level), 1 meter thick and with radius of curvature of a few kilometers. The accuracy of arrival

Source	Periodicity	Energy	Flux ($cm^{-2}s^{-1}$)	Distance (kpc)
Pulsars				
Crab	33ms	1TeV	4×10^{-12}	2.0
Vela	89.2ms	1TeV	3×10^{-12}	0.5
PSR 1937+21	1.56ms	1TeV	2×10^{-11}	5
PSR 1953+29	6.13ms	1TeV	1.2×10^{-12}	3.5
PSR 1802-23	112ms	1TeV	2.3×10^{-10}	2.7
Binary X-ray sources				
Cyg X–3	4.8h	1TeV	5×10^{-11}	> 11.4
		100TeV	10^{-13}	
		1PeV	2×10^{-14}	
Her X–1	1.24s	1TeV	3×10^{-11}	5
		0.5PeV	3×10^{-12}	
4U0115+63	3.61s	1TeV	7×10^{-11}	5
Vela X–1	8.96d	1TeV	2×10^{-11}	1.4
		3PeV	9×10^{-15}	
Cen X–3	2.09d	?PeV	?	10
LMC X–4	1.41d	10PeV	5×10^{-15}	50
Supernova remnants				
Crab Nebula	steady	1TeV	10^{-11}	2
Radio galaxies				
Cen A	steady	1TeV	4×10^{-12}	4400

Table 2.1: *Kataloque of VHE/UHE γ–ray sources (from Weeks, 1988)*

direction of the primary up to of $\pm 1^\circ$ can be achieved by measurements of a time delay between different particle detectors.

In order to select showers that are initiated by photons with respect to these initiated by charged particles, usually two parameters were used: muon contents and age parameter. The Monte Carlo simulations of γ–ray showers showed that their muon contents should be much less (< 0.1) in comparison to average shower (see e.g. Protheroe and Turver, 1979; Stanev *et al.*, 1985). The age parameter was supposed to be big for γ–ray showers ($> 1.$). This last criterium of selection was applied in searches of excesses in some experiments (e.g. Samorsky and Stamm (1983) for Cyg X–3; Protheroe *et al.* (1984) for Vela X–1). However recent Monte Carlo simulations show that the age parameter should be less than 1. for γ–ray initiated showers (Fenyves, 1985). Next surprising discovery was that the excesses of showers from Cyg X–3 and Her X–1 were not muon poor. The discrepeances between observations and computer simulations suggest that:

- what we observe are not really photons;
- approximation of particles interaction parameters to higher energies is not correct and muons can be also efficiently produced in air showers initiated by γ–rays;
- Observed excesses do not really exist.

The UHE γ–ray telescope is composed of a system of separate detectors of secondary particles distributed over large area. Each detector is equipped in scintillator (plastic or liquid) able to detect secondary particles. Plastic scintillators are more expensive but have better time resolution which is directly connected with angular resolution of the telescope. The detector's electronics should measure intervals of time of the order of 1ns or even less. Many existing UHE γ–ray telescopes contain also muon detectors which in simplest form are similar to previous detectors of electrons plus additional shielding eliminating electron component. For details of some working telescopes in this energy range see review by Weeks (1988).

The results of observations $> 10^{15} eV$ are collected in Tab. 2.1. Most of the reported sources (candidates) are X–ray binary systems in which one of the companion is probably a neutron star. However results reported by different experiments are not quite consistent and at least postulates strong variability of some UHE sources. One of the best searched representatives (Cyg X–3) was reviewed in more details in chapter 4 of this thesis.

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Chapter 3

Mechanisms of γ–ray production

3.1 Introduction

The general mechanisms of γ–ray production are well known and were discussed in many books and review articles (see e.g. Fazio, 1967; Blumenthal and Gould, 1970; Stecker, 1971; Hillier, 1984). However production of γ–rays in astrophysical sources is very difficult to investigate because of their strong dependence on internal geometry of the sources (spherical or not?), propagation processes (optical depth low or high?) and internal structure (existance of magnetic field, background photons, distribution of matter?).

In the past, the work in this topic concentrated on calculations of simplest cases i.e. sherical symmetry, thermal or power low distribution of particles and low optical depth. At present, the most interesting directions of investigation seems to be analysis of the influence of the propagation effects and nonsherical structure of the source on the emerging spectrum of γ–ray photons.

In this chapter we shortly discuss the present state of γ–ray production mechanisms in the context of specific models of sources (without detailed description of formulae which can be found in references). The following mechanisms will be mentioned:

- Transitions between nuclear energy levels (nuclear reaction and deexcitations),
- annihilation of particles with antiparticles (electron–positron, proton–antiproton, etc ...),
- decay of elementary particles (e.g. π° decay),
- acceleration of charged particles (synchrotron radiation, bremsstrahlung, Compton scattering).

3.2 Nuclear Reactions and Nuclear Excitations

This mechanism of γ–ray line generation is well known and in the astrophysical context was reviewed in many books and papers (e.g. Shen, 1967; Ramaty *et al.*, 1979; Hillier, 1984; Ramana Murphy and Wolfendale, 1986).

The γ–ray lines can be produced during a capture of neutrons by nuclei or in interactions of fast nucleons and next in decay of excited nuclei. As an example of the first kind of process is the radiative capture of thermalized neutrons by deuterium with emission of 2.22MeV γ–ray line ($n + p \rightarrow d + \gamma$). The cross section for this reaction is inversely proportional to the kinetic energy of the neutron and capture of neutron by nuclei is much efficient for low energies. From the other side, the intensity of the 2.22MeV line strongly depends on the density of the plasma (is essential for $> 10^{16}\ particles/cm^3$), because of decay time of neutrons ($\sim 930s$). Neutrons can originate in the interactions of energetic particles with ambient matter in reactions e.g. $^4He(p,pn)^3He$, $^2H(d,n)^3He$, $^3H(d,n)^4He$ and later become thermalized in collisions with protons. In astrophysical objects capture of neutrons by ^{56}Fe nuclei with emission 7.632 and 7.646MeV γ-ray lines can be also important.

Interactions of fast particles (in cosmic space mainly protons) with matter at rest leads to production of excited nuclei which later produce γ– ray lines during de–excitation. The threshold energy for these processes is of the order of 10MeV (slightly depending on the nuclei). The most important lines are generated in the collisions of protons with the most abundant nuclei like: 4.438MeV line from ^{12}C, 2.313 and 5.105MeV lines from ^{14}N, 2.741, 6.129, 6.917, 7.117MeV lines from ^{16}O, 1.634, 2.613, 3.34MeV lines from ^{20}Ne, 1.369 and 2.754MeV lines from ^{24}Mg, 1.779 and 6.878MeV lines from ^{28}Si and 0.847, 1.238 and 1.811MeV lines from ^{56}Fe. The emission of γ–ray lines is also expected during supernova explosion. For example, in the chain of decays $^{56}Ni \rightarrow ^{56}Co \rightarrow ^{56}Fe$ produce 0.847 and 1.238MeV lines, $^{44}Ti \rightarrow ^{44}Sc \rightarrow ^{44}Ca$ 1.156MeV line, $^{26}Al \rightarrow ^{26}Mg$ 1.809MeV line. All above excited nuclei have relatively long time of decay and should be observed in a few years after a supernova explosion.

The observations in MeV γ–rays have reported the detection of some of the above mentioned lines from Galactic Center, γ–ray bursts, SS 433, supernova SN1987a, Cen A and Solar flares. For review of these observations see e.g. Ramaty and Lingenfelter (1982), Chupp (1984) or Chuikin (1988).

Moreover, the γ–ray line emission during Solar flares were studied by Ramaty *et al.* (1984), from accretion onto a black hole by e.g. Ramaty (1973), Brecher and Burrows (1980), from supernova explosion by e.g. Clayton *et al.* (1969) and 1.809MeV line from decay of ^{26}Al by e.g. Clayton (1969), Hillebrand and Thielmann (1982) and Prantzos and Casse (1986).

The excitation of very energetic nuclei is expected in sources surrounded by low energy photons. The photons emitted during deexcitation have very high energies in the observer frame.

3.3 Annihilation

The production of γ–rays in the e^+e^- annihilation is one of the most important mechanism in astrophysics (see. e.g. Burns *et al.*, 1983). In sources, positrons can arise from: β–decays of nuclides; decay of charged pions; in photon–photon, photon–particle, particle– particle collisions; in pair creation by photon in strong magnetic field.

In general, positrons and electrons can annihilate in a one, two, three or greater odd number of photons, depending on circumstances. In low energies, e^+e^- pairs form positronium atoms, 25% of which are in singlet state and decay on two photons but 75% of positronium are in triplet state and decay on three or on odd number of photons with much less probability (see for details Bussard *et al.*, 1979; Crannell *et al.*, 1976). The decay on two photons produce 0.511MeV annihilation line but decay on three photons produce continuum spectrum extending below 0.511MeV.

The annihilation on one–photon requires the presence of a strong magnetic field to supply momentum of the photon. The annihilation line at energy $2mc^2$ can be produced if annihilating pairs are not relativistic and occupy the ground state Landau level (see Daugherty and Bussard, 1980). The one–photon annihilation rate of pair at rest is much lower than the two–photon annihilation rate until the field approaches $10^{13}Gs$.

One–photon annihilation from a thermal, hot plasma (pairs in excited Landau states) produce much broader photon spectra which also show structure near the threshold due to contribution from individual quantized pair states (Harding, 1986). The ratio of total rates of one–photon to two–photon annihilation is extremely sensitive on the magnetic field strength as well as on the plasma temperature. However contribution of one–photon annihilation for transrelativistic plasma temperatures is significant for fields $> 5\times10^{12}Gs$. The similar features show also pair plasma with non–thermal distribution of particles (Harding, 1986).

The formulae for two–photon annihilation rates of e^+e^- thermal plasma were given by Svensson (1982) and Daugherty and Bussard (1980). The photon spectrum from annihilation of e^+e^- with thermal distribution was calculated by e.g. Ramaty and Meszaros (1981), Svensson (1983) and Dermer (1984). These spectra becomes broadened and blueshifted at higher temperatures. In the case of different temperatures between electrons and positrons, the annihilation spectra were calculated by Tkaczyk and Karakuła (1985). The authors find that the photon spectra are much flatter than those ones for equal electron and positron temperatures and approaches a power low shape with index close to 1. for big difference between e^+ and e^- temperatures.

Up to now we have only described production of photons in optically thin e^+e^- plasma. However as a rule the emergent spectrum is strongly determined by transport effects. The influence on the spectrum of: high magnetic field was investigated by Erber (1966), Daugherty and Harding (1983) or Brainerd (1989); high photon densities by e.g. Burns and Harding (1984), Carrigan and Katz (1984); and high particle densities by e.g. Guilbert and Stepney (1985), Zdziarski (1984). Taking into account some of these effects, Zdziarski (1986) have calculated photon spectra from weakly magnetized relativistic thermal plasma in pair–equilibrium.

The γ–ray production in annihilation of other particles was also investigated. Stecker (1985) derived the γ–ray spectra from proton–antiproton annihilation and suggested explanation of MeV bump in diffusive γ–ray spectrum by this process. The significance of dark matter annihilation (WIMP – Weakly Interacting Massive Particles, see e.g. review by Trimble, 1987) to the γ–ray emission in our Galaxy was suggested in some papers (see e.g. Sciama, 1984). Detailed calculations of the annihilation spectra from WIMPs were performed by e.g. Stecker (1989) – continuum spectra and Rudaz (1989) –γ–ray line emission. Stecker (1989) suggested that contribution of photino annihilation can be important from the direction of Galactic Center and high Galactic latitudes in the directions were column density of the background matter is low (spectra from this process are expected to be flatter in GeV photon energy range). Moreover, Cline and Yi–Tian Gao (1990) proposed explanation of MeV bump in diffusive γ–ray spectrum as caused by photino annihilation at cosmological distances.

3.4 Synchrotron and Curvature radiation

Radiation emitted by relativistic electrons moving with Lorentz factors γ_e in perpendicular magnetic field is called synchrotron radiation. The general description of this process and calculation of photon spectrum from single particle (in week magnetic field) is available in many books and review articles (see e.g. Ginzburg and Syrovatskii, 1965; Pacholczyk, 1970; Blumenthal and Gould, 1970; Rybicki and Lightman, 1979). However if the magnetic field approaches the critical value ($B_c \sim 4.4 \times 10^{13} G$), the kinetic energy of electron is less than $h\nu_B/\gamma_e$ (where $\nu_B = eB/2\pi mc$ – Larmor frequency) or if the energy loss in a Larmor orbit becomes comparable to the particle energy, the quantum mechanical effects become important. For description of the synchrotron emissivity in quantum approach see e.g. Klepikov (1954) or Sokolov and Ternov (1968). However described by them formulae are very complicated and analytical approximations obtained under certain conditions are very useful. In the case of isotropic, thermal distribution of electrons approximate formulae were derived by e.g. Petrosian (1981), Imamura *et al.* (1985), Pavlov and Golenetskii (1986) and Baring (1988). The exact numerical calculations of the thermal synchrotron spectra were performed by e.g. Brainerd and Lamb (1987) and Harding and Preece (1987).

In the case of isotropic, power law electron distribution with spectral index δ and in classical limit, the optically thin synchrotron photon spectrum is also a power law type with spectral index $(\delta + 1)/2$, see e.g. Ginzburg and Syrovatskii (1965) or Rybicki and Lightman (1979). Using the full quantum approach, the spectra from isotropic, non–thermal distribution of electrons were derived by Bussard (1984).

In the low energy part of synchrotron spectrum the self–absorption of radiation becomes important. The photon spectrum in such optically thick case is a power law type with constant spectral index -2.5 independent on the spectral index in the optically thin part of the spectrum (see e.g. Rybicki and Lightman, 1979).

If the very high energy electrons are moving along the lines of strong, curved magnetic field of the order $10^{11} - 10^{13} Gs$, emitted by them radiation is called curvature radiation. The expression describing this emission can be calculated by replacing Larmor radius by curvature radius of magnetic lines in formulae describing synchrotron radiation. For example, electron with energy $10^{13} eV$ moving along a field line with curvature $10^{8} cm$ produce photons with energy $2.5 \times 10^{9} eV$.

The calculations of photon spectra from cascade process initiated by electrons in a strong curved magnetic field of a pulsar (see models of Sturrock, 1971; Ruderman and Sutherland, 1975) were performed by Cheng *et al.* (1986) and Preece and Harding (1989) taking into account synchrotron and inverse Compton processes and by Sturrock *et al.* (1989) taking into account synchrotron and curvature processes.

The thermal synchrotron mechanism was applied to the γ–ray bursts by several authors, see e.g. Katz (1982), Lamb (1982), Liang (1982) and Pavlov and Golenetskii (1986).

3.5 Inverse Compton Scattering

The soft energy photons can be scattered to higher energies by interaction with high energy electrons in process called inverse Compton scattering. If $\gamma_e \cdot \epsilon \ll m_e c^2$, where γ_e is a Lorentz factor of electrons and ϵ is energy of soft photons, the energy of scattered photon in laboratory frame is $\sim \gamma_e^2 \cdot \epsilon$ (Thomson limit). If $\gamma_e \cdot \epsilon \gg m_e c^2$ the energy of scattered photon is $\sim \gamma_e \cdot mc^2$ (Klein–Nishina limit).

For description of the kinematics of this process and cross sections in

Thomson and Klein–Nishina limits see e.g. Heitler (1968), Blumenthal and Gould (1970), Stecker (1971) or Rybicki and Lightman (1979). The formulae for inverse Compton spectrum from single scattering of isotropic, arbitrary background photon spectrum were first derived by Jones, 1968 (see also Blumenthal and Gould, 1970).

In the case of the power law electron spectrum, $f(E_e) \sim E_e^{-\delta}$, and blackbody distribution of low energy photons, the Comptonized photon spectrum for single scattering is also a power law and in Thomson limit have the spectral index $(\delta + 1)/2$ (Ginzburg and Syrovatsky, 1964) but in Klein–Nishina limit have the spectral index $\delta + 1$ (Blumenthal and Gould, 1970). If optical depth is high, the scattering of the photon spectrum with a power low electron distribution and low energy cut–off, $f(\gamma_e) = \gamma_e^{-\delta} \cdot exp(-\gamma_\circ/\gamma_e)$, turns to the power law spectrum with spectral index $log\tau/log\gamma_\circ^2$ where τ – is the optical depth (see Pozdnyakov *et al.*, 1977).

In order to derive evolution of the photon spectrum in time during scattering with arbitrary distribution of electrons in the optically thick medium, the Boltzman equation should be solved. In special cases, this problem can be simplified and analytical solution is possible. For photons scattering off a nonrelativistic, thermal distribution of electrons (keeping only second order terms) Boltzman equation simplifies to Kompaneets equation (see, Kompaneets, 1957). The solution of Kompaneets equation for different regimes turns to different emergent photon spectra, depending on the values of Compton parameter Y (which is the product of average fractional energy change of photon per scattering and mean number of scatterings) and on coherence frequency ν_c (which is the energy of photons above which Compton effects are important, defined $Y(\nu_c) = 1$). If:

- $Y \ll 1$ – modified blackbody spectrum will emerge;
- $Y \gg 1$ and $h\nu_c \ll kT$ – Wien spectrum (saturated Comptonization);
- $Y \gg 1$ and $h\nu_c \sim kT$ – power law spectrum with cut–off (unsaturated Comptonization).

The solutions of Kompaneets equation for spatially limited astrophysical scenarios (analytical, numerical) were derived and calculated by different authors (for review see Pozdnyakov *et al.*, 1983 and references therein).

Recently, the models applying comptonization of synchrotron radiation originated by these same electrons (called synchrotron self Compton models) are very popular. Photon spectra calculated according to these models, were obtained by e.g. Königl (1981), Reynolds (1982) or Atoyan and Nahapetian (1989) in Thomson limit and by Canfield *et al.* (1987) applying Klein–Nishina cross section. The photon spectra from comptonization of thermal radiation produced by the accretion disk were obtained by Melia and Königl (1989), Melia and Fatuzzo (1989) and Maraschi and Molendi

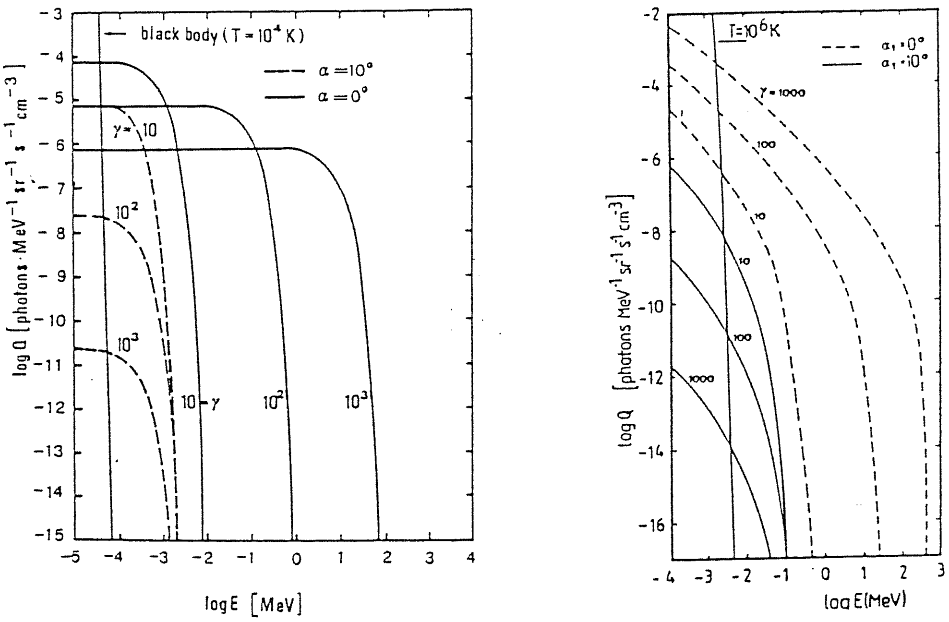

Figure 3.1: *The comptonized thermal blackbody ($T = 10^4$) and bremsstrahlung ($T = 10^6$) photon energy spectra (normalized to the value $1 MeV/cm^3$ of background photon density) for two angles of photon emission $\alpha_1 = 0°$ and $10°$ and selected values of electron beam Lorentz factors (from Bednarek et al., 1989).*

(1990). Daugherty and Harding (1989) have developed a numerical calculations of γ-ray photons produced by Compton scattering of electron beam on thermal photons close to the surface of magnetized neutron star. The photon spectra from cascade initiated by relativistic electrons in isotropic background photons were obtained under different assumptions by Zdziarski (1988, 1989).

Bednarek *et al.* (1989, 1990a) have calculated the angular dependent photon spectra from Comptonization of background radiation by relativistic electron beam applying exact Klein–Nishina cross section (for details, see Appendix A in Bednarek *et al.*, 1990a). Some numerical results of these calculations for black body and bremsstrahlung background spectra and different Lorentz factors of the electron beam γ_e are shown in Fig. 3.1. In general, for small angles of observation, the Comptonized spectra strongly depends on the beam Lorentz factor but for large angles are mainly determined by the value of this angle.

The comptonization of background photons by relativistic beam was also analyzed by Bednarek and Calvani (1990a,b). The authors have calculated the Inverse Compton spectra produced by secondary electrons originated in the interaction of highly collimated, relativistic proton beam with ambient matter (see section 3.7 in this thesis). Since the secondary electrons are highly relativistic, the Comptonized photons are strongly collimated along the direction of motion of the electrons (see, Bednarek *et al.*, 1990a). We can assume that significant contribution to the Comptonized photon spectrum emitted at the angle α (with respect to the beam axis) is given by the secondary electrons moving very close to α. Under such assumption the spectrum of the Comptonized photons produced by secondary electrons (which in tern were calculated according to eq. 3.4) is given by:

$$\frac{dN_{Comp}}{d\epsilon_\gamma d\Omega dt dV} \simeq \frac{l}{c} \int\int \frac{dN}{dE_e d\Omega_e dt dV} n(\epsilon) \frac{dQ(E_e, \epsilon)}{d\epsilon_\gamma} dE_e d\epsilon \tag{3.1}$$

where: l – the distance on which Comptonization occurs; c – the velocity of light; $dN/(dE_e d\Omega_e dt dV)$ is the angular dependent spectrum of secondary electrons from decay of polarized muons, (see eq. 3.4); $n(\epsilon)$ is the spectrum of background low energy photons; and $dP(E_e, \epsilon)/d\epsilon_\gamma dt$ is the Inverse Compton spectrum produced by monoenergetic electrons with energy E_e scattered background photon spectrum $n(\epsilon)$ (see, Blumenthal and Gould (1970) formula 2.42). For application of these calculations to the quasar 3C 273 see Fig. 5.3.

3.6 Bremsstrahlung

The γ–ray photons produced by a charged particle accelerated in the Coulomb field of another charged particle is called bremsstrahlung or free–free emission. The comprehensive description of this process is summed in many books describing radiation mechanisms in astrophysics and γ–ray astronomy (see e.g.Rybicki and Lightman, 1979; Ginzburg, 1969). The electron–proton and electron–electron bremsstrahlung cross sections are a complicated functions of the energy of the radiating electrons and the resultant photon energy and direction and in order to calculate them quantum electrodynamics approach is needed. For different approximations see e.g. Koch and Motz (1959) and references therein, Heitler (1968) or Blumenthal and Gould (1970) and for $e^+ - e^-$ bremsstrahlung see Haug (1985). The important role in this process plays screening of the field of the nuclei by electrons on the atomic levels or free electrons in plasma. This is the reason of the dependence of the photon spectrum on the ionization state of the matter (see e.g. Dogiel and Ginzburg, 1989).

In this section I will mention the main astrophysical importance of this process as a γ–ray production mechanism. For description of the bremsstrahlung photon spectrum emitted by a single electron see e.g. Blumenthal and Gould (1970) or Rybicki and Lightman (1979).

In spite of complicated formula for the bremsstrahlung cross section, the shape of the bremsstrahlung photon spectrum from isotropic, thermal distribution of electrons can be approximated by a simple law. In general, the shape of the photon spectrum can be described by a power law (in log–log plot) with spectral index of -1. up to exponential cut–off at about $E_\gamma \sim kT$. However, for photon energies $E_\gamma \ll kT$, the optical depth of the self–absorption cuts the spectrum according to the Rayleigh–Jeans law. For more detailed formulae of thermal bremsstrahlung with quantum corrections (Gaunt factors) see Rybicki and Lightman (1979). The simple formula for thermal bremsstrahlung spectrum in the limits of $kT \ll mc^2$ and $kT \gg mc^2$ were calculated by Quigg (1968) and Gould (1980,1982). However Gould (1982) stressed that existence of relativistic thermal distribution of electrons is questionable because at such energies Coulomb collisions rate is slower than energy losses on bremsstrahlung process. The detailed calculations of the photon spectra in the range $0.1mc^2 < kT < 10mc^2$ was done by Górecki and Kluźniak (1981) (e–p bremss.) and Dermer (1986) ($e^- - e^-$, $e^+ - e^-$ and $e^- - p$ bremss.).

The situation with the calculation of the photon spectrum from non–thermal distribution of electrons is similar to the thermal case. The exact formulae are very complicated but general shape (after neglecting slowly varying terms) can be described by a simple form (see e.g. Blumenthal and Gould, 1970; Harding *et al.*, 1986). In the case of isotropic, power law differential electron spectrum, $f(E_e) = K \cdot E_e^{-\delta}$, the differential photon spectrum is also a power law type with spectral index of $\delta + 0.5$ for $E_\gamma \ll mc^2$ and of δ for $E_\gamma \gg mc^2$ (a change in spectral index at $E_\gamma = mc^2$).

The calculations of non–thermal bremsstrahlung spectrum originated by secondary electrons (from p–p interactions) with background matter in our Galaxy were performed by Schlickeiser (1982). Because the confinement time of the electrons is long compared to the bremsstrahlung loss time (the radiation length in hydrogen is $\sim 60g/cm^2$), the thick target model was applied and solution of propagation equation was necessary. The author concluded that the bremsstrahlung contribution dominates the π° decay component for photon energies $< 50MeV$.

Dermer and Ramaty (1986) have calculated the bremsstrahlung γ–ray spectra (depending on the observing angle) from non–isotropic beam with different electron spectrum. In such scenario, the photon spectra are steeper than the parent electron energy spectrum at low energies and become flatter at high energies (changing in this tendencies depends on the observing angle). The results of these calculations were applied to Solar γ–ray flares.

Bednarek and Calvani (1990a,b) have calculated the bremsstrahlung spectra produced by secondary electrons originated in the interaction of highly collimated, relativistic proton beam with ambient matter (see section 3.7). Since secondary electrons are highly relativistic, the produced photons are strongly collimated along the direction of motion of the electrons (Koch and Motz, 1959) and we can assume that significant contribution to the bremsstrahlung spectrum emitted at the angle α (with respect to the beam axis) is given by the secondary electrons moving very close to α. Under such assumption the spectrum of the bremsstrahlung radiation produced by secondary electrons (calculated according to eq. 3.4) is given by:

$$\frac{dN_{brem}}{dE_\gamma d\Omega dt dV} \simeq \lambda \int \frac{dN}{dE_e d\Omega_e dt dV} \frac{dQ(E_e)}{dE_\gamma} dE_e \tag{3.2}$$

where: $\lambda-$ mean column density traversed by relativistic electrons in particles$/cm^2$; $dN/(dE_e d\Omega_e dt dV)$ is the angular dependent spectra of secondary electrons from decay of polarized muons, (see eq. 3.4); and $dQ(E_e)/dE_\gamma$ is the bremsstrahlung spectrum produced by monoenergetic electrons with energy E_e (Blumenthal and Gould, 1970). The intensities of the calculated photon spectra strongly depend on the angle between the beam axis and the direction of photons emission similarly to the dependence of the secondary electron spectra according to the beam axis.

3.7 Gamma rays from hadronic interactions

In principle, high energy protons can produce γ–rays directly via bremsstrahlung or curvature radiation processes. However because of much higher mass–to–charge ration than for electrons these processes are relatively much less efficient. γ–ray photons can be generated in decay of neutral pions or in bremsstrahlung and inverse Compton processes of secondary electrons originated in decay of charged pions where pions in tern are produced in p + p interactions ($p + p \rightarrow \pi^\circ; \pi^\circ \rightarrow 2\gamma$ or $p + p \rightarrow \pi^\pm; \pi^\pm \rightarrow \mu^\pm \rightarrow e^\pm$; brem. and ICS of $e^\pm$). In general, the kinematics of decay of the neutral pions is well known and is described in many books (see e.g. Stecker, 1971; Ramaty, 1974; Hillier, 1984). That's why in this section we concentrate on practical applications of this mechanism in specific astrophysical scenarios.

In this kind of calculations a very important thing is the correct description of production of pions in p + p interaction process. A few different models proton–proton interaction (or their combinations) were applied, e.g.: Isobar + Fireball model – Stecker (1970), Isobar + Phase Space model – Cavallo and Gould (1971), Scalling model – Stephens and Badhwar (1981) , Isobar + Scalling model – Dermer (1986). In this last paper, the author concluded that the best description of experimental data of p + p interaction can be achieved by application of Isobar model below $\sim 3GeV$ and Scalling model at higher energies.

The above mentioned models of p + p interactions were applied in calculations of the cosmic γ–ray spectrum as a secondary result of the interaction of relativistic cosmic ray protons with matter at rest. Assuming the spectrum of cosmic particles (protons, He) as a power law type, the calculated spectrum of γ–rays, from π° decay created in p + p collisions, is also a power

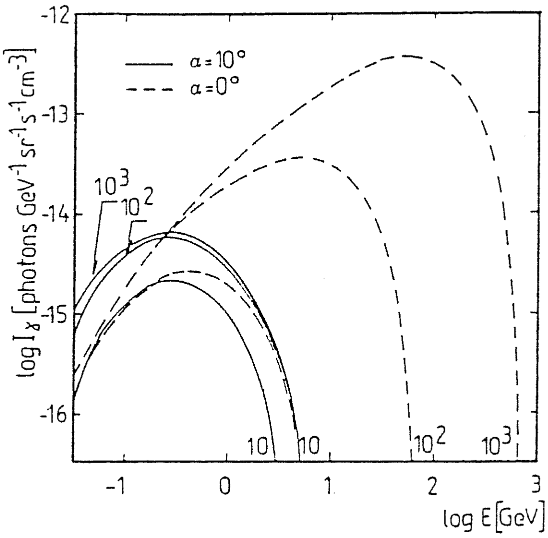

Figure 3.2: *The photon energy spectra from π° decay produced by proton beam with Lorentz factors $\gamma = 10, 10^2, 10^3$ and two angles of photon emission with respect to the beam axis $\alpha = 0°$ and $10°$ (from Bednarek et al., 1989).*

law with similar spectral index above a few GeV and with peak close to $\sim 67.5 MeV$ (half mass of π°), see e.g. Stecker (1973).

Murphy *et al.* (1987) calculated the γ–ray spectra from π° decay created in interaction of isotropic, monoenergetic protons with protons at rest using Isobar + Scalling model. The results were successfully applied to γ–ray emission during solar flares.

The case of γ–ray emission from spherically–symmetric thermal plasma was studied by Dahlbacka *et al.* (1974); Kolykhalov and Sunyaev (1979) applying Isobar model; Giovannelli, Karakuła, Tkaczyk (1982) and Dermer (1986). The authors have calculated γ–ray emission in the spherically–symmetric, adiabatic model of accretion of matter onto the $10 M_\odot$ black hole ($10^{36} erg/s$ – first two papers and $10^{34} erg/s$ – Giovannelli, Karakuła, Tkaczyk). In more complicated non–adiabatic model (the electron–proton coupling was taken into account), the γ–ray emission was predicted to be much lower because of lower maximal temperature of proton plasma (see Colpi *et al.*, 1984). γ–ray production in plasma (via π° decay) from the accretion onto a rotating black hole was calculated by Colpi *et al.* (1986).

The γ–ray production (via π° decay) by relativistic proton beam interacting with background matter was analyzed by Bednarek *et al.* (1989, 1990a). The authors have calculated the γ–ray spectra depending on the angle of photon emission to the proton beam axis for monoenergetic, one–dimensional beam (see, Fig. 3.2).

It is worth to note that in such scenario very high energy photons (energy close to energy of parent particle) can be emitted only within a very small

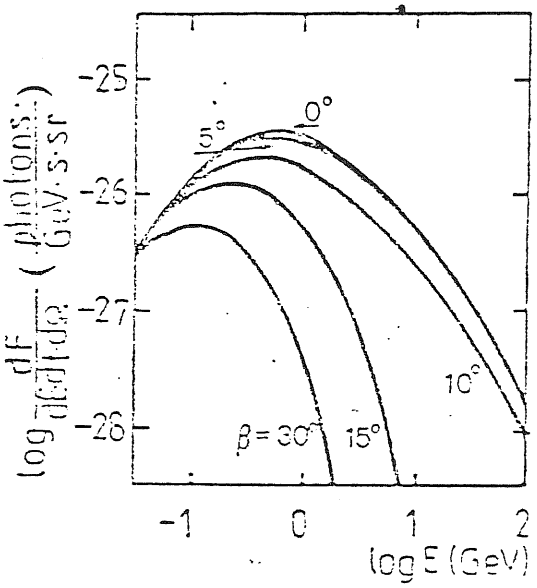

Figure 3.3: *The photon spectra from the interaction of cone proton beam with Lorentz factor $\gamma = 10^3$, half angle of the cone $\tau = 10°$, and selected angles of the photon emission with respect to the beam axis (from Bednarek et al., 1990b).*

cone around the beam axis. In the case of relativistic proton beam and large angles (with respect to $1/\gamma_p$), the shape and intensities of the photon spectra are mainly determined by the value of the angle and do not depend significantly on the proton beam Lorentz factor. Influence of noncollisional processes (Rose *et al.*, 1984) and photon–photon absorption on the shape of the γ–ray spectrum were considered in paper Beall *et al.* (1987).

The calculation of the γ-ray spectra from a cone, relativistic proton beam with fixed spectrum of particles were performed by Bednarek *et al.* (1990b). As an example, in Fig. 3.3 are shown the calculated γ–ray spectra from proton beam with Lorentz factor $\gamma_p = 10^3$, half angle of the beam $\tau = 10°$ and selected angles of the photon emission with respect to the beam axis. The shape of the γ–ray spectrum and their intensities seen by the observer located inside the cone are very similar to each other but the cutoff of the γ–ray spectrum observed outside the cone is strongly determined by the value of the angle. This model can describe the γ–ray spectrum emitted by Cyg X–3 and Geminga (see also chapter 4).

The secondary electrons (really electrons and positrons) from decay of charged pions ,created in p +p interactions, can produce high energy γ–rays via bremsstrahlung and inverse Compton processes. However, the calculation of the spectrum of secondary electrons is much more complicated because of three body decay ($\mu^{\pm} \rightarrow e^{\pm} + \nu_e + \nu_\mu$). Such calculations in the case of isotropic, power law spectrum of protons were performed by Ramaty (1974) and Marscher and Brown (1978) with purpose to describe the of cosmic ray spectrum of electrons and positrons. Based on the results obtained by Marscher and Brown (1978), the diffusive spectrum of γ–ray photons in our Galaxy from bremsstrahlung of secondary electrons was calculated by Schlickeiser (1982).

Discussed above mechanism (production and decay of charged pions) was also applied by Murthy *et al.* (1987) to explain the γ–ray spectrum of the solar flares. The authors have calculated the spectra of γ–ray photons from bremsstrahlung of secondary electrons and from annihilation of secondary positrons assuming isotropic and monoenergetic distribution of protons interacting with matter at rest. In this calculations Isobar + Scalling model of particle + particle interaction was applied.

The production of secondary electrons was also analysed by Bednarek and Calvani (1990a,b) in the model of the relativistic proton beam interacting with background matter. We have considered a monoenergetic, one–dimensional proton beam with Lorentz factor γ_p. The beam propagates at an angle α to the line of sight. The spectrum of muons from the decay of pions is then described by the formula:

$$\frac{dR}{dE_\mu d\Omega_\mu dt dV} = A \int\int\int \frac{d\sigma(p_\pi, \cos\theta_\pi, \phi_\pi)}{dp_\pi d(\cos\theta_\pi) d\phi_\pi} P(\gamma_\pi, E_\mu, \Omega_\mu) dp_\pi d\Omega_\pi \qquad (3.3)$$

where:

$$\frac{d\sigma(p_\pi, \cos\theta_\pi, \phi_\pi)}{dp_\pi d(\cos\theta_\pi) d\phi_\pi} = \frac{{p_\pi}^2}{E_\pi}\left(E_\pi \frac{d^3\sigma}{dp_\pi^3}\right)$$

and: $E_\pi \times d^3\sigma/dp_\pi^3$ is the invariant cross–section for the production of charged pions, taken from Tan and Ng (1983); $P(\gamma_\pi, E_\mu, \Omega_\mu)$ describes the energy and angular distribution of muons, in the observer's frame, from the decay of pions with momentum p_π and Lorentz factor γ_π; $A = \beta_b c n_b n_H$ with $\beta_b =$ relative velocity of the beam, $c =$ velocity of light, $n_b =$ concentration of the beam, $n_H =$ concentration of ambient matter. For details of the calculations see Appendix A.

Assuming then that muons decay instantaneously, the angular dependent spectrum of secondary electrons is given by:

$$\frac{dN}{dE_e d\Omega_e dt dV} = \int\int\int \frac{dR}{dE_\mu d\Omega_\mu dt dV} J n^*(E_e^*, \Omega_e^*) dE_\mu d\Omega_\mu \qquad (3.4)$$

where: $dR/(dE_\mu d\Omega_\mu dt dV)$ is the angular dependent spectrum of muons from decay of pions expressed by eq.(3.3); $J = \gamma_\mu^{-1}(1 - \beta_\mu \cos\theta_e)^{-1}$ is the Jacobian of the transformation from the muon rest frame to the observer's frame, neglecting the electron rest mass with respect to electron's energy and $n^*(E_e^*, \Omega_e^*)$ is the energy and angular distribution of electrons in the rest frame of polarized muons (Lee and Young, 1957). For details of the calculations see Appendix B.

Numerical results of calculations of the spectrum of secondary electrons are presented in Fig. 3.4 for Lorentz factors $\gamma_p = 10,\ 10^2,\ 10^3,\ 10^4$ of the monoenergetic proton beam and for angles $\alpha = 0°,\ 10°$. Concentrations of the proton beam n_b and of background matter n_H were taken equal to one particle per cubic centimeter.

The general behaviour of the spectra of secondary electrons is very similar to the spectra of photons from π^0 decay (Bednarek *et al.*, 1990). The shape and maximum intensity of the secondary electron spectra strongly depend on γ_p and α. For small α's (with respect to $1/\gamma_p$) and in the relativistic limit $\gamma_p >> 1$, the value and the position of the maxima grow proportionally to γ_p (Fig. 3.4). The spectra of secondary electrons have smaller intensities and are shifted to lower energies than the spectra of secondary positrons because of the difference in the cross sections for π^- and π^+ production in p + p collisions. For large α's the shape of the spectra and the position of the maxima are practically determined only by the value of α, the intensities for different Γ's in relativistic limit being comparable (Fig. 3.4).

The spectra of secondary electrons (derived according to above formulae) were used in calculations of the X and γ–ray spectra depending on the angle of photon emission with respect to the proton beam axis (for details see sections 3.5 and 3.6 in this thesis and for their application to the quasar 3C 273 see also chapter 5).

The high energy γ–rays can be also generated in a direct interactions of relativistic particles with low energy photons if the energy of photon exceeds the electron or pion production threshold ($p + \gamma \rightarrow p + e^+e^-$; $p + \gamma \rightarrow p + \pi^\circ + \pi^\pm$). Such processes can occur for extremely energetic protons of extragalactic origin propagating in the 2.7K mickrowave background radiation or in the sources of relativistic particles surrounded by extended halos of low energy photons (see, e.g. Mannheim and Biermann, 1989; Mitra, 1990). The resulting charged particles (electrons and positrons) have very high energies and can start electromagnetic cascades in background photon field via pair production and inverse Compton processes (see e.g. Wdowczyk *et al.*, 1972).

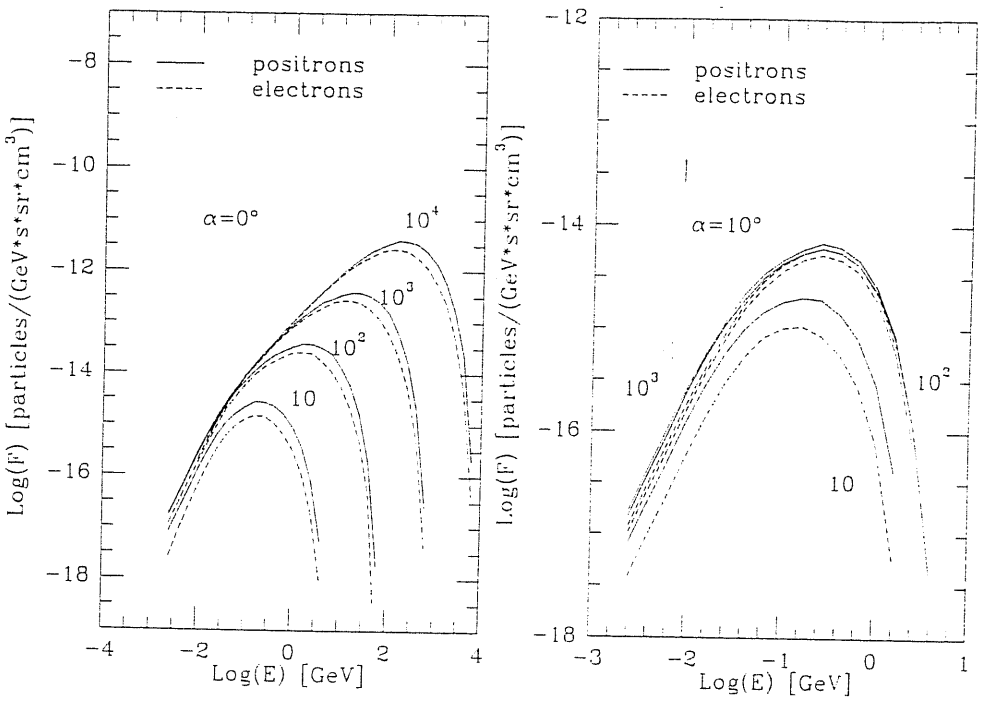

Figure 3.4: *The spectra of secondary electrons produced by proton beam for selected values of the proton beam Lorentz factor and two angels of photon emission with respect to the beam axis:* $\alpha = 0°$ *- left side and* $\alpha = 10°$ *-right side (from Bednarek and Calvani, 1990b).*

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Chapter 4

Specific Galactic γ–ray sources

4.1 Introduction

The observations of soft γ–rays from the Galactic sources started in early 70' when γ–ray detectors were successfully launched in a number of balloon flights. Later experiments on the board of SAS 2 and COS B satellites showed evidence for as many as 25 discrete objects in the energy region 70–5000MeV. To detect higher energy γ–rays ($> TeV$), technics based on the observations of atmospheric Cherenkov radiation and secondary particles from cosmic ray air showers were applied.

In general, high energy γ–rays from discrete sources give us information about the most energetic and nonthermal processes. Moreover, the variability is a feature which seems to be characteristic for most sources. They are usually black hole candidates, pulsars or X–ray binaries.

In this chapter, we review a few representative, peculiar γ–ray sources in the following sequence:

- Galactic Center – e^+e^- line emitter, massive black hole candidate;
- γ–ray bursts – transient γ–ray emitters with the frequency of events up to a few hundred per year;
- Cyg X–1 – solar mass black hole candidate (other similar sources e.g.: Sco X–1, SS433?);
- Geminga (2CG195+04) – emitted power concentrated in 100MeV–1GeV photon energy range (no other candidates discovered);
- Crab (2CG184-05) – 33ms pulsar and supernova remnant (other similar sources e.g.: Vela pulsar, PSR 1953, ...)
- Cyg X–3 – X–ray binary system (other similar sources e.g.: Her X–1, Vela X–1, Cen X–3, LMC X–4, ...).

4.2 Galactic Center

The Galactic Center region is usually defined as the region compressed in 200pc around the galactic nucleus. Because of the 30 magnitudes of visual extinction between us and the galactic nucleus, our knowledge is mainly based on the low–energy (radio, infrared) and the high–energy (X–rays, γ–rays) observations. For details of results of these observations see review papers by e.g. Oort (1977), Brown and Liszt (1984), Hyland (1986), Genzel and Townes (1987) and proceedings of the conferences : Riegler and Blangford (1982), Backer (1987), Yusef-Zadeh and Morris (1989). Here we only mention the most important features from the viewpoint of γ–ray observations.

In general, the structure of the Galactic nucleus is complex. It is not completely clear what kind of forces dominate this region: gravitational or magnetic ? Poloidal magnetic field is present at distances 10 to 100 pc from the center, whereas the field appears to lay in the galactic plane at distances of a few parsecs (with average strength of about a milligauss). Magnetic forces probably dominate in a pair of lobes (omega–shaped), extending (for about 30pc) from the Galactic Center in the direction perpendicular to the galactic plane (Yusef Zadeh, *et al.*, 1984). Gravitational forces dominate many features with circular motion like: 3kpc arm, the nuclear ring (Liszt and Burton, 1978), the molecular ring (Kaifu *et al.*, 1972) and the disk in the central 2–3pc from the Galactic nucleus. In the central cavity is observed complex spiral–like structure, known as Sgr A West, very bright in radio and infrared wavelengths ($\sim 10^7 L_\odot$). Near the center of Sgr A West lays two peculiar sources $SgrA^\star$ and IRS 16. The first one is a nonthermal compact source with size less than $\sim 2 \times 10^{14} cm$ (Lo *et al.*, 1985). the second one is a strong infrared source, consisting of a number of point–like components, with spectral features similar to that of Seyfert nuclei.

X–ray observations discovered a few sources close to the Galactic center. However the most interesting (from viewpoint of high energy emission) seems to be the neutron star GX1+4 which is one of the brightest X–ray source at energies 20–100keV (see Levine *et al.*, 1984).

The measurements of rotation velocity suggest the existence of a very big mass ($1 - 4 \times 10^6 M_\odot$) within 0.1pc to the center (Crawford *et al.*, 1985). Such concentration of mass in small volume supports the hypothesis about the existence of a massive black hole in the center of our Galaxy (first proposed by Lynden–Bell and Rees, 1971). However, it is not sure in which source lays Galactic center of gravity, in Sgr $A^\star$ or IRS 16 (Mezger, 1986). Moreover, there are some arguments that the central black hole (if it really exists?) is not more massive than $\sim 100M_\odot$ (Allen *et al.*, 1986) or $\sim 1000M_\odot$ (Lingenfelter and Ramaty, 1989).

γ–ray emission from Galactic Center.
The γ–ray emission close to 0.511 Mev from the direction of the Galactic Center was first detected in balloon observations with low resolution NaI detectors (Johnson *et al.*, 1972; Johnson and Haymes, 1973; Haymes *et al.*, 1975). Clear identification with e^+e^- annihilation line was possible in 1977 when Leventhal *et al.* (1978) observed this emission with high resolution Ge detector and reported very narrow 0.511 MeV line (FWHM $\leq$ 3.2 keV). Observations on HEAO-3 satellite during 1979–1980 (Riegler *et al.*, 1981) showed that the source coincides with the Galactic Center within the $\pm 4°$ of observational uncertainty and that the line varies very fast with time. Within six months of the period 1979–1980, the intensity of annihilation line falls down by a factor of three from $(1.85 \pm 0.21) \times 10^{-3} photons/cm^2/s$ to $(0.65 \pm 0.27) \times 10^{-3} photons/cm^2/s$. During 1980–1984 annihilation line from the direction of Galactic Center was not seen by detectors with angular resolution better than $\sim 15°$ (Leventhal *et al.*, 1980; Riegler *et al.*, 1982; Paciesas *et al.*, 1982; Leventhal *et al.*, 1986). Recently, Leventhal *et al.* (1989) reported observations with relatively narrow field of view. The measured flux in 0.511MeV line $(9.8 \pm 1.9) \times 10^{-4}$ photons/cm^2/s on 1May 1988 and $(12.3 \pm 1.6) \times 10^{-4}$photons/$cm^2$/s on 29October 1988 means that between 1984–1988 the line emission from the direction of the Galactic Center re–emerged (confirmed by Niel *et al.*, 1990). For details of time history of line observations see Fig. 4.1.

The continuum emission in X and γ–rays from the direction of Galactic Center was reported as variable, with power law spectrum (spectral index $0.5 \div 1.0$) in $\sim 1keV$ to $\sim 2MeV$ range (with apparent hardening above 300keV) and slope < 2.5 above $\sim 2MeV$ (Matteson, 1982). During the observation period 1979/1980, the emission in the range $0.511MeV \div 3MeV$ seems to be correlated with variability of 0.511MeV line emission . In the spring 1980, observation of the Galactic Center showed no detectable luminosity above 0.511MeV (Riegler *et al.*, 1985), see Fig. 4.2.

From analysis of the results of these observations have been derived parameters of the source: the size of annihilation region $< 10^{18}$ cm (from variability), the density $> 10^5 H/cm^3$ (from the time of slowing down of higher energy e^+e^-), temperature $< 5 \times 10^4 K$ (from width of the 0.511MeV line) and ionization fraction greater than 10% (from

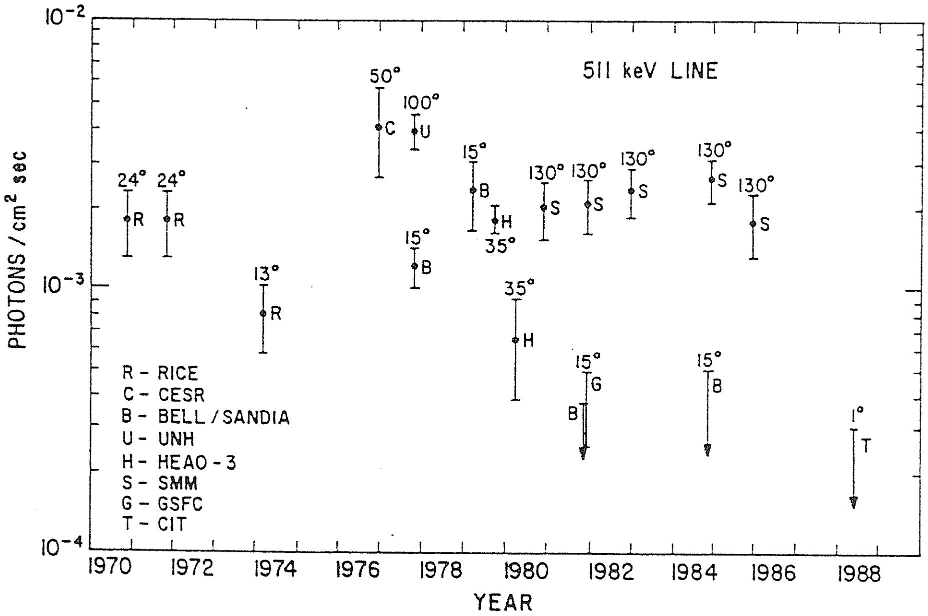

Figure 4.1: *The flux of the 0.511MeV annihilation line from the direction of the Galactic Center versus time. Also fields of view of detectors were included (from Lingenfelter and Ramaty, 1989).*

relevance of two–photon to three–photon annihilation (see, Bussard *et al.*, 1979; Riegler *et al.*, 1983).

One of the sources in COS B cataloque (Swannenburg *et al.*, 1981), 2CG359–00, has error box ($\sim 1°$) which includes the position of Galactic Center. Its reported luminosity $\sim 8 \times 10^{36} erg/s$ is typical like for Galactic γ-ray source, that's why is questionable if this source is really close to Galactic Center.

Another very interesting observation was reported by Mahoney *et al.* (1982, 1984). They observed emission line 1.8MeV (^{26} AL decay) with intensity $(4.3 \pm 0.8) \times 10^{-4}$ photons/cm^2/s from the general direction of Galactic Center (angular resolution 42° in FWHM). This result was confirmed by Share *et al.* (1985) (however FWHM was $\sim 130°$). Since very low angular resolution of these observations, 1.8MeV line was usually interpreted in terms of diffusive origin in Galactic disk. Recent observations by von Ballmoos *et al.* (1987) with much better angular resolution ($\sim 10°$) suggest their origin in Galactic Center. If so, giant explosion in the center of the Galaxy within last few $10^6 yr$ producing $(4.8 \pm 2.) \times M_\odot$ of ^{26}AL seems to be real alternative.

Summarizing, there is a strong evidence of unusually narrow 0.511MeV line emission from the Galactic Center. However, because of the poor angular resolution of detectors, it is impossible to distinguish which of the few peculiar sources in this region is responsible for this MeV emission (there are at least three candidates: Sgr A^*, IRS 16, GX1+4).

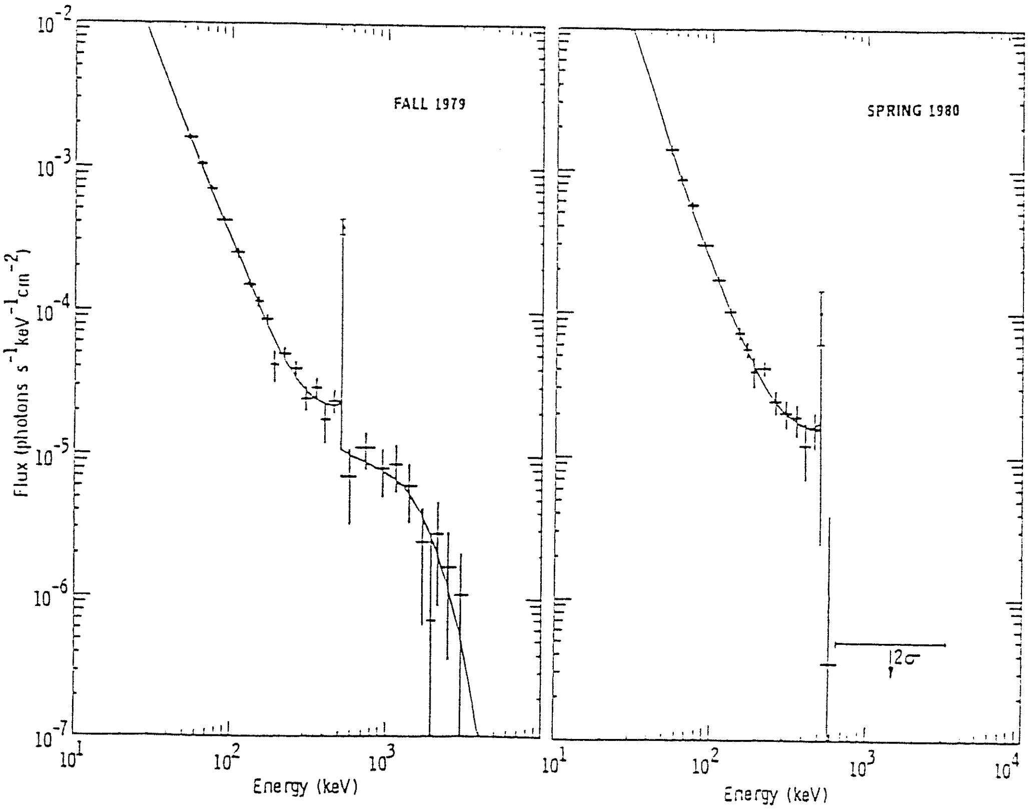

Figure 4.2: *The photon spectra from the direction of the Galactic center in γ-ray range during the fall of 1979 (left) and the spring of 1980 (right), from Riegler et al., 1985*

Mechanism of MeV emission from Galactic Center.
The main problems with modeling the MeV emission from the Galactic center concern explanation of the intensity of annihilation line (annihilation rate $\approx 2 \times 10^{43} s^{-1}$, for a distance of 10kpc), width of this line (FWHM $< 2.5 keV$) and the variability of the MeV emission (time scale $\sim 10^7 s$). Up to date, a few mechanisms of production of positrons were proposed:

- Jet models – relativistic positrons are produced in the accretion disk or magnetosphere around $\sim 10^6 M_\odot$ black hole (Blandford, 1982; Burns, 1983; Aharonian, 1986). In this scenario, relativistic particles can develop electromagnetic cascade first on ambient soft photons (e.g. from accretion disk) and next using itself as a scattering medium. In model proposed by Kardashev *et al.* (1983)

γ–ray beam interacts with gas cloud. Produced positrons annihilate after thermalization in surrounding medium.

- Thermal plasma model – Aharonian (1986) considered production of positrons in high temperature plasma $kT_e \sim 1 - 2MeV$ and Thomson optical depth $\tau \gg 1$. He concluded that for such plasma parameters, it is possible to provide the necessary positron production rate ($\sim 10^{43}s^{-1}$).
- Pulsar model – Brecher and Mastichiadis (1983) suggests that e^+e^- pair production can be caused by young pulsars with high surface temperature $T \approx 10^7K$, strong magnetic field $B = 5 \times 10^{12}Gs$ and speed of rotation $\omega = 350s^{-1}$ (similar to Crab pulsar at birth). McClintock and Leventhal (1989) proposes that 0.511MeV line can be connected with X–ray binary GX1+4 which is in the error box of observations of 0.511MeV line, because of similar time variation. However, pulsar in the system GX1+4 has different parameters (at least ω) than the ones suggested by Brecher and Mastichiadis.
- Supernova models – Colgate (1983) and Shklovskii (1983) proposed recent supernova explosion close to the Galactic center. The positrons can be produced in radiative sequence $^{56}Ni \rightarrow ^{56}Co \rightarrow ^{56}Fe$ (Colgate, 1983) or in magnetosphere of recently created neutron star (Sklovskii, 1983). Suggestions of Lingenfelter and Ramaty (1989) that part of the continuum MeV emission from the direction of Galactic center is diffusive origin support supernova model. Moreover, Webber (1986) postulates connection between 0.511MeV line (e^+e^- annihilation) and 1.81MeV line (^{26}Al decay), where ^{26}Al can be produced in supernova explosion.
- Stellar mass black hole – Lingenfelter and Ramaty (1982, 1989) consider e^+e^- pair production in $\gamma - \gamma$ collisions near an accreting black hole. Based on the analysis of the ratio of the 0.511MeV line to continuum emission ($> 0.511MeV$), they concluded that black hole mass is less than $\sim 1000M_\odot$. Moreover, continuum MeV emission is very similar to the spectrum of Cyg X–1 which is widely believed to be a few stellar mass black hole.
- Low-mass X–ray binaries – Kluźniak *et al.* (1989) suggested that X and MeV emission (including 0.511MeV line) can be due to contribution from many Low-mass X–ray binaries close to the Galactic center. However this proposition is in contradiction to reported variability of 0.511MeV line emission during 6 months.

The intensity of 0.511MeV annihilation line is surprisingly high in comparison to continuum emission below 0.511MeV if we take into account that most of the annihilations in neutral or partially ionized hydrogen should go through positronium (Brown *et al.*, 1986; Bussard *et al.*, 1979). Annihilation via positronium formation means that the number of annihilations on three photons (orthopositronium state) should dominate annihilations on two photons (parapositronium state). This is not observed from the Galactic center where at most 40% of the positrons annihilate via $3-\gamma$ (Riegler, 1983). The only possibility to avoid this problem is to find a mechanism of conversion of orthopositronium before annihilation. Zurek (1985) proposed annihilation of positrons in dust which is observed in the Galactic center (1% of total mass). Lingenfelter and Ramaty (1989a) applied UV photons from an accretion disk around the central source to photoionize the orthopositronium. Moreover, orthopositronium can be suppressed if the density of the ambient medium exceeds $\sim 10^{15} electr./cm^3$ or magnetic field is stronger than $\sim 10^3 Gs$ (Cronnell, 1976).

The big exceess in photon spectrum just below 0.511MeV (see Fig. 4.2) does not coincide with variability of 0.511MeV line. This fact suggests that continuum emission is not caused by $3-\gamma$ annihilation via orthopositronium state. Bildsten and Zurek (1988) propose its origin in delated Compton scattering of 0.511MeV and higher energy photons in the spherical medium surrounding central source with dimensions of the order of one light year.

It is not clear what kind of mechanism is responsible for observed variability of MeV emission from the direction of the Galactic center. According to Lingenfelter and Ramaty (1989b) correlation between the 0.511MeV line and continuum (> 0.511) fluxes suggests that their observed variability is due to a variable positron source and not to variations in the properties of the annihilation site. However, if annihilation line source is a companion of binary system (McClintock and Leventhal, 1989), eclipse or episodic ejection of mass from big massive companion (Manchanda, 1988) seem to be alternative hypothesis.

Conclusions.

- Very narrow lines, 0.511MeV (e^+e- annihilation) and 1.81MeV (^{26}AL decay) were discovered from general direction of the Galactic center. The nature of the 1.81MeV line emission seems to be diffusive. Annihilation line 0.511MeV is probably originated in one of the point–like sources (e.g. Sgr A*, IRS 16, GX1+4) located close to the Galactic center, because of reported significant variability (during 6 months intensity decreases by a factor of 3).

- Continues emission (up to 3MeV) is probably sum of diffusive and point source origin. MeV emission above 0.511MeV had similar variability like 0.511MeV line emission. Emission below 0.511MeV was stable which suggests different mechanism of production (diffusive ?) or time-delayed emission in comparison to 0.511MeV line variability.
- There exist several models of MeV emission from the direction of the Galactic center (e^+e^- or γ–ray beam, supernova, neutron star, Low–mass X–ray binary, etc.). Some of them postulate existence of the black hole in the Galactic center (massive $\sim 10^6 M_\odot$ or an order of a few $M_\odot$). From the observational point of view, the best candidates responsible for 0.511MeV line emission seem to be Sgr A* (black hole?) and GX1+4 (pulsar in binary system). However, progress in real identification is expected after significant improvement of the angular resolution of detectors in MeV range which seems to be impossible in the near future (up to date, position is estimated as $\pm 4°$ around The Galactic center).

4.3 γ–ray bursts

Bursts of hard X-ray radiation, exceeding the background up to of 4 orders of magnitude during the time of $0.1 \div 100s$, were first discovered by Vela satellites in 1969. Their astrophysical origin was announced by Klebesadel *et al.* (1973). Up to now there were observed about 400 γ -ray events in the energy range 20 keV to several MeV, but their origin and nature is still an outstanding mystery in spite of many observational efforts and intensive discussions (see e.g. reviews: Mazets and Golenetskii, 1981; Vedrenne and Chambon, 1983; and proceedings of the conferences: Lingenfelter *et al.*, 1982; Burns *et al.*, 1983; Woosley, 1984; Liang and Petrosian, 1986).

The main problems with deep investigating of γ-ray burst sources concerns lack of their identification in other parts of photon spectrum (e.g. there is no optical counterpart up to the 22nd magnitude in their error boxes). Moreover, the time structure of bursts is very complicated and there is no something like 'typical event'. In some cases are seen gvasi-periodic oscillations but only 3 bursts were reported as repeating. Some information about locations of γ–ray bursts can be obtained from studies of their distribution in the sky. Now, this distribution seems to be isotropic which implies their local ($< 500pc$) or extragalactic ($> 100Mpc$) origin. Discovery of 'absorption' and 'emission' features in burst spectra by (Mazets *et al.* 1980, 1981c), if interpreted as cyclotron absorption in strong magnetic field and gravitationally redshifted e^+e^- annihilation line, suggests a neutron star origin of bursts and their local (galactic) situation. However, we will shortly discuss some other interesting explanations.

From the theoretical point of view,synchrotron and compton processe were considered as the most promising mechanisms of γ–ray production. However in earlier works thin thermal bremsstrahlung was very popular, too. In some models the e^+e^- annihilation plays an important role. Non-thermal particle distribution is favourable at least for bursts with emission above 1MeV.

Many questions concerning the detailed behaviour of γ–ray bursts remain unanswered which is a big complication for theoretical progress. It is a chance that future observational efforts (e.g. detector BATSE on the board of Gamma Ray Observatory) will be able to solve many of them.

In the first part of this section we overview the observational statement of γ-ray bursts which is still very incomplete. In the second part we discuss the main mechanisms and some specific models. we put this section in part of the thesis dedicated to the Galactic sources since most astrophysicists believe in their Galactic origin.

Observational Characteristics of γ-ray Bursts.

From the observations of γ–ray bursts we can obtain the information concerning their characteristics like: distribution in the sky, location, time history, general shape of the spectrum and spectral features. We describe them in the above sequence.

The distribution of γ–ray bursts in the sky can give us information about their origin. In general there are two statistical tools to determine the spatial distribution: investigation of the brightness distribution and investigation of their angular distribution in the sky.

The brightness distribution is usually plotted as a dependence of the number of sources "N" with total fluence greater than S according to the value of the fluence "S". For uniform distribution of sources this dependence in log N – log S scale should follow power law with index –1.5. Display of the data from different experiments (Vela catalogue, Konus data, PVO data) in this coordinates show significant breaks from –1.5 power law (Klebesadel *et al.*, 1984). The simplest interpretation of this result is location of γ-ray bursts in the Galactic disk (Fishman, 1979; Jennings and White, 1980, Mazets and Golenetskii, 1981). However Paczynski (1986) proposes cosmological origin of this deviation. Moreover, nonspherical models of burst sources can explain this result

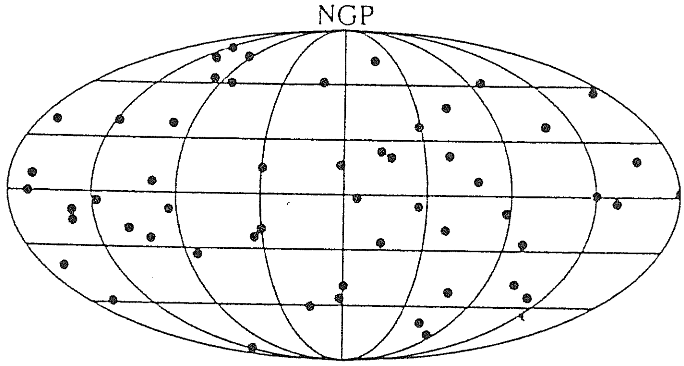

Figure 4.3: *Distribution of the bursts sources in galactic coordinates, taken from the catalog of Atteia et al. (1987)*

even for uniform distribution (Pizzichini, 1984). The log N–log S representation of data was strongly criticized in many papers (Klebesadel *et al.*, 1984; Mazets, 1985; Higton and Lingenfelter, 1986; Paczynski and Long, 1988; Yamagami *et al.*, 1986), because of selection effects caused by different time profiles of the bursts (specially important for small bursts for which deviation from –1.5 law is the biggest). Mazets and Golenetskii (1981) used relation log N – log P, where P is the flux in the peak of the bursts, but still found disagreement (however much lower) with –1.5 low, opposite to this same kind of analysis made by Yamagami *et al.* (1986). After correcting Konus data (analysed by Mazets and Golenetskii) for all biases, Jennings (1988) reached good agreement to –1.5 index accept for the faint end of log N – log P curve, see Fig. 4.3. This last result is supported also by Higdon and Schmidt (1990) who applied the V/V_{max} test which does not depend on the detection of influence on $\gamma-$ ray bursts. But, if the distribution of burst events is uniform (like suggests good agreement of previous results with –1.5 index in most papers), the prototype burst detector (BATSE) sent on balloon by Meegan *et al.*, (1985) should observe about 40 bursts during the time of flight and observed only 1. The final conclusion of these all analysis is that we need new more sensitive observations in order to definitively solve the problem of burst distribution. Up to now results in different papers are not completely consistent.

The second tool which can give information about γ–ray burst distribution is the analysis of their directions of arrivals. It was done in two papers by Mazets *et al.* (1981b) and by Atteia *et al.* (1987). Mazets *et al.* had capability to estimate the directions of bursts arrivals (an order of $arcmin^2$) in two methods: using anisotropic sensitivity of detectors

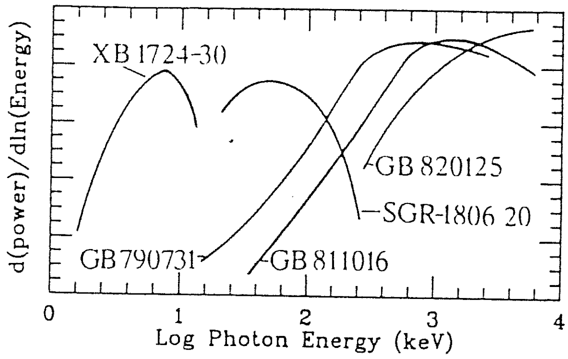

Figure 4.4: *Distribution of power in some γ-ray bursts spectra (from Epstein, 1986).*

and the time delay in arrival of the front of the burst to different satellites. Atteia *et al.* used only this second method. The distribution of arrival directions in the Galactic coordinates (according to Atteia *et al.*) is presented in Fig. 4.4. As we can see, the distribution is very close to isotropic. This result is also supported by Hartmann and Epstein (1989) who have calculated low-order multipole moments of bursts distribution (using Atteia *et al.* data). They confirmed consistence with an isotropic distribution. However, these results were critisized because of possibility of big systematic errors in time-delay method (see discussion in Vahia and Rao, 1988). The method applying angular sensitivity of detectors was critisized by Klebesadel *et al.* (1982) because of possible influence of backscatering from the spacecraft.

Precise location of γ-ray bursts is very important if we try to identify them in the other parts of electromagnetic spectrum. Some of their error boxes were examined in radio range (e.g. Hjellming and Ewald, 1981; Barat *et al.*, 1984), infrared (e.g. Apparao and Allen, 1982; Schaefer *et al.*, 1987), X-rays (e.g. Boer *et al.*, 1987, Murakami *et al.*, 1990) and γ-ray (Bhat *et al.*, 1981; Morrello *et al.*, 1981) and in VHE range above $10^{15} eV$ (Clay *et al.*, 1982). No counterparts were found. These observations give strong restrictions on parameters of γ-ray burst models or confirm motivation of criticism of their locations derived by Mazets *et al.* (1981b) and Atteia *et al.* (1987).

The temporal behaviour of γ-ray bursts is very complicated. There is nothing like a typical burst. Timescales of pulses ranges from around 50 ms up to over a minute with time of rising $> 5\ ms$. Morphological classification based on time duration and appearance of the peaks has been proposed according to the scheme (Mazets *et al.*, 1981a; Barat *et al.*, 1984):

- very short bursts with 1 peak;
- bursts with doublet or quasi–periodic time structure;
- long and irregular bursts.

Periodicity in burst time history were observed only in the case of three events: GB790305 which display 8s period (Cline *et al.*, 1980), GB771029 with 4.2 period (Wood *et al.*, 1981) and GB840805 with 2.2s and 5s periods (Kouveliotou *et al.*, 1988). This periodic behaviour in γ–ray burst time scales is usually explained in terms of comet showers falling onto neutron stars (Livio and Taam, 1987) or white dwarfs (Boer *et al.*, 1989). However Paczynski (1986,1987) propose that quasi–periodic time structure can be a result of gravitational lensing by a cluster of galaxies of a single non–repeating γ–ray burst. Different ways of photons travel lead to a series of micro–imagines that arrive to the observer at different times.

There is a possibility of a separate class of γ-ray bursts called the soft γ-ray repeaters. Only three sources were observed: GB790305 – 15 bursts; GB790324 – 3 bursts; GB790107 – at least 110 bursts, (see Atteia *et al.*, 1987).

γ–ray bursts spectra were observed in more than ten different experiments (e.g. Apollo 16, Vela, Konus, SINGE, SMM), however most of them had poor energy and/or time resolution. The early measurements ($< 1MeV$) show spectra which can be in general described by a simple two parameter low $KE^{-1}exp(-E/E_o)$ (where, E – photon energy) in the energy range 30 keV – 1 MeV with typical values of E_o – 150-400 keV (Mazets *et al.*, 1981d). The observations in higher energy range by SMM satellite show that over 60% af all γ–ray bursts are observed above 1 MeV and about 24% above 5 MeV (Matz *et al.*, 1985). Some of them extends up to about 30 MeV (Rieger, 1982) and can be well fitted from 300 keV by a single power low (see Fig. 2). This results were very surprising since so energetic emission can not be explained by thermal models of γ–ray bursts, which was possible in the case of earlier observations (e.g. data from Konus experiment). Moreover, photons with energies $> 1MeV$ should be strongly attenuated on pair production processes in photon–photon interactions or in strong magnetic field (Daugherty *et al.*, 1983). These processes give strong restrictions on physical models and geometry of γ–ray bursts.

One of the most important features of γ–ray bursts spectra were the discovery of emission features around 400 keV in about 7% of events (Mazets *et al.*, 1980; Teegarden and Cline, 1980), and absorptions features between 30–70 keV in about 20% of events (Mazets *et al.*, 1981c, recently confirmed by Ginga observations, Fenimore *et al.*, 1988). An example of burst with absorption and emission features is presented in Fig. 4.5. Mazets *et al.* (1980) proposed that emission features are the e^+e^- annihilation lines gravitationally redshifted about 25% to lower energies and absorption features are due to cyclotron absorption of radiation in magnetic field of order 10^{12} Gauss. However, there are different explanations of these emission line. For example, Vahia and Rao (1988) interpret it as the nuclear line from reaction He(α,n) Be. Such emission is sometimes seen in solar X–ray bursts. In fact, Teegarden and Cline (1980) observed several lines close to : 413, 800, 1150 and 1500 keV and Ling *et al.* (1982) close to 413, 1790, 2200, 5900 keV.

It seems therefore that observations of γ–ray bursts clearly suggest their neutron star origin. However there are many important unanswered questions . It is not clear how the time evolution of γ–ray burst spectrum really looks like since time resolution was too small. There are some evidences that spectra appear harder (with emission and absorption features) at the earlier part of the event and next evolve to softer spectrum without line features (Barat, 1983b).

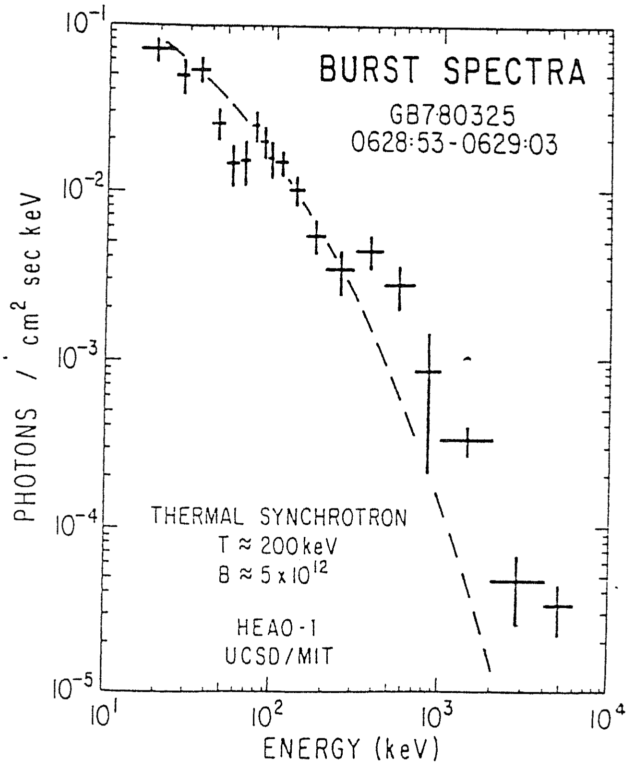

Figure 4.5: *Spectrum of the γ–ray burst GB780325 with typical 'absorption' and 'emission' features (from Harding et al., 1986)*

There is real possibility that spectral features are caused by time–integrations of their spectra. Moreover, we do not know what is the geometry of bursts emission regions which is very important for modeling of their sources.

Theory of γ–ray bursts. The observations of γ–ray bursts described above provide the constraints on the models trying to explain features of their spectra and their time evolution. At the beginning of this part we present mechanisms of photon production which seems to be important in burst sources (for details of these mechanisms see review papers in Lamb, 1984; Harding *et al.*, 1986).Then, we try to review the most promising models of bursts origin.

The continuum emission of burst spectra from Konus experiment (which reported more than 100 events) were fitted successfully by the spectra of optically thin thermal bremsstrahlung (Mazets *et al.*, 1981a,c). The discovery of cyclotron line called people attention on different mechanisms. Liang (1982) explained the shape of the spectrum (and existence of cyclotron line) using optically thin thermal synchrotron spectra. However this fitting was criticised by Pavlov *et al.*, (1986) because magnetic field quantum corrections should be taken into account in deriving synchrotron spectra. In strong magnetic field, the synchrotron emission is much more efficient than bremsstrahlung emission. Bremsstrahlung mechanism can explain bursts of total energy only if the source is at a distance less than about 10 pc (Liang, 1987). Moreover, Inverse Compton Scattering was suggested as a possible explanation of bursts continuum emission (Fenimore *et al.*, 1982; Liang, 1988).

However all above mentioned mechanisms are useful in the case of bursts with spectra below 1 MeV, they cannot explain hard MeV emission in spectra reported by SMM observations. To describe them, Golenetskii *et al.* (1986) proposed a two–component model in which the soft emission is explained by thermal model (e.g. bremsstrahlung) but the hard MeV part is caused by thermal spectra of the e^+e^- annihilation integrated over the volume with temperature gradient.

Tkaczyk and Karakula (1985) have described this hard emission (and also emission line close to about 400 keV) by annihilation spectra of e^+e^- plasma with different temperatures of electrons and positrons. Calculated by them spectra have power law shape starting (approximately) at rest energy of electron with extenssion proportional to difference in temperatures between electrons and positrons.

Since spectra of bursts reported in SMM observations have power law form (up to at least 20 MeV), non–thermal and non–isotropic mechanisms were suggested. Detailed calculations in these kind of models are much more complicated. For example, Sturrock *et al.* (1989) have examined photon production in electron–photon cascade in curvature magnetic field where primary electrons accelerated in the electric field close to the surface of the neutron star. General shape of the calculated spectrum is very similar to these one reported by SMM observations and can explain in natural way characteristic features like emission and absorption lines.

There is a big number of models of γ–ray bursts (see, e.g. reviews by Woosley, 1984 or Hameury and Lasota, 1986). Most of the models apply surface or vicinity of neutron star as a most favourable place of bursts origin. However, different mechanisms of energy generation were proposed. It is possible to distinguish:

- Accretion models – the energy is released in very rapid infall of matter onto the surface of the neutron star. In model proposed by Colgate and Petschek (1981), and applied by Tkaczyk and Karakula (1985), asteroid falling onto the neutron star is disrupted by tidal forces and heated adiabatically. Produced hot plasma emits radiation above Eddington limit. The radiation pressure can induce electric potential able to accelerate electrons (and/or positrons) to high energies. In model proposed by Van Buren (1981), plasma created by compression and heating of asteroid in strong magnetic field can be slowed down on the surface of neutron star by emission of Alfen waves. The main difficulty of these models is too law probability of capture of asteroid by neutron star to explain observed frequency of γ–ray bursts (about 100 per year). However, this difficulty is omitted in model presented by Epstein (1985) in which accretion occurs from unsteady disc in the form of small blobs.
- Thermonuclear models – the energy is released by the explosion of matter slowly accumulated at the polar cups of strongly magnetized neutron star (Woosley and Taam, 1976; Maraschi and Cavaliere, 1977). Detailed model of such accreated layer was worked out by Hameury *et al.* (1984) in which flash can be initialized by burning explosion of hydrogen or helium (depending on the temperature of the neutron star).
- Pulsar wind model – photons released in thermonuclear explosion can radiatively accelerate particles (Woosley, 1984) or particle wind can be created in strong electric field close to the polar cap of neutron star (Sturrock *et al.*, 1989). Such energetic particles can produce hard MeV photons via synchrotron process and curvature radiation.
- Magnetic flare models – Liang and Antiochs (1984) propose that

the field of the neutron star is not always a rigid dipole. It can be sometimes stressed (e.g. by starquakes, nuclear flashes or accretion disc) and can form a coronal loop sustained by electric currents and filled by relativistic particles. Such relativistic plasma can oscillate in close magnetic field lines and produce γ–rays via Inverse compton process (see Melia, 1990). During reconnection of this magnetic field the energy of the order of $10^{42} - 10^{43}$ ergs is released (if field is of the order of $10^{12} - 10^{13}$ Gauss).

- Starquake models – the energy is released in phase transition in nuclear matter of neutron star (pion condensation) caused by accreated matter onto a neutron star with mass close to the maximum. Such model was proposed by Ramaty *et al.* (1980) for the extraordinary burst GB790305. Detailed calculations made by Haensel and Proszynski (1981) report that the energy of order 10^{48} ergs during 10^{-4} s can be released and diameter of the star will change only for about 10 m. Such kind of quakes can happen only ones in neutron star life which is too rearly to explain all bursts events.

There are models which do not consider neutron star as a necessary place of origin of γ– ray bursts. For example, Vahia and Rao (1988) suggest that bursts are originated by magnetically active stars with Sun like flare activity. Paczynski (1990) proposes their origin in collision of neutron stars in binary systems. Rotational energy of binary stars is lost on emission of gravitational waves. Such burst can be seen from distance up to about 100 Mpc and statistics of events is in agreement with observations. Zdziarski *et al.* (1990) propose their origin at large gravitational redshifts (z about 100) in Compton scattering of the microwave background photons by relativistic electron beams. Electrons can be accelerated by cusps on superconductive cosmic strings.

As we can see, the number of different proposed mechanisms and models is very big. However, it is quite probable that there are a few different mechanisms of production of γ–ray bursts. We strongly need new more precise observations to make apparent progress.

Conclusion.

- The brightness distribution and angular distribution in the sky of γ–ray bursts cannot definitively answer the question concerning location of γ–ray bursts, however suggest their Galactic origin. Searching the history of γ–ray bursts one can take to the conclusion that probably exist more than one type of sources. There are no identifications of γ–ray bursts counterparts in other wavelengths of photon spectrum. Spectra of bursts extends from few keV up to at least 20 MeV. Absorption and emission features (however not well documented) are usually interpreted as cyclotron absorption (in magnetic field 10^{12} Gauss) and e^+e^- annihilation line (shifted in strong gravitational field).

- In general, the shape of γ–ray spectrum can be described by synchrotron, Inverse Compton and bremsstrahlung spectra. However hard MeV emission requires non–thermal models (e.g. non–thermal e^+e^- annihilation). Emission and absorption features is difficult to take into account if we keep in mind MeV emission in most of the bursts.
- Many models of γ–ray bursts are based on the acceptance of their neutron star origin. However up to now, it is impossible to select which one or ones (if any) are true. Moreover, there are few propositions of their extragalactic origin (Paczynski, 1990; Zdziarski *et al.*, 1990).
- We need experiments more sensitive and with much better angular resolution. Probably GRO satellite will be able to give answer on many questions. Theoretical work in the field: behaviour of relativistic plasma in strong magnetic field, radiation processes, transport of radiation and neutron star physics is needed.

4.4 Cyg X–1

Cyg X–1, since its discovery by Bowyer *et al.* (1965), has been one of the most studied X–ray sources because of its high, chaotic and rapidly varying luminosity (see for review: Oda, 1977; Liang and Nolan, 1984). Since small X–ray error box and evident 5.6 day variability, Cyg X–1 was identified in optical observations with HDE 226868 (Bolton, 1972; Webster and Murdin, 1972) which is an O9.7 Iab supergiant. The main parameters of this system were derived in many papers (e.g. Ninkov *et al.*, 1987): separation of the components $\approx 3 \times 10^{12} cm$, mass function $\approx 0.22 M_\odot$, orbital inclination angle $\approx 30°$. The mass of the unseen companion (responsible for X–ray emission) was estimated between 8 and $11 M_\odot$ for distance $\approx 2.5 kpc$ (Webster and Murdin, 1972; Bolton, 1972), confirmed in recent papers (e.g. Ninkov *et al.*, 1987; Gies and Bolton, 1986). This mass is bigger than critical mass for stable neutron star and strongly suggests the existence of the black hole in HDE 226868/Cyg X–1 system.

The flow of matter between supergiant and compact object (Cyg X–1) is required by most of mechanisms of X–ray production. There are arguments that matter falls onto Cyg X–1 via accretion disk (Bolton *et al.*, 1975). Such scenario is also supported by observed 294 day X–ray (Priedhorsky and Terrell, 1983) and optical (Kemp *et al.*, 1987) periodicity, if interpreted as due to precision of the accretion disk.

Moreover, observations of low level iron–line, discovered by EXOSAT satellite (Barr *et al.*, 1985) and confirmed by Tenma satellite (Kitamoto, 1990), can be explained as a fluorescent emission from the inner parts of an accretion disk inclined at $\sim 30^{\circ}$ (Fabian *et al.*, 1989).

X and γ–ray observations of Cyg X–1.

Cyg X–1 is one of the brightest X–ray sources in the sky with total luminosity $> 10^{37} erg/s$ above 10keV. Moreover, total power of observed sporadic hard MeV emission is comparable to X–ray flux below 400keV.

The spectral measurements of Cyg X–1 at energies less than 10keV show metastable states of "high" and "low" luminosity with irregular durations of weeks to years (see review Liang and Nolan, 1984). A low state is characterised by low, soft X–ray fluxes and high, hard X–ray fluxes, and a high state have opposite characteristic. There was discovered third very low state of Cyg X–1 emission in HEAO 3 observations (Ling *et al.*, 1983), confirmed by MISO telescope on balloon (Perotti *et al.*, 1986). It is characterised by low, soft and hard X–ray flux and very strong emission (about half of total X-ray power) in MeV range.

From 10–100keV, the spectrum can be fitted by single power low with spectral index ≈ 0.5 but between 100keV and 1MeV the γ–ray spectrum begins to fall down steeply.

Balloon observations in 1–10MeV range reported very flat spectrum (Baker *et al.*, 1973; Mandrou *et al.*, 1978; Nolan and Matteson, 1983; McConnell *et al.*, 1987,1989; Ling *et al.*, 1987). All spectral measurements in this range have similar spectral index only in the energy range up to 1.6MeV. The spectrum measured in 1972 by Baker *et al.* up to 4.4MeV was not observed by Ling *et al.* in 1979/1980 and Mandrou *et al.* in 1976. The hard component in the energy range 2–9.3MeV detected in 1984 by McConnell *et al.* is approximately a factor of five lower than that one observed by Baker *et al.* but is consistent with upper limits placed by Ling *et al.*. Moreover, upper limits in the MeV region observed in 1978 by White *et al.* (1980) are at least an order of magnitude lower than all reported fluxes. Analysis of these results suggests that the MeV component in Cyg X–1 spectrum is strongly variable (see, Fig. 4.6).

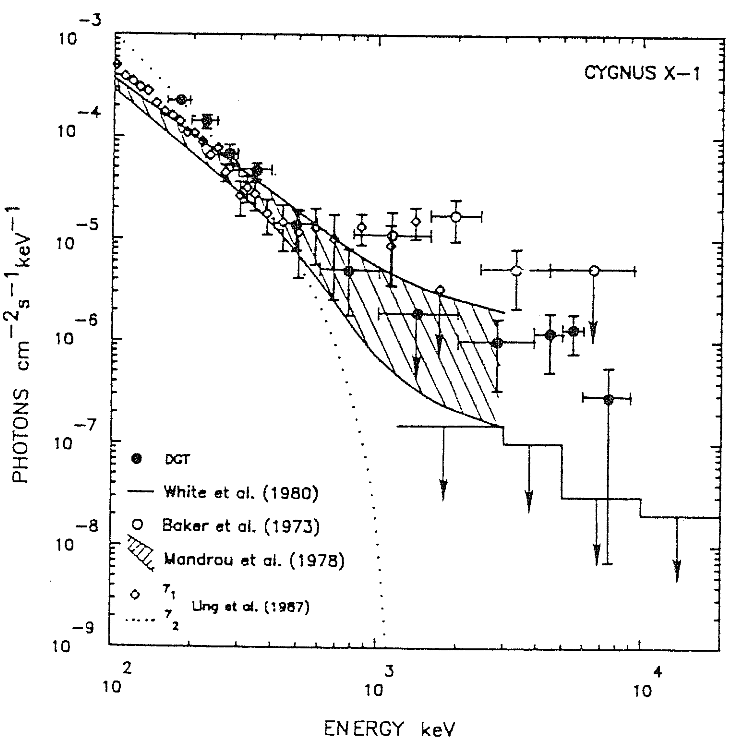

Figure 4.6: *The photon spectrum of Cyg X-1 measured by different experiments (collected by McConnell et al., 1989)*

New exciting result have been reported by Fomin *et al.* (1987) who found the shower excess from the direction of Cyg X–1. It can be interpreted as the emission of very high energy photons ($> 10^{15} eV$) by this source. However up to now, this information was not supported by any other experiments.

Models of X and γ–ray emission from Cyg X–1.

It is widely believed that energy in the binary system HDE 226868/Cyg X–1 is produced via accretion of gas from the supergiant primary companion. However, how the infall process goes and how the gravitational energy is converted into high energy photons remain unsetteled questions.

In general, the spectrum of Cyg X–1 seems to have at least two components: the first one (below a few hundred keV), with the power law spectrum up to $\sim 100 keV$ and then the exponential cut–off and the second one (above $\sim 1 MeV$), with very flat spectrum (spectral index $\sim$ 0.). The first component is usually explained in terms of Comptonization of soft energy photons by hot thermal electrons. Such mechanism can work in the accretion disk around black hole in which low energy photons are originated in the outer part of geometrically thin disk and high energy photons in the inner part of the two–temperature, geometrically thick disk (Shapiro *et al.*, 1976; Katz, 1976). In such model, variability of the spectrum (and anticorrelation between low and high X–ray states) can be caused by changes in Comptonization parameter (Shapiro and Lightman, 1976) or in the flux of soft photons (Guilbert and Fabian, 1982). In fact, Comptonization model can fit very well observed spectrum of Cyg X–1 below 200keV for parameters: temperature of electrons $20 - 80 keV$ and optical depth 2–5 (Sunyaev and Titarchuk, 1980; Steinle *et al.*, 1982). However, recently Miyamoto *et al.* (1988), using Ginga observations of Cyg X–1, found no time delay between soft and hard energy X-rays which should be observed in Comptonization model. If this result is confirmed, it will be a strong argument against origin of high energy X-ray photons in such model.

Another explanation of hard X–ray emission from Cyg X–1 was proposed by Kazanas (1986). In his quasi–spherical accretion model, the change in the X-ray spectrum is due to drastic increase in compactness parameter (L/R) of the source and conversion of most of the energy into e^+e^- pairs. Photons from annihilation are backscatered in colder medium and create power law photon spectrum similar to that one of Cyg X–1. However, there was observed small amount of polarization in low energy X-rays ($\sim 3 - 5\%$, Long *et al.*, 1980), if confirmed, would rule out spherical accretion and support disk model with inverse

Compton mechanism.

The second part of Cyg X–1 photon spectrum (above a few hundred keV) cannot be explained by above models. Some thermal models were proposed:

- Pair dominated plasma models – Nolan and Matteson (1983) mentioned that the MeV emission of Cyg X–1 up to 2MeV can be described by the high temperature spectrum of e^+e^- annihilation line (e.g. Ramatÿ and Meszaros, 1981). The detailed model appying this mechanism was developed by Liang and Dermer (1988) and Liang (1990). They propose that high temperature pair dominated plasma can be produced in the inner part of accretion disk around the black hole (temperature$\approx$ $400keV$; Thomson optical depth ≈ 2; volume $r_g < 17$). Their model is able to describe the Cyg X–1 spectrum reported by Ling *et al.* (1987) accept most energetic point at 1.5MeV which they interpret as a contribution from diffusive line emission not connected with Cyg X–1. However, very energetic emission (up to 9.3MeV) was also reported by McConnell *et al.* (1989) and cannot be explained in this way.
- Two temperature Compton model – Pozdnyakov *et al.* (1983) proposed that MeV emission can originate as a result of Comptonization of softer photons from the thin disk by very hot plasma in disk corona (similar to stellar's corona) for plasma temperature $\sim 400keV$ and optical depth ~ 5. However, this model cannot explain McConnell *et al.* (1989) observations.
- A hot two–temperature accretion disk model – Eilek and Kafatos (1983) proposed that very flat MeV spectrum can be originated via bremsstrahlung process of secondary electrons from decay of charged pions. However, their model predicts strong photon emission from hundred MeV up to a few GeV which was not observed by COS B satellite (maybe observations were not simultaneous ?).

Summarizing, thermal models have problems in explanation of hard MeV emission from Cyg X–1 (specially with observations made by McConnell *et al.*, 1989). Application of non–thermal mechanisms seem to be more successful. A few models of of this kind were proposed:

- Guilbert and Stepney (1985) suggest a blueshifted annihilation line from a cool pair wind expanding at relativistic speeds as a possible explanation of the MeV bump.
- Aharonian and Vardanian (1985) postulate origin of MeV photons in an electromagnetic cascade initiated by relativistic particles in

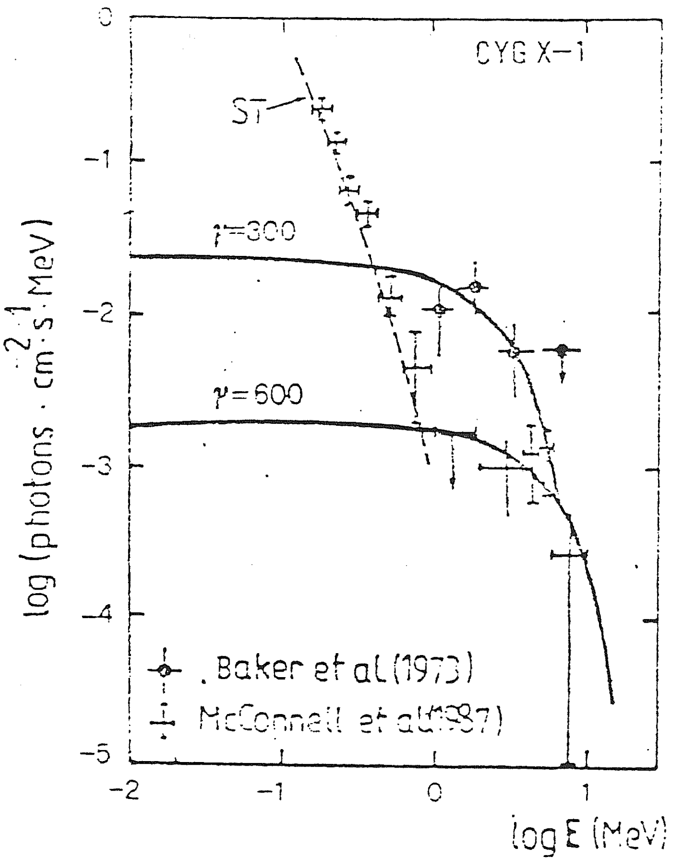

Figure 4.7: *The MeV bump in the photon spectrum of Cyg X-1 fitted by spectra calculated by Bednarek et al. (1990d).*

the accreting plasma. The authors fit Mandrou *et al.* (1978) data but it is not sure if they are able to describe very flat spectrum reported by McConnell *et al.* (1989).

- Bednarek *et al.* (1990c,d) propose the comptonization of soft black body photons from the companion star HDE 226868 by relativistic electrons emitted by the compact object (Cyg X–1).

Spectra calculated according to the last model can fit well results of observations reported by Baker *et al.* (1973) and McConnell *et al.* (1987) for temperature of HDE 226868 $\sim 3\times10^4 K$ and Lorentz's factors of electrons equal to 300 and 600, respectively (see, Fig. 4.7). For details of these calculations see Bednarek *et al.* (1989). From the best fit it is possible to estimate the lower limit on the luminosity of the relativistic electrons equal to $L = 2.4 \times 10^{35} erg/s$ for Baker *et al.* data and $L = 7 \times 10^{34} erg/s$ for McConnel *et al.* data.

We note that definitively non–thermal spectrum in radio wavelengths was observed by Woodsworth *et al.* (1980) which strongly supports existence of relativistic electrons in this source. Moreover, this model predicts modulation of the MeV emission according to the period of the binary system (5.6 days), since comptonization of photons to the MeV range depends on the angles of interaction between relativistic electrons and soft black body photons from HDE 226868. This prediction can be easy tested in the future long time observations on the board of GRO satellite.

Conclusion.

- Cyg X–1 is one of the best documented black hole candidates ($\sim 10M_{\odot}$) with very strong and variable X–ray emission and unusually flat MeV emission up to 9.3MeV.
- Soft and hard X–ray spectrum show metastable states of low and hard X–ray emission and is usually described in terms of Inverse Compton thermal model.
- There are a few propositions of explanation of MeV emission. Thermal models (annihilation, two temperature comptonization) can describe MeV spectrum only up to $\sim 2MeV$. More successful seems to be non–thermal models: electromagnetic cascade, blueshifted annihilation in relativistic wind, comptonization of photons from HDE 226868 by relativistic electrons. We favourite that last proposition since it is able to describe very flat spectrum reported by McConnell *et al.* (1989) and can be easy tested by future experiments.

4.5 Geminga (2CG195+04)

Geminga (2CG195+04) was firstly discovered by Kniffen *et al.* (1975) in SAS–2 data and then this observation was confirmed by Hermsen (1980) in COS B data. The significant detection of $\sim 59s$ periodicity was reported by Thomson *et al.* (1977) but further analysis did not confirmed this result (Masnou, *et al.*, 1981). The uncertainty in derivation of position of Geminga from the above observations is a circle of radius of 0.4°.

There were two propositions of Geminga counterpart in other wavelengths: the first, the radio source 0630+180 with flat spectrum, identified as a quasar (Moffat *et al.*, 1983), and the second, relatively strong X–ray source 1E0630+170 detected by Einstein satellite (Bignami *et al.*, 1983). Second candidate was more promising because of its unusual properties and $60s$ variability. However this argument is not statistically significant (Buccheri *et al.*, 1985).

Optical searches in the error box ($\sim$ 3.2") of 1E0630+170 reported two candidates:

– 21 magnitude blue star (Caraveo *et al.*, 1984). Further observations reported no unusual properties of this source (Halpern *et al.*, 1985).

– 25 magnitude blue star (Bignami *et al.*, 1987; Halpern and Tytler, 1988).

Up to now this second object seems to be the most promising candidate for γ–ray source. It has very unusual ratio of the luminosities $L_\gamma : L_X : L_{opt}$ equal to $10^6 : 10^3 : 1$, which means that the most of the energy emitted by this source is concentrated in γ–rays. From the analysis of optical and X–ray spectrum it is possible to derive column density between the source and the earth. Obtained value suggests that the most probable distance to Geminga is between 500–1000pc, however distance $< 100pc$ cannot be definitively excluded (Halpern and Tytler, 1988).

The photon spectrum from the direction of Geminga.

The high energy γ–ray source Geminga is the second brightest object in COS B catalog (Swanenburg *et al.*, 1981). Its energy spectrum was measured in the range 70MeV–6GeV (Masnou *et al.*, 1981). The main part of this spectrum can be fitted by a single power law with spectral index –1.8 up to $\sim 2GeV$. Below 100MeV the spectrum flattens which is in agreement with upper limits found in hard X–rays and soft γ–rays (Haymes *et al.*, 1979; Graser and Schönfelder, 1982; Baker *et al.*, 1983). The highest energy point reported by COS B has significantly lower intensity than expected from 1.8 power law extrapolation. This suggests spectral steepening from the very high energy site.

The observational situation at TeV energies is not clear. Two groups have claimed detection of pulsed emission with periods, 59.28s (Zyskin and Mukanov, 1985) and 60.25s (Kaul *et al.*, 1985). However, significance of these results is low and detection of 59s periodicity in lower energies questionable. The negative observations were reported in three other experiments (Helmken and Weeks, 1979; Cawley *et al.*, 1985; Bhat *et al.*, 1985).

There is also evidence that Geminga is not seen in very high energies. Karakuła *et al.* (1985) derived upper limit on the photon flux at energies $> 10^{15}eV$ which suggests at least the break in high energy photon spectrum of Geminga.

Models and mechanisms applied to Geminga

The lack of definitive identification of Geminga with object in other wavelengths gives field for many speculations concerning mechanisms of γ–ray production and energy generation. There are a few models based on 59s periodicity which is now in some doubt, e.g.:

- Nulsen and Fabian (1984) propose close binary pair of neutron stars at distance $\sim 11pc$. In this model , rotational energy of the system is converted to γ–ray photons. However source with expected optical luminosity (surface emission of neutron stars) was not observed in Geminga error box.
- Bisnovatyi–Kogan (1985) performed the model of close binary system in which matter is accreating onto the black hole from degenerate dwarf filling its Roche lobe. Modification of this model with accretion of matter from the main sequence star onto the neutron star was suggested by Leahy *et al.* (1986).

Another group of models suggest single neutron star as a possible explanation of Geminga puzzle:

- Katz (1985) proposed slowly rotating neutron star which convert its rotational energy into the non–thermal photon spectrum. In fact, the X–ray spectrum of the best candidate for Geminga is possible to describe by nonthermal process. However, it is not sure if optical spectrum can be described in this way.
- Halpern and Tytler (1988) searching the best optical candidates for Geminga concluded that good description can give Vela–type pulsar assuming that its radio beam is more collimated than γ–ray beam. In their proposition radio beam emitted by Geminga is not observed on the Earth.

There is an extragalactic proposition of identification of Geminga with flat spectrum, radio source found in its γ–ray error box (Sieber and Schlikeiser, 1982). This source was identified by Moffat *et al.* (1983) with 19 magnitude, high redshift (z$\sim$ 1.19) quasar not detected in X–rays. However this candidate should have very large luminosity in γ–rays ($\sim 5 \times 10^{49} erg/s$) which seems to be unrealistic. Moreover, Tkaczyk *et al.* (1984) have found that it is impossible to describe γ–ray spectrum from Geminga by thermal model of spherically symmetric accretion of matter onto the black hole although such scenario successfully describes the spectrum of quasar 3C 273. In the case of Geminga, they propose non–thermal distribution of relativistic particles during accretion of matter onto the black hole.

Most of the above models are purely qualitative. The quantitative description of the photon spectrum from Geminga was proposed by Schlickeiser (1981). He analysed different models of high energy photon production and concluded that the best description can be achieved by inverse Compton scattering of ultraviolet and soft X–ray photons by relativistic electrons. The calculated by him photon spectrum from the above process in MeV and GeV range have not significant evidences of cut–off at lower and higher sites which is clearly seem in COS B observations of Geminga. Moreover, derived by him flux above $10^{11}eV$ seems to be above reported lower limits.

Another mechanism was proposed by Bednarek *et al.* (1990b,c). They propose that high energy photons coming from Geminga originate in the interaction of relativistic particle beam with surrounding matter. Photon spectrum produced in such scenario can fit well Geminga photon spectrum for proton beam Lorentz factor $\gamma \geq 30$, half angle of the beam $\tau = 40°$ and the angle between the directions to the observer and the beam axis $\beta = 50°$ (see, Fig. 4.8). From this fit, it is possible to estimate the emissivity of the proton beam equal to:

$$N_p \cong 6 \times 10^{20} \cdot d^2 \cdot \Delta\Omega_c / x_H [particles/cm^2] \qquad (4.5.1)$$

where: d – distance to Geminga; x_p – column density of matter traversed by the proton beam in $particles/cm^2$; $\Delta\Omega_c = 2\pi(1 - \cos\tau)$ – solid angle of the cone beam.

It is worth to note that such mechanism of high energy photon production can be applied to another energetic source, Cyg X–3. However in this case the observer on the earth have to be inside the cone of particles emitted by Cyg X–3.

Conclusions

- Geminga (2CG195+04), is one of the strongest γ–ray sources in the sky with very untypical features (e.g. $L_\gamma : L_X : L_{opt}$ equal to $10^6 : 10^3 : 1$; 59s periodicity, however now in doubt).
- The identification of this source is still a big puzzle. The best candidate seems to be X–ray source 1E0630+170 and in its error box, 25 magnitude blue star probably at distance 500–1000pc (however $< 100pc$ cannot be excluded either).
- The high energy spectrum of Geminga is very flat (spectral index – 1.8) with features of flatening from lower energies and steepening from higher energies. Up to now, observations in TeV energies reported by different groups are not consistent.

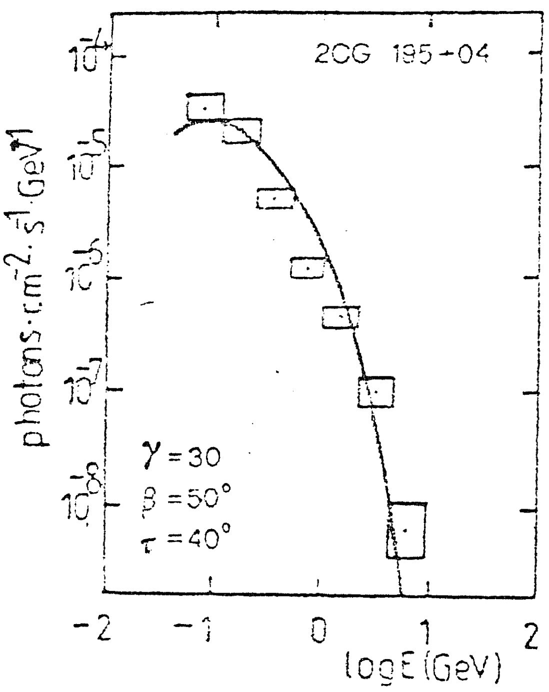

Figure 4.8: *The γ–ray spectrum of Geminga (Masnou et al., 1981) fitted by spectrum calculated by Bednarek et al. (1990).*

– The most popular models for Geminga are binary systems of stars (in deferent combinations, e.g. black hole – dwarf star, two neutron stars or neutron star – main sequence star) or single neutron star. As a possible mechanisms of spectrum formation are proposed: inverse Compton scattering of lower energy photons, production of γ–rays by Vela–type pulsar or in interaction of relativistic proton beam with background matter.

4.6 The Crab Nebula and Pulsar (2CG184-05).

The Crab Nebula is one of the best investigated supernova remnants which protogenitor star (with mass $\sim 9M_{\odot}$) exploded in the year 1054. The distance to the Crab Nebula was estimated as 2kpc (Trimple, 1968), but a value in the range 1–3kpc cannot be excluded either. The Nebula contains about $1M_{\odot}$ of matter with the density 10^4 cm^3 and temperature 10^4K in its filaments. The big overabundance of helium with respect to hydrogen is observed inside the nebula (61% of the total mass in He, Henry and MacAlpine, 1982) and normal contribution of heavier nuclei. These facts is difficult to explain by the models of stellar evolution.

The Crab Nebula is clearly seen in all photon energies, from radio to $10^{12}eV$ and possibly up to $10^{15}eV$. The radio spectrum is relatively flat (spectral index –0.26) and the emission is highly polarized, which indicate the existence of the magnetic field and synchrotron origin of the photons. At higher energies, the energy spectrum steepens showing in optical band spectral index –0.85 (Marsden *et al.*, 1984), in soft X–rays –1.1 (Toor and Steward, 1974) and above 80keV –1.4 (Strickman *et al.*, 1979). The radio observations see reviewed by Weiler (1985), X–ray observations by Seward (1989) and in general the Crab Nebula by Woltjer (1985).

One of the most interesting features discovered in the Crab Nebula is a luminous jet moving outwards at about 4000 km/s from the North–East boundary of the nebula (Van den Bergh, 1970). The jet is observed in line (thermal) and continuum (synchrotron) emission and its axis does not coincide with present and previous position of the pulsar inside the nebula. However, recently Bietenholz and Kronberg (1990) studding polarization of radiation from the Crab Nebula conclude that most likely the jet is originated by high–velocity beam inside the Nebula (emitted by pulsar?).

The very fast pulsar (PSR0531+210) with period 33ms was discovered inside the Crab Nebula (however not exactly in the middle). It is losing rotational energy at the rate of $4.5 \times 10^{38} erg/s$ which is amazingly similar to the number of total energy extracted in the Crab Nebula. It is widely believed that connection between these two objects is caused by magnetic fields and relativistic particles emitted by the pulsar. The pulsar emission, from radio to γ–rays, is mainly concentrated in two big peaks. Its photon spectrum is essentially flatter than from the Nebula and in the high energy region (hard X–rays, γ–rays) can be described by a single power law with spectral index close to –2.1.

γ–rays from the Crab Nebula and pulsar below $\sim$ 1GeV. The Crab Nebula is one of the best studied γ–ray sources in the sky. The first identification of this source below $\sim 1GeV$ was reported by Kniffen *et al.* (1974), however observations of lower energy photons (hard X–rays and soft γ–rays) have been performed starting from late '60 and early '70. The results of these observations (from different experiments) were collected on Fig. 4.9 and 4.10 (Graser and Schönfelder, 1982). In general, the observed flux from Crab Nebula consists from pulsed emission (from the pulsar PSR0531+21 inside the nebula) and steady emission whose origin is not completely clear (the nebula or

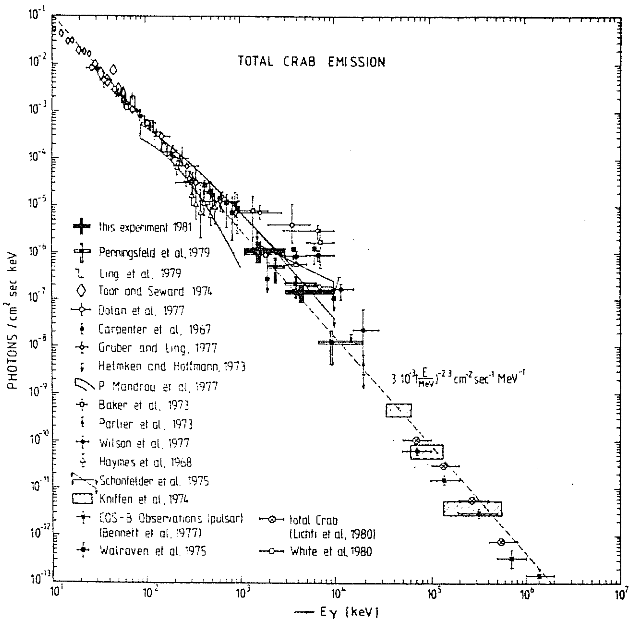

Figure 4.9: *The energy spectrum of the total Crab emission between 10keV and 2GeV. For references see Graser and Schonfelder (1982).*

the pulsar ?), because of too small angular resolution of detectors in this energy range. However extrapolation of observations from lower energies suggests its origin in the Crab nebula.

The emission spectrum connected with the nebula can be represented by a power law with spectral index changing from ~ 2.1 in X–rays (Toor and Steward, 1974), through ~ 2.5 between 150keV and several MeV (Jung, 1989) and ~ 2.7 up to 500MeV (Clear *et al.*, 1987), see Fig. 4.9.

The pulsed γ–ray emission (from PSR0531+21) may be represented by a single power law of index $\sim 2.1 \pm 0.1$ (Bennett *et al.*, 1977; Clear *et al.*, 1987), see Fig. 4.10. Moreover, a systematic variation in the pulsar spectral index with phase has been noted by Pravdo and Serlemitsos (1981). They suggested the existence of the two components of emission from the main peaks and from the interpulse (seen also in optical energies). The emission from the interpulse corresponds to $15 - 30\%$ of the total pulsed emission.

Detailed analysis of these two components was performed by Clear *et al.* (1987) based on COS B data in the energy range 50–3000MeV. They found that steady emission from the Crab region accounts for $53 \pm 15\%$ and pulsed emission $47 \pm 12\%$ over the energy range 50 MeV to 500MeV. These results are consistent with previous estimations of Thompson *et al.* (1977). The pulsar emission is dominated by two

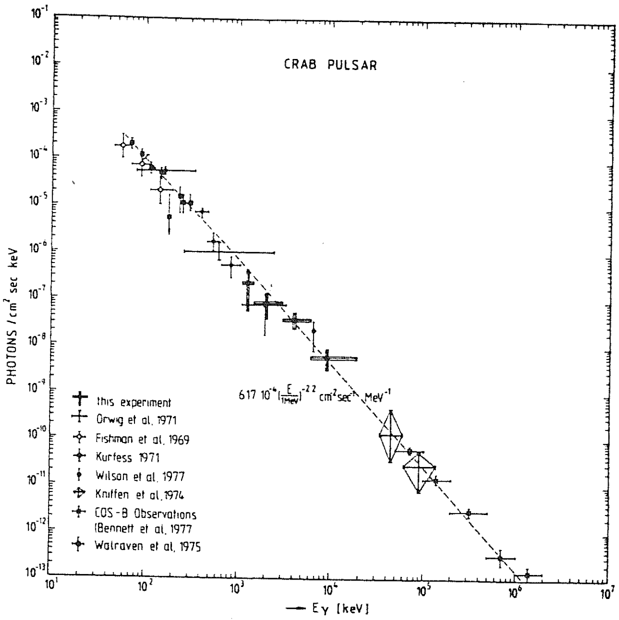

Figure 4.10: *Same as in Fig. 1 but for Crab Pulsar.*

peaks whose position corresponds with radio, optical and X–ray measurements (Wills *et al.*, 1982). The relative strengths of each pulses are: $50 \pm 9\%$ the first pulse, $34 \pm 8\%$ the second pulse and $16 \pm 5\%$ the interpulse region. Moreover, the statistical analysis of these features indicates their fluctuations as a function of time with significance of 2.0σ the first pulse, 3.0σ the second pulse and 1.3σ the total pulsed flux.

γ–rays from the Crab Nebula and pulsar above $\sim$ 0.1TeV.
The detection of the Very High Energy (VHE) photons above $10^{11}eV$ is based on the observations of Cerenkov light which is induced by a cascade of secondary electrons initiated by these photons in the Earth atmosphere. First positive observation of the Crab Nebula were reported by Fazio *et al.* (1972) after three years of data collecting. The deduced flux above 0.14TeV was $(5.7 \pm 1.8) \times 10^{-11} photons \cdot cm^{-2} \cdot s^{-1}$ with only the 3 σ significance level. No periodicity according pulsar 33ms period was detected.

From the discovery of pulsar PSR0531+21 in the Crab Nebula, the searches of TeV γ–ray photons concentrated on detection of pulsed emission because greater sensitivity could be achieved by reduction of stable cosmic ray background. Results of these observations are shown in Table 4.1 and Fig. 4.11. Statistical significances of these measurements are not very high and some derived upper limits are in conflict with them (e.g. Helmken *et al.*, 1973; Bhat *et al.*, 1986).

Reference	Energy (TeV)	Flux $photons cm^{-2} s^{-1}$	Epoch	Comments	In Fig. 4.11
Chudakov *et al.*, 1965	5	5×10^{-11}	1960-63	Cherenkov	L1
Long *et al.*, 1965	27	$< 1.3 \times 10^{-11}$	1963-64	Cherenkov	G
Fazio *et al.*, 1972	0.14	$(5.7\pm1.8)\times10^{-11}$	1969-72	Cherenkov	S
Mukanov, 1983	2	$(5.7\pm1.3)\times10^{-11}$	1979-81	Cherenkov	T1
Cawley *et al.*, 1985	0.4	6×10^{-11}	1983-85	Cherenkov	W
Chadwick *et al.*, 1986	1	$< 3 \times 10^{-11}$	1981	Cherenkov	D
Tornabene, 1977	20	$< 2 \times 10^{-12}$	1973-75	Cherenkov	B
Morrello *et al.*, 1985	30	$< 10^{-11}$	1982-84	air shower array	P
Boone *et al.*, 1984	1000	$< 2 \times 10^{-12}$	1980	Cherenkov	F
–	–	$< 5 \times 10^{-13}$	1981	–	–
Kirov *et al.*, 1985	350	$(2.8\pm0.8)\times10^{-13}$	1974-82	7.5° bins	T2
–	550	$(1.9\pm0.7)\times10^{-13}$	1974-82	muon-poor	–
Dzikowski *et al.*, 1983	10000	2×10^{-13}	1968-71	37.5° bins	L
–	–	–	1975-82	muon-poor	–
Watson, 1985	1000	$< 1.5 \times 10^{-13}$	< 1985	6° bins	H
–	10000	$< 10^{-15}$	–	–	–

Table 4.1: *Summary of the high energy observations from the Crab Nebula; for references see Weeks (1988).*

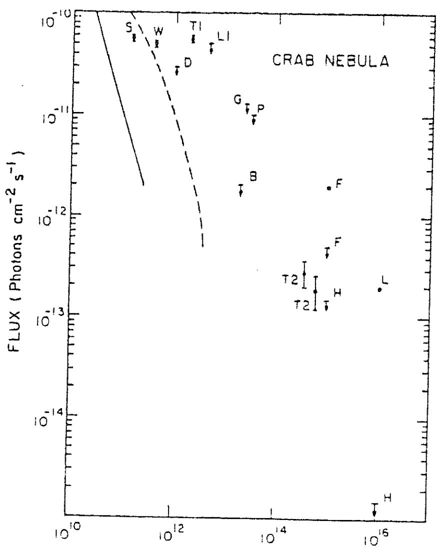

Figure 4.11: *The high energy spectrum of the Crab Nebula. Parameters of different points are collected in Table 4.1.*

Recently, Weeks *et al.* (1989) reported the observations of the flux above 0.7TeV in the epoch 1986 –1988, applying selection of showers based on their predicted properties. They found a flux of $1.8 \times 10^{-11} photons \cdot cm^{-2} \cdot s^{-1}$ at the 9.0 σ significance level. Less than 25% of the observed flux was pulsed at period of PSR0531+21. They did not found variability on time scale from months to years. However there are a few reports of γ–ray burst emission from PSR0531+21 (Gibson *et al.*, 1982; Bhat *et al.*, 1986). Three bursts were observed above $10^{12} eV$ with duration about 15min in 450 hrs of observation.

The observation of the Crab Nebula at higher energies ($> 10^{14} eV$) apply detection of the secondary particles of the intensive air showers which are initiated by very energetic photons. Using this technics (Lodz Air Shower Array), Dzikowski *et al.* (1981) reported detection of the photon flux above $10^{16} eV$ during 1968–1971 and 1975–1979. Derived by them excess (5.4 σ) corresponds to a flux of $2 \times 10^{-13} photons \cdot cm^{-2} \cdot s^{-1}$. However this result was strongly critisized because of very poor angular resolution of observations and being in conflict with other experiments (for discussion see Weeks (1988)).

Positive observation of the Crab Nebula was reported by Kirov *et al.* (1985). Based on the selection of muon–poor showers, they found a flux of $(2.8 \pm 0.8) \times 10^{-13} photons \cdot cm^{-2} \cdot s^{-1}$ above photon energies $3.5 \times 10^{14} eV$ with significance level 4 σ. This value is comparable to this one reported by Dzikowski *et al.* (1981) but for energies 30 times lower.

Also Fly's Eye experiment (Boone *et al.*, 1984) reported positive result in December 1980 (3 σ) but they did not confirme this observation in February 1981.

Watson (1985) derived an upper limit of about $1.5\times10^{-15} photons\ cm^{-2}\ s^{-1}$ at energies $> 10^{16} eV$, using a relatively high angular resolution (bins of $6^\circ \times 6^\circ$). This result is in serious conflict with that one claimed by Dzikowski it et al. (1985).

The general photon spectrum observed from the Crab Nebula by different experiments can be described with spectral index 1.10 ± 0.02 in the energy interval $10^8 - 10^{16} eV$ (Karakuła *et al.*, 1987). However the result of observation in TeV energies by Weeks *et al.* (1989) is about an order of magnitude higher then the extrapolation of COS B observations from 70–3000MeV energy interval.

Models of γ–ray production in the Crab Nebula.
The polarized radiation observed in the Crab Nebula from radio up to X–ray wavelengths can be well understood as a synchrotron radiation of relativistic electrons with energies up to $10^{14} eV$ in a weak magnetic field. Based on these observations , Gould (1965) developed a Compton–synchrotron model of the Crab Nebula without specifying the source of the electrons. He predicted the flux of $10^{-10} photons\ cm^{-2}\ s^{-1}$ at energy $> 10^{12} eV$, assuming magnetic field of $10^{-4}\ Gs$. The Compton–synchrotron model was next developed by Rieke and Weeks (1967) and Grindlay and Hoffman (1971), taking into account new observational results. For example, Grindlay and Hoffman calculated inverse Compton spectra of synchrotron radiation assuming the rotating magnetic dipole field in the Nebula and electrons accelerated by the pulsar.

Other authors have proposed different mechanisms of acceleration of electrons. Rees and Gun (1974) and Kennel and Coroniti (1984) suggested that relativistic wind from pulsar forms a standing shock which can accelerate electrons. Aschenbach and Brinkmann (1975) suggested acceleration of electrons radially outwards in the neighbourhood of the Crab pulsar within a regions of limited angular extent around the rotational equatorial plane of the pulsar (in this way they have explained asymmetry of the Crab Nebula, either).

The above models have problems with claimed observations of the very high energy photons ($> 10^{15} eV$) which cannot be explained in terms of relativistic electrons and need acceleration of protons (and/or nuclei?) and different production mechanism (probably π° production and decay).

Looking for the pulsar (PSR0531+21) inside the Crab Nebula. There are no satisfactory models able to explain its emission from radio to γ-rays. Most of them apply the acceleration of electrons to TeV energies and production of photons in pulsar magnetosphere including curvature radiation, synchrotron radiation or Compton scattering. However, location of region of very high energy photon production must be close enough to the neutron star (because the magnetic field is necessary), but not so close that the γ-rays cannot escape (because of the pair production in magnetic field). Here we mention some of the models:

- Polar gap models – γ-rays are produced by electrons accelerated up to $10^{14}eV$ close to the polar gaps where $E \times B \neq 0$ (Ruderman and Sutherland, 1975). The relativistic electrons moving along magnetic field lines emit γ-rays as a curvature radiation (see, Hardee, 1977; Salvati and Massaro, 1978). For recent developments of these models see, Zhao *et al.* (1989); Lu and Shi (1990).
- Outer gap model – particles are accelerated by means of potential drops maintained in magnetospheric gaps. This model, applied for the Crab pulsar, can reproduce the energy independent light curve and double peaks structure, using only one magnetic pole (Cheng and Ruderman, 1980). Detailed calculations according to this picture were derived by Cheng *et al.* (1986). They analysed cascade created by primary electrons (synchrotron radiation, creation of pairs, acceleration of pairs, comptonization of synchrotron radiation).
- light cylinder models – γ-rays are produced by relativistic electrons close to the light cylinder at $10^8 cm$ from the stellar surface. In model proposed by Hardee (1977), curvature high energy radiation is produced in magnetic field shared by rotation of the neutron star.
- wind zone model – energy from the pulsar to the Crab Nebula is transformed via low frequency (30Hz) electromagnetic waves with electrons (Lorentz factor up to 10^9) remaining in this same phase. Pulsed γ-rays are produced on the way from the pulsar out to the nebula whose inner edge is located at ≈ 1 *light year* (Kundt and Krotscheck, 1980).

All of the above models propose explanation of pulsed emission from pulsar PSR0531+21. Knight (1982) suggested that steady X and γ-ray emission from the Crab Nebula can originate via thin thermal bremsstrahlung (KT$\approx 150keV$) or Comptonized bremsstrahlung (KT$\approx 26keV$ and $\tau \approx 5$). However, the steady emission from pulsar up to 500MeV observed by COS B satellite cannot be explained in this way.

For extensive reviews of the pulsar models, see e.g. Manchester and Tylor (1977), Michel (1982), Taylor and Stinebring (1986) or Ruderman (1985).

Conclusion.

- The Crab Nebula is the supernova remnant which emits in all photon energies. Its polarized radiation indicates the existence of a magnetic field and relativistic particles inside the Nebula. The energy release in the Nebula is supported by losses of rotational energy of the very fast pulsar PSR0531+21.
- γ–ray emission below $\sim$ 1GeV from The Crab accounts from $53 \pm 15\%$ of steady emission and $47 \pm 12\%$ of pulsed emission. The pulsed γ–ray emission is concentrated in two pulses observed in this same phase from radio up to γ–rays.
- There is a strong evidence of TeV γ–ray emission from the Crab Nebula although not all reported results are in agreement (see, Table 4.1). The observations in higher energies ($> 10^{15}eV$) are in serious conflict (see results of, e.g. Dzikowski et al. (1985) and Watson (1985)). However variability of these flux cannot be excluded (three bursts where detected in TeV photons).
- The most popular mechanisms of γ–ray production in the Nebula apply Comptonization of synchrotron radiation caused by relativistic electrons in weak magnetic field of the Nebula. However it is not sure what is the origin of relativistic electrons; acceleration by pulsar or acceleration in the shocks inside the Nebula. Different models were proposed to explain the pulsed emission from the direction of the Crab nebula, acceleration of electrons in: polar gap, outer gap, close to the light cylinder or in relativistic wind from the pulsar. First three, locate this region in the vicinity of the pulsar and usually apply synchrotron, compton and curvature mechanisms of photon production. Forth, suggests origin of pulsed emission close to $\sim$ 1 light year from the Nebula applying energy transformation from the pulsar via low frequency waves (30Hz).

4.7 Cyg X–3

Cyg X–3 was one of the earliest sources discovered in X–rays (Giacconi *et al.*, 1967). Intensive observations of this source in wide energy ranges started from the great radio outburst on September 2nd, 1972 (Gregory *et al.*, 1972) and detection of periodical variations 4.8hr in the X–ray emission (Persignault *et al.*, 1972), confirmed in infrared observations (Becklin *et al.*, 1972). During sporadic outbursts, the radio flux from Cyg X–3 can increase by more than three orders of magnitude in a few hours and the source becomes the stronger radio emitter in the galaxy.

The distance to Cyg X–3 was estimated as greater than 8kpc (often the value of 11–12kpc is assumed). The big amount of matter close to the Galactic plane made it obscured in optical range (7–8 magnitudes of absorption), although is still visible in the near infrared, radio, X–rays and probably high energy γ–rays. The absence of optical observations makes impossible verification of Cyg X–3 parameters derived in other wavelengths which is a big inconveniences in investigation of this source.

The period of 4.8hr, because of its stability, is usually connected with orbital motion and argues that Cyg X–3 is a binary system. There is no conclusive evidence of a pulsar in the system. However, unusual properties in all wavelengths, big luminosity and suggestions of 12.59ms period in TeV γ–ray observations support this hypothesis.

Radio mapping of Cyg X–3, during the outbursts, showed nonspherical structure and collimated expansion of the radio emission. Geldzahler *et al.* (1983) derived an apparent transverse velocity during the September 1983 outburst equal to 0.48c, assuming distance of 8.5kpc. Such extraordinary features (jets) were observed up to now only in a few Galactic sources (e.g. SS433, Cir X–1, Sco X–1).

The soft X–ray luminosity of Cyg X–3 (2–12keV) is $\sim 1.6 \times 10^{38} erg/s$, for 8.5kpc (Prtiedhorsky, 1985). The flux varies continuesly according to 4.8hr period (however low and high states of emission are observed), without outburst features observed in the radio wevelengths. In soft X–ray spectrum, there is observed a very strong iron line (between 6–7keV) which is probably produced by fluorescence of X–rays irradiated cool material (the atmosphere of companion or the outer edge of the accretion disc?). Hard X–ray spectrum was detected up to $\sim 400keV$ with spectral index close to –2.2 (Hermsen *et al.*, 1987) and luminosity $\sim 10^{37} erg/s$ between 20–200keV.

We only mentioned here the most important features of Cyg X–3. For details, see recent reviews by: Bonnet-Bidaut and Chardin (1988) and Weeks (1988).

γ–ray emission from Cyg X–3.

First balloon flight observations of γ-rays from Cyg X–3 were reported at energies $> 40MeV$ by Galper *et al.* (1975). However these results were not confirmed by other flights (e.g. McKechnie *et al.*, 1976; McConnell *et al.*, 1989 – in the energy range 2–9.3MeV). Analysis of data from SAS 2 satellite (Lamb *et al.*, 1977; Fichtel *et al.*, 1987) showed positive detection of γ–rays from the direction of Cyg X–3 at energies $> 35MeV$. The derived flux $(4.4 \pm 1.1) \times 10^{-6}$ $photons\ cm^{-2}\ s^{-1}$ above 100MeV was reported as modulated according to the 4.8hr period. However, this flux was not confirmed by COS B satellite which looked at this source for a much longer time (Bennett *et al.*, 1977; Hermsen *et al.*, 1987). The 4.8hr period seen by COS B in X–rays was not observed in γ–rays (Van der Klis and Bonnet-Bidaud, 1981). A recent reanalysis of COS B data by Li and Wu (1989) indicates detection of Cyg X–3 above 100MeV with total flux $(1.3 \pm 0.6) \times 10^{-6}$ $photons\ cm^{-2}\ s^{-1}$. This is significantly less than the result of SAS-2 group and suggests time variability of γ-rays from Cyg X–3.

The first announcement of Cyg X–3 detection in energies $> 10^{12}eV$ was reported by Vladimirsky *et al.* (1973), a few days after the giant radio outburst of September 1972. During the period 1972–80 observations were continued in USSR, based on the detection of Cerenkov radiation induced by very high energy photons. The main results can be summarizing in following way. Cyg X–3 emits photons with energies $> 10^{12}eV$ in two phases of 4.8hr cicle: first, [0.157,0.212] detected with 5.4σ and second, [0.768,0.823] detected with 3.3σ. Moreover, longer term periodicity were also discovered: 328days and 19.6days. There was observed sporadic component of TeV emission not connected with two mentioned above phase intervals. Its integrated intensity is comparable to the total periodic flux and may be correlated with the irregular radio outbursts seen in Cyg X–3. For more detailed review of these observations see, Stepanian (1988).

The above results were generally confirmed by observations starting after 1980 outside the USSR. However, a significant excess was usually seen only in the second peak $\sim$ [0.6–0.8] of 4.8hr period (Danaher *et al.*, 1981; Lamb *et al.*, 1982; Dowthwaite *et al.*, 1983). The biggest discrepancy of these later observations concerns the 12.6ms periodicity, obtained by Chadwick *et al.* (1982) and recently confirmed by this same group (Brazier *et al.*, 1990). This result was not observed by other groups (e.g. Resvanis *et al.*, 1987; Stepanian, 1988; Fegan *et al.*, 1989). Moreover, the Crimean group mentioned another period equal to 9.22ms (Stepanian, 1988).

The observation of photons with energy $> 10^{15}eV$ is very difficult from experimental viewpoint because of the limitations connected with the Cosmic Ray (CR) background. Only sources with spectrum flatter than CR spectrum and with flux modulated by characteristic periodic-

Reference	Energy threshold	Epoch	phase detection	Flux $photons\ cm^{-2}s^{-1}$
Samorsky and Stamm, 1983	2PeV	1976–80	[0.1-0.3]	7×10^{-14}
Lloyd-Evans *et al.*, 1983	3PeV	1979–83	[0.225-0.25]	1.5×10^{-14}
Morello *et al.*, 1983	30TeV	1980-83	[0.6-0.65	4×10^{-12}
Alexeenko *et al.*, 1987	300TeV	1984-85	[0.6-0.7	4×10^{-14}
Kifune *et al.*, 1986	1PeV	1981-84	[0.5-0.8]	1.1×10^{-14}
Dingus *et al.*, 1988	50TeV	1986-87	-	$< 8 \times 10^{-14}$

Table 4.2: *Main characteristic of air shower experiments observed Cyg X–3 (taken from Bonnet-Bidaud, 1988).*

ity seem to be good candidates for detection. The first announcement of the detection of Cyg X–3 at energies $> 10^{15}eV$ was reported by the Kiel group (Samorsky and Stamm, 1983). Their observations were confirmed by the Haverah Park group (Lloyd–Evans *et al.*, 1983). These experiments showed significant phase excess in the interval [0.1-0.3] of 4.8hr period. However, the result reported by the Kiel group was selected analysing "old" showers (with age $s > 1.1$), which make questionable their photon origin. Recent simulations by Fenyves (1985) suggests that showers initiated by photons should be rather "young".

Analysis of results from other experiments generally confirmed the excess from the direction of Cyg X–3 (e.g. Lambert *et al.*, 1985;Kifune *et al.*, 1986), although the phase analysis of results of these later experiments usually shows maximum in the phase [0.5-0.8]. This same phase of emission, but with poor significance, is also reported in lower energies (e.g. $> 3 \times 10^{13}eV$ – Morello *et al.*, 1983; $> 3 \times 10^{14}eV$ –Alexeenko *et al.*, 1987). For details of some observations, see Table 4.2.

The integrated photon spectrum from Cyg X–3 in broad energy range (from MeV up to PeV), summed over different periods, can be described by a power law with spectral index –1.1, see Fig. 4.13. Results reported by Lloyd-Evans *et al.* (1983) suggest cut–off at energies above 10PeV.

Bhat *et al.* (1986) mentioned that there are evidences of long period variations of PeV emission with delay time of a few years, see Fig. 4.12. However this proposition is very controversial because it postulates that we are lucky to observe this source exactly in its short active phase.

If really Cyg X–3 emits photons with energies $> 10^{15}eV$, a break in its

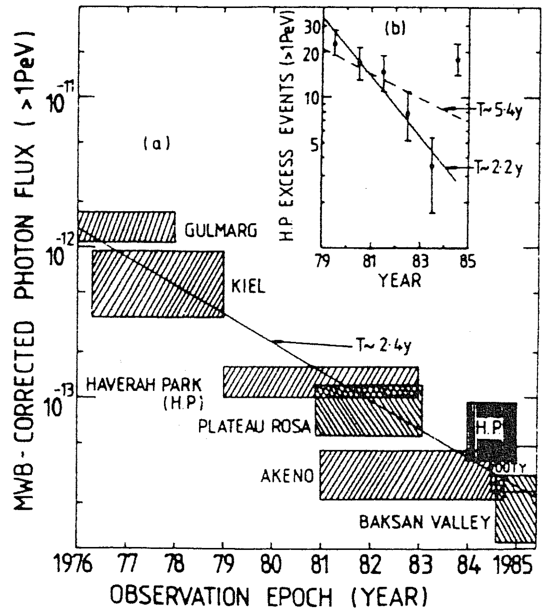

Figure 4.12: *Photon flux from Cyg X-3 corrected on the microwave background attenuation versus time of observation (from Bhat et al., 1986).*

spectrum close to $2 \times 10^{15} eV$ is expected because of $\gamma + \gamma \rightarrow e^+e^-$ absorption of high energy photons on 2.7K relic radiation. The detection of such feature will be the first direct confirmation of the existence of 2.7K radiation.

Models and mechanisms applied to Cyg X–3.
The explanation of γ–ray emission from Cyg X–3 is very difficult since their inconsistence and poor quality. It is not sure which results reported up to now will be verified in the future.

Most scientists argue that the best source of energy generation in binary systems seems to be extraction of the gravitational energy of matter accreating close to the Eddington limit onto compact object. However, problems arises if we consider photon emission above 1TeV which needs energy generation of the order of $\sim 2 \times 10^{39} erg/s$ in relativistic particles ($\sim 10^{17} eV$), see Hillas (1984). This is much above the Eddington luminosity for typical neutron star and requires accretion onto black hole.

Another solution seems to be extraction of rotational energy of a fast rotating neutron star (e.g. Basko *et al.*, 1976; Eichler and Vestrand, 1984), which is of the order $\sim 2 \times 10^{50} \cdot (P/10ms)^{-2}$ erg. The rotational energy can be converted into energetic particles in electric field induced by strong magnetic field (Gunn and Ostriker, 1969), energetic wind

(Arons *et al.*, 1986) or in a flywheel mechanism (e.g. Treves and Bocci, 1987).

Three different mechanisms of particle acceleration to very high energies were proposed:

- Pulsar acceleration – in the case of Cyg X–3 such mechanism was suggested by Milgrom and Pines (1978) and Vestrand and Eichler (1982). For different scenarios see discussion of mechanisms in section 4.6. Confirmation of 12.6ms pulsations of the flux (in TeV photon energy range) from Cyg X–3 would strongly support this kind of explanation.
- Acceleration in shock – matter infalling towards the pole of a neutron star forms a collisionless shock, which can accelerate particles via Fermi mechanism (Eichler and vestrand, 1985; Kazanas and Ellison, 1986). In this models, neutrons (produced in proton–proton interactions) are the best candidates which emerge from the central source. Similar model of acceleration but in the shock formated by the wind from the pulsar striking the companion star was proposed by Bignami *et al.* (1977).

  However in general, there are problems with accelerating of protons to very high energies in the strong magnetic field of the pulsars because of proton synchrotron losses.
- Dynamo model acting in accretion disk – large electric potential differences should be induced in the accretion disk rotating in magnetic field of the order $< 10^9 Gs$ (Chanmugan and Brecher, 1985). For optimal parameters, a potential drop of $\sim 10^{17} eV$ can be achieved. However, short periodicities (e.g. 12.6ms) is difficult to explain in this model.

Detailed review and discussion of the above models was done by Hillas (1987).

It is often assumed that relativistic particles are emitted in wide range of directions and the observed peaks (in 4.8hr period) are caused by distribution of matter, which is a target for γ–ray production in particle–particle collisions. However, different geometries of source were suggested to explain the periodicity of photon emission. Vestrand and Eichler proposed production of γ–rays in the atmosphere of the companion star which postulates emission in two peaks close to 0.2 and 0.8. However, now emission seems to be concentrated only in one peak close to ~ 0.6. To explain this more recent result, interaction of relativistic particles in an accretion tail formed by the stellar wind or with matter falling from the companion to the accretion disk were suggested.

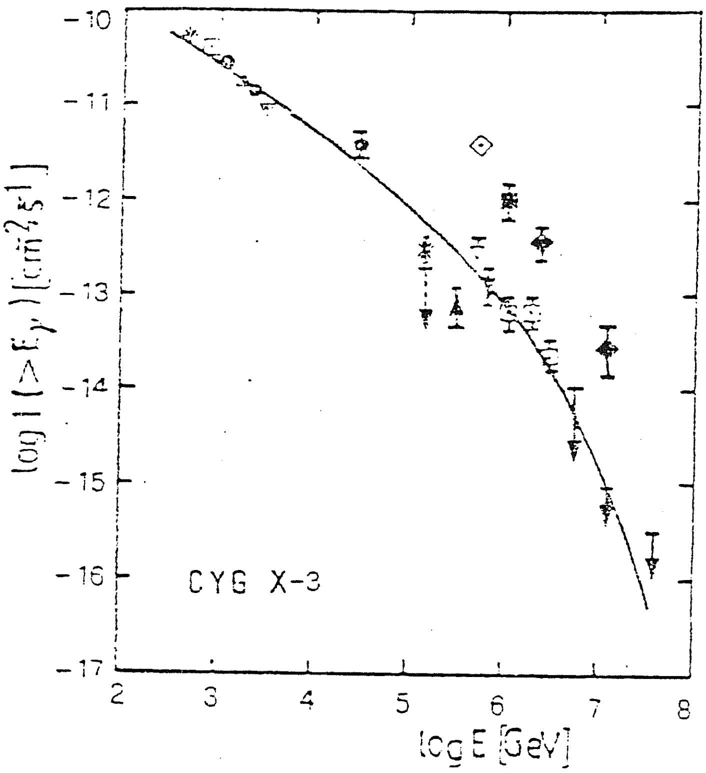

Figure 4.13: *The integral photon spectrum from Cyg X-3 (collected by Watson, 1985) and the spectrum calculated by Bednarek et al. (1990b).*

Another interesting explanation of this puzzle was proposed by Protheroe and Stanev (1987) who analysed the trajectories of relativistic protons in the dipole magnetic field of the companion. They found that magnetic deflection can be responsible for this effect.

The mechanism of the origin of the high energy photons is unclear, either. Eichler and Vestrand (1984) considered inverse Compton and bremsstrahlung or via π^{o} photon production in particle–particle interaction. They preferred this latter mechanism. Hillas (1984) described the photon spectrum from Cyg X–3 by spectrum originated in electron–photon cascade iniciated by monoenergetic protons of $10^{17}eV$.

Bednarek *et al.* (1990b) considered the high energy photon production by a relativistic, conical proton beam interacting with background matter. The spectrum of high energy photons calculated by them can fit Cyg X–3 photon spectrum above $10^{11}eV$ for spectral index of the proton spectrum of ~ -1.8 and cut–off at energy $10^{17}eV$, see Fig. 4.13.

The proton beam emissivity in the case of Cyg X–3 (energy range $10^{11} - 10^{17}eV$) can be expressed by the formula: $N_p \cong 3 \times 10^{16} \cdot d^2 \cdot \Delta\Omega_c/x_H/\Delta t \; particles/s$. where: d – distance to Cyg X–3 in cm; $\Delta\Omega_c =$

$2\pi(1.-\cos\tau)$ – solid angle of the proton beam; x_H – the column density of the background matter traversed by the proton beam; Δt – the width of the photon pulse divided by orbital period (Hillas, 1985).

Recently, comptonization mechanism of PeV emission from Cyg X–3 was proposed by Sclickeiser (1989). In his model, monoenergetic electrons with Lorentz factors $\sim 10^{10}$ comptonize soft X–ray photons. However, it is not sure if such energetic electrons can exist because of very big synchrotron losses.

Cyg X–3: Relevance to Particle Physics and Cosmic Rays studies.

Very amazing results of observations of Cyg X–3 by two underground experiments (Soudan–1 and NUSEX) were reported in papers Marshak *et al.* (1985) and Battistoni *et al.* (1985). They observed muon excess which coincided with phase interval derived from the observations of photons ([0.65-0.9] of the 4.8hr period). In the case of NUSEX experiment the significance level was $\sim 4\sigma$. However, analysis of results collected by other experiments working during this time (Kamioka, Frejus, Baksan) did not confirmed any muon excess (Oyama *et al.*, 1986; Berger *et al.*, 1986; Andreyev *et al.*, 1987).

Positive observation would require non–standard production of muons in showers induced by γ–ray photons or postulate the existence of a new neutral particle. From observations can be estimated the hypothetical parameters of these new particles,(collected by Bonnet-Bidaud, 1988):

- a lifetime $\tau > 10^{12} \cdot m/E$ seconds (m and E are the mass and energy of the particle) – derived from the travel distance from Cyg X–3 to the Earth;
- $g/g_e < 2 \times 10^{-9} \cdot (E/10^4\ GeV)$ (g and g_e - is particle and electron charge) – from directionality and the value of the galactic magnetic field, $\sim 10^{-6} Gs$;
- $m/E < 10^{-4}$ – from the observed phase peaks of 4.8hr period and distance to Cyg X–3 $\sim 8kpc$.

Two known neutral particles (neutrino and neutron) have to be excluded because of the lifetime of neutrons ($\sim 10^3 s$) and lack of expected distribution of showers initiated by neutrino in the Earth's atmosphere. Also very sceptical opinions concerning reported positive result came from the particle physicists.

The highest detected photon energies (1–10PeV) from Cyg X–3 mean that this source should accelerate particles to even greater energies. If we assume mechanism of photon production (e.g. $p + p \rightarrow \pi^o; \pi^o \rightarrow 2\gamma$), it is possible to estimate total power emitted by Cyg X–3 in relativistic particles. Wdowczyk and Wolfendale (1983) have pointed out that 30 cosmic sources with power similar to Cyg X–3 might maintain the observed cosmic ray flux in our Galaxy. Hillas (1984) estimated the total power emitted by Cyg X–3 in monoenergetic protons with energy $\sim 10^{17} eV$ at $\sim 10^{39} erg/s$ and concluded that only one source like Cyg X–3 active for a part of Galactic life is enough to supply cosmic ray power in the Galaxy.

Recently, new exciting results were reported by Fly's Eye group (Cassiday *et al.*, 1989) who announced an excess of air showers from the direction of Cyg X–3 with flux $(2 \pm 0.6) \times 10^{-17}$ $particles\ cm^{-2}\ s^{-1}$ at energies $> 5 \times 10^{17} eV$. This result was firstly not confirmed by Haverah Park group (Lawrence *et al.*, 1989) who putted the upper limit 4×10^{-18} $particles\ cm^{-2}\ s^{-1}$. But this year, positive excess of $(1.8 \pm 0.7) \times 10^{-17}$ $particles\ cm^{-2}\ s^{-1}$ at energies $5 \times 10^{17} eV$ was reported by Akeno group (Teshima *et al.*, 1990) with 3.5σ of significance level. It is not sure what kind of particles might be responsible for this excess:γ–rays or neutrons. For reported energies, the probability of survival against decay for neutrons is given by: D=exp(−0.108·D/E), which for parameters: D=11kpc, E=1EeV gives 0.3 (see, Sommers and Elbert, 1990). The approximation of γ–ray spectrum from lower energies (with exponent −1.1) clearly correspond with these reported fluxes. If it is confirmed, it will be the first direct sign of $10^{18} eV$ cosmic ray acceleration within our Galaxy.

Conclusion.

- There are strong evidences of high energy γ–ray emission from the direction of Cyg X–3. However, most of the observational results are not well documented and with high probability some of them will be not confirmed. The MeV flux was reported by SAS 2 group but not derived from COS B data.

  Different periods of variability (328day, 19.6day, 12.6ms, 9.22ms) in TeV photon energies announced by different experiments are not consistent. Excess of showers above PeV energies were reported but different phases of 4.8hr period were mentioned. It is even not completely sure if we observe photons in this energy range (and in EeV range) because of very untypical contents of muons in showers initiated by particles arriving from the direction of Cyg X–3. Some features of this source will be easier to understand if time variability in high energies is confirmed.

- Evidences of a muon excess from the direction of Cyg X–3 reported by underground experiments (however not confirmed) and discovery of an excess of showers with extremely high energies ($> 5 \times 10^{17} eV$) from the direction of this source will stimulate farther studies of this extraordinary object.
- Cyg X–3 is the first candidate for source of Cosmic Rays (CR) in our Galaxy. Wdowczyk and Wolfendale estimated that 30 sources similar to Cyg X–3 can supply total power of Galaxy in CR. Hillas (1984) pointed out that only one source like Cyg X–3 active for a part of Galaxy's life is sufficient.
- There is no model which is able to explain all features of high energy photon emission from Cyg X–3. Usually, the energy generation via accretion of matter onto compact object or extraction of rotational energy of fast pulsar were applied. Three models were proposed to accelerate particles to very high energy in Cyg X–3 (pulsar model, acceleration by shock, accretion disk dynamo model). Although all of them have some problems with explanation of observational results. The best mechanism of γ–ray production seems to be interaction of relativistic protons with background matter (Eichler and Vestrand, 1984; Hillas, 1984; Bednarek *et al.*, 1990b).

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Chapter 5

Specific extragalactic γ–ray sources

5.1 Introduction

A large number of extragalactic sources is observed in the hard X–ray region with flat spectrum which suggests significant emission also in γ–ray region.

In early observations only a few of them were observed above two hundred keV. Most of these sources are specific 'active' galaxies (AGN) like:

- Quasars – only one, 3C 273, was clearly identified by SAS 2 and COS B satellites, although the closest one, 2S 0241+622, was found in the error box of γ–ray source CG135+1 (Pollock *et al.*, 1981).
- BL Lac objects – only NGC 1275 was reported as a γ–ray source in COS B data (Strong and Bignami, 1983).
- Radio galaxies – the closest object of this type, Cen A, was observed in soft MeV range and TeV range but only the upper limit from SAS 2 and COS B data were derived.
- Seyfert galaxies – two of them, NGC 4151 and MCG8-11-11 were reported in the MeV range, however upper limits from SAS 2 and COS B experiments are below extrapolation of results from lower energies.

Recent reanalysis of data from SAS 2 satellite by Young and Yu (1988) have identified 15 AGNs in γ–rays including 11 quasars, 3 BL Lac objects and 1 radiogalaxy.

In this chapter, we shortly review 3 the three best investigated extragalactic γ-ray sources which seem to be good representatives of a broader group of objects. They are in sequence: NGC 4151 (type I Seyfert galaxy), 3C 273 (one of the closest quasar), and Cen A (the closest radiogalaxy).

5.2 NGC 4151

NGC 4151 is one of the closest ($\sim 19Mpc$) type I Seyfert galaxy, observed from the radio up to 10MeV γ–rays. The radio emission of this galaxy is relatively weak in comparison to other objects of these kind. However, a pair of radio jets (950pc in length) with londitudinal optical polarization were discovered (see, e.g. Johnson *et al.*, 1982; Booler *et al.*, 1982). There are evidences that the size of the central region of NGC 4151 may decrease with increasing photon energies from $\sim 300-400pc$ in radio wavelengths (Ulvestad *et al.*, 1981) to $\sim 0.01-5pc$ for infrared, optical and ultraviolet (see, Baity *et al.*, 1984), up to $\sim 10^{-3}pc$ in soft X–rays (Lawrence, 1980).

Earlier observations suggest variation of photon spectrum in intensity and spectral index, although correlations between different wavelengths are not definitively examined. Beall *et al.* (1981) have measured comparable variability in optical and soft X–rays (2–6keV) but no variability in infrared or radio frequencies was observed.

The results of recent experiments (MIFRASO, HEXE, GINGA) detecting X–ray spectrum and its variability from the direction of NGC 4151 have been reported in Proceeding of 23rd ESLAB Symposium (Hunt and Battrick, 1989). These results report variability of the spectral index of the X–ray spectrum between 1.35 and 1.7 above 3keV while the intensities varies between $\sim 4-40\times10^{-11}\ erg\ cm^{-2}\ s^{-1}$ on a timescale of several hours (Yagoob and Warwick, 1989). They have also reported variation of column density in NGC 4151 between $35-150\times10^{21}cm^{-2}$ on a timescale of months.

γ–ray observations of NGC 4151

Low energy γ–ray emission up to about 19 MeV from the direction of NGC 4151 was detected for the first time in May 1977 by the MISO telescope (Di Cocco *et al.*, 1977; Perotti *et al.*, 1979). The measured spectrum follows the spectral index from the lower energy range and after about 3MeV breaks into a very steep spectrum. Observations of this source using this same telescope in September 1979 (Perotti *et al.*, 1981), generally confirmed the shape of the spectrum (spectral index of 1.3 ± 0.3 before the break), however the γ–ray luminosity in the energy range 0.5–5MeV showed reduction of the order of 4 ± 2.

The three positive observations of soft γ–rays was also reported by HEAO 1 satellite up to 2MeV (Baity *et al.*, 1984). Results of the two observations can be well fitted by a power law photon spectrum with index $\approx 1.6\pm0.1$ in the 2keV–2MeV energy range. The third observation shows clear break in the spectrum above 50keV. Moreover, the

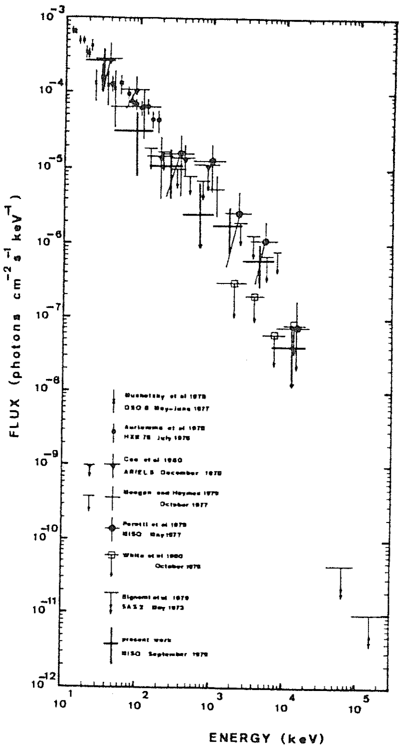

Figure 5.1: *The photon spectrum from the direction of NGC 4151 in X and gamma–ray ranges (for references see Perotti et al., 1981).*

upper limits in this energy range reported by other balloon experiments (Meegan and Haymes, 1979; White *et al.*, 1980) are at much lower level.

From analysis of the above observations, it seems to be evident that γ–ray intensity from the direction of NGC 4151 is highly variable within a factor of 3–10 over a time scales of months (Bassani *et al.*, 1985). Moreover, MeV γ–ray results may vary simultaneously with the photon flux below 100keV (Baity *et al.*, 1984).

The sharp change in the γ–ray spectrum of NGC 4151 above a few MeV is also postulated by the upper limits reported by SAS 2 and COS B satellites between 35–200MeV (Bignami *et al.*, 1979; Pollack *et al.*, 1981). Results of observations in X and γ–ray range from the direction of NGC 4151 are shown in Fig 5.1.

Models applied to NGC 4151.

The luminosity of NGC 4151 in X and γ–ray energy bands is of the order of $10^{44} erg/s$. This energy is produced in the volume of $10^{-3} pc$ in diameter derived from variability of X–rays (e.g. Lawrence, 1980; Tennant and Mushotzky, 1983). To explain this generation of energy in such small volume a few models were suggested:

– the extraction of the rotational energy from a speedy rotating massive object (spinar) or from black hole (Penrose process);

- the accretion of matter onto a black hole via accretion disk (thin or thick) or in spherically symmetric model.

For detailed review of these mechanisms, see Wiita (1985) and references therein.

Several radiation mechanisms could be responsible for the production of γ–rays in NGC 4151. The most popular are Compton scattering models of lower energy photons by thermal or nonthermal electrons.

Schlickeiser (1980) suggested the model in which the ultraviolet and soft X–ray photons below 20keV are scattered by relativistic electrons ($\gamma_e \approx 5$) into the hard X–ray and γ–ray regions. This scenario seems to be unlikely in the case of NGC 4151 because of different scales of variability in these to regions. Also comptonization of UV photons to γ–ray region is difficult to apply because of steeper UV photon spectrum (2.1–2.3; e.g. Wu and Weedman, 1978) than the γ–ray photon spectrum (1.6; Perotti *et al.*, 1981).

Synchrotron self–Compton mechanism was successfully applied to NGC 4151 by Mushotzky *et al.* (1978). In their model X and γ–ray photon spectrum is due to Comptonization of an inferred synchrotron milimeter to optical photon field. Variability of the γ–rays, they explained by competition between injection of relativistic electrons and its energy losses.

The comptonization models in which lower energy photons are scattered by thermal electrons are not able to explain the photon spectrum above 300keV (Baity *et al.*, 1984). However they can be applied in connection with other mechanisms, like Penrose Compton Scattering. In such model (suggested by Leiter, 1980), γ–ray bursts up to a few MeV are produced in the ergosphere of a rotating supermassive Kerr black hole. Such bursts should have duration of $> 2.2hr$ (for $M = 10^8 M_\odot$) separated by a period of the order of days. Up to now, such periods were not observed.

Another type of mechanism uses photon production in e^+e^- plasma created near the black hole horizon. Theoretical calculations show that photon spectrum emerging from optically thick e^+e^- hot plasma should have a break in the MeV range. This is probably the case in NGC 4151. Its rapid variability suggests large compactness parameter (L/R, where L is luminosity and R source diameter). Such kind of model (called pair atmosphere around a black hole) was proposed by Fabian *et al.* (1986).

e^+e^- pair annihilation process was also applied by Tkaczyk and Karakuła (1986) to describe the photon spectrum of NGC 4151 from soft X–rays up to MeV γ–rays. Calculated by them photon spectra from the annihilation of positrons with temperature $3 \times 10^{12} K$ and electrons with temperature $10^8 K$ can fit the observed photon spectrum of NGC 4151 if the theoretical spectrum is redshifted by $z \approx 100$. This requires the location of photon production very close to the black hole horizon ($r = 1.0001 r_g$). According to authors, high temperature positrons can be produced in decay of charged pions from p–p interaction (Giovannelli *et al.*, 1983) or in Penrose pair production process (Leiter and Kafatos, 1978).

Conclusion.

- NGC 4151 is the closest type I Seyfert galaxy with evidences of two radio jets and very compact nucleus $< 10^{-3} pc$. The spectrum, from radio up to $\sim 10 MeV$ is variable and some correlations between different wavelengths were observed. However farther simultaneous observations are strongly recommended. X–ray spectrum shows variabilities in intensity of the order of ~ 10 and in spectral index of 1.35–1.7.
- γ–ray emission from NGC 1451 was reported up to $\sim 19 MeV$. The photon spectrum can be described by power law with spectral index of 1.3 ± 0.3 up to $\sim 3 MeV$ with steep break above this energy. Results of different experiments are not consistent and support strong variations of NGC 4151 in γ–rays. The SAS 2 and COS B experiments only reported upper limits (35–200MeV) which are in agreement with spectral break above $\sim 3 MeV$.
- The central engine of NGC 4151 seems to be black hole (like in other AGNs). The γ–ray emission can be explained in terms of synchrotron self-Compton model via comptonization of milimeter and optical photon field to X and γ–ray ranges (Mushotzky *et al.*, 1978) or by Penrose Compton Scattering process (Leiter, 1980). Also e^+e^- plasma models can explain spectral features in γ–ray range (Fabian *et al.*, 1986; Tkaczyk and Karakuła, 1986).

5.3 3C 273 (CG291+65)

The quasar 3C 273 was discovered in optical range as a 13.0 magnitude object (Schmidt, 1963). The reported redshift ($z \cong 0.157$) makes it one of the closest objects of this type. The structure of 3C 273 is unusual because of one–sided optical jet extending about ~ 20" from the nucleus (Greenstein and Schmidt, 1964). This optical jet is elongated at least 22° to the direction of the inner jet discovered in the radio range (e.g.

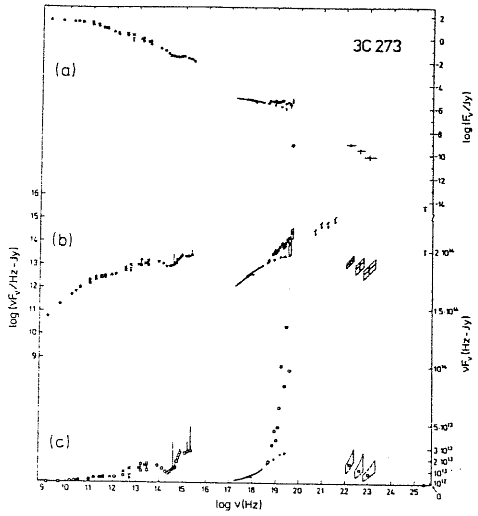

Figure 5.2: *The photon spectrum of 3C 273; different plots of the observed photon flux against log of the frequency (taken from Perry et al., 1987)*

Unwin *et al.*, 1985). The discovery of superluminal motion ($\beta \approx 5$) in inner radio jet (Seilstad *et al.*, 1979; Pearson *et al.*, 1981) implies existence of relativistic particles with Lorentz factor of $\sim 6 \times h^{-1}$ and propagation at an angle $\alpha < 16^\circ \times h^{-1}$ to the line of sight, where: $h = H_\circ/100km/s/Mpc$ and $H_\circ$ –Hubble constant (e.g. Unwin *et al.*, 1985).

The spectrum of the quasar 3C 273 extends over several decades in frequency — from radio to γ–rays — being variable and complex with no strong evidence of correlation between different wavelengths (Courvoisier *et al.*, 1987). The first identification of 3C 273 in X–rays was reported by Bowyer *et al.* (1970) and Kellogg *et al.* (1971). Soft X–ray emission was detected during several rocket flights and the shape of the spectrum was approximated by a power law with spectral index of 1.5 (Turner *et al.*, 1985; 1990). Hard X–ray emission was first reported by Worrall *et al.* (1979) and Primini *et al.* (1979) and subsequently confirmed by balloon flights (e. g. Dean *et al.*, 1990). In this energy range the spectrum is usually described by a power law with index 1.5 (however Bezler *et al.*, 1984 observed a much flatter spectrum with an index of 1.2 up to 200 KeV). A small fraction of the soft X–ray emission is connected with the optical part of the jet of 3C 273 (Willingale, 1981; Harris and Stern, 1987).

For collected spectral data of 3C 273 from radio up to γ–rays, see Fig. 5.2 (Perry *et al.*, 1987).

γ–rays from 3C 273.
The best evidences of γ–ray emission from 3C 273 comes from mea-

surements on board of SAS 2 and COS B satellites. Swanenburg *et al.* (1978) found in these data γ–ray excess ($> 50 MeV$) signed CG291+65 which was identified with quasar 3C 273. This result was confirmed by Bignami *et al.* (1981) who pointed out that γ–ray spectrum in the energy range 70–600MeV can be fitted by the lower law: $(3.7 \pm 1.4) \times 10^{-6} \cdot (E/150)^{-2.5\pm0.6}$ $photons\ cm^{-2}\ s^{-1}$, E – is the photon energy in MeV. The total emitted power in this spectrum is $\sim 2 \times 10^{46} erg/s$. In lower energy range, there were reported only the upper limits equal to: $5, 3, 1, 0.4 \times 10^{-4}$ $photons\ cm^{-2}\ s^{-1}$ for intervals: 1.2–3, 3–5, 5–10, 10–20 MeV, respectively (see White, 1980). They are above interpolation of the photon spectrum between hard X–rays and hard MeV γ–rays.

A few upper limits in the very high energy range were derived (see Weeks, 1988). The most recent one equal to 4×10^{-10} $photons\ cm^{-2}\ s^{-1}$ in TeV range was derived by Cawley *et al.* (1985).

As we can see in Fig. 5.2 the emitted power in γ–rays is clearly peaked at soft MeV range.

According to Bassani and Dean (1981,1986), the variability of the X–ray flux implies that X and γ–rays cannot be produced isotropicly in the same place because of the large compactness parameter of the X–ray source. They conclude that either X and γ–rays are both beamed or that they are produced in different places. Moreover, Bignami *et al.* (1981) reported the γ–ray emission to be stable during observations with COS B. It seems therefore quite reasonable to locate the production of γ–rays in the jet of 3C 273 and that of hard X–rays in the compact core.

Models and mechanisms applied to 3C 273.

Several models have been suggested in order to explain the X and γ–ray emission from the quasar 3C 273. However all of them have some difficulties. Let us see some of them in more details:

- Synchrotron Self–Compton models in which γ–rays are produced by Comptonization of X–ray photons (Jones, 1979) or by first order Comptonization of lower energy photons (radio or ultraviolet: Königl, 1981; Jones and Stein, 1990) have troubles in explaining the observed lack of correlations between different wavelengths (Bignami *et al.*, 1981; Courvoisier *et al.*, 1987; Turner *et al*, 1990).
- Spherically symmetric models in which X and γ–rays are produced in (p + p) interactions (via pions decay) in the core of 3C 273 have difficulties with the compactness of the central source evaluated from X–ray variability (Marshall et al. 1981; Dean and Bassani,

1981), lack of correlation between X and γ–rays (Bignami *et al.*, 1981) and do not take into account the existence of the jet in 3C 273. In particular Protheroe and Kazanas (1983) assume that protons are accelerated in spherical shocks around the central black hole, while Giovannelli *et al.* (1984) investigate the γ–ray production in a high temperature electron–proton plasma which forms during accretion onto the black hole.

- Models which locate the production of γ–rays in the jet (Morrison *et al.*, 1984; Anyakoha *et al.*, 1990) postulate isotropization of relativistic particles during propagation and one–sideness of the jet. However this assumption is difficult to reconcile with the observed orientation of the magnetic field along the jet axis and with the lack of deceleration of relativistic motion in the inner part of the jet.

Bednarek and Calvani (1990a,b) have shown that the entire spectrum of 3C 273, X–rays from the jet (Willingale, 1981; Harris and Stein , 1987)and γ–rays (Bignami, 1981) from the direction of this source, can be explained with a simple model in which these radiations are produced by the interaction of the relativistic proton beam with matter entrained in the jet volume. Their model is similar to the one of Morrison *et al.* (1984), but it differs in that they assume that a relativistic proton beam propagates along the magnetic field which is parallel to the jet axis. They have considered the angular dependence of the spectrum of secondary electrons produced in the interaction of a relativistic proton beam. In such magnetic field, the trajectory of secondary electrons is a helix along the jet axis. The X (from the jet) and γ–ray spectrum from 3C 273 can be accounted for by Inverse Compton scattering of mickrowave photons and bremsstrahlung radiation of secondary electrons and photons produced by π^0 decay assuming a Lorents factor $\Gamma \approx 6$ for the bulk motion of the proton beam and an angle of $\alpha \approx 35°$ between the jet axis and the line of sight.

From the fit of the observed spectrum with the theoretical one, Inverse Compton spectrum calculated according to eq. 3.1, bremsstrahlung spectrum calculated according to eq. 3.2 and γ–ray spectrum from π^0 decay calculated in Bednarek *et al.* (1990) (see Fig. 5.3), they have found that the total power emitted in relativistic protons by the central core of 3C 273 is equal to $P = 2.6 \times 10^{47}\ ergs/s$ which corresponds to a mass loss of $\dot{M} = 0.7 M_\odot/yr$. However they note that a high column density in the jet of 3C 273 is required: $\lambda \approx 70\ g/cm^2$, and accumulation of high amount of matter in the jet volume is possible (see e. g. discussion in Morrison *et al.*, 1984). Numerical simulations of propagation of a jet in the extragalactic medium by De Young (1986)

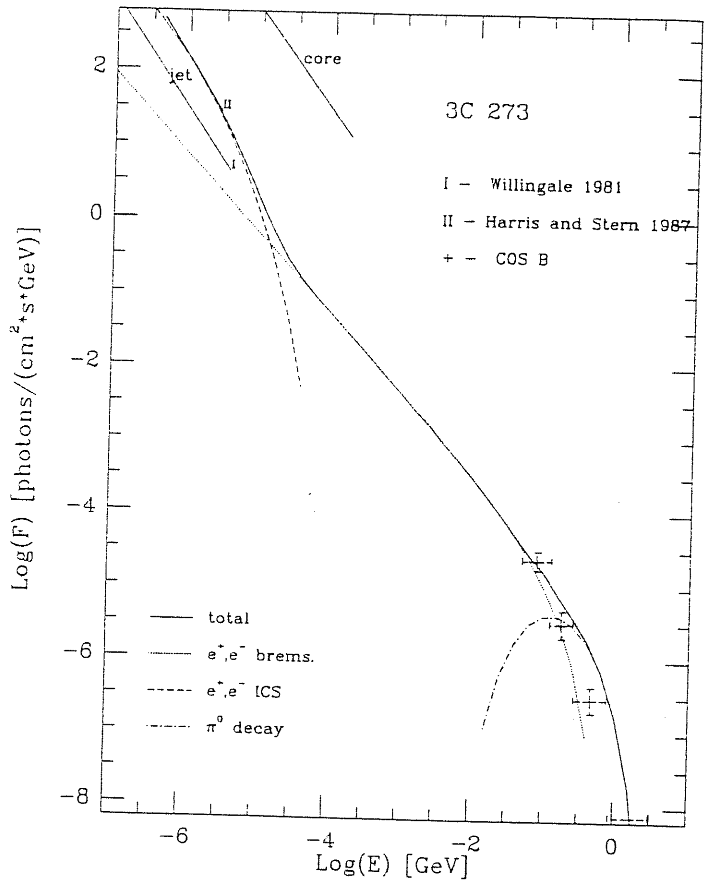

Figure 5.3: *The observational data of X and γ–ray emission from 3C 273 are shown. The full line is the fit to the data by calculated photon spectrum (from Bednarek and Calvani, 1990b)*

show that a jet can entrain a minimum of $\approx 5M_{\odot}/yr$, which implies a total enrichment as high as $10^9 M_{\odot}$ for some jets.

This model can work if the energy losses of electrons are dominated by bremsstrahlung processes which is true if the magnetic field (the perpendicular component to the electron's motion) is less than $1.1 n_H^{1/2}/E\ (\mu G)$ and the energy density of background photons is less than $5.6 n_H/E\ (eV/cm^3)$, where E is the energy of electrons in Gev (see Schlickeiser, 1982).

From polarization measurements, Röser and Meisenheimer (1986) estimate that the magnetic field in the jet of 3C 273 is of the order of $10\mu G$. This value is near the acceptable limit for most the energetic secondary electrons (with energy $\approx 1\ GeV$) but is well acceptable for the lower energy electrons. The electron Inverse Compton losses on mickrowave background radiation are less than electron losses on bremsstrahlung radiation although the Comptonized photon spectrum of mickrowave background radiation (2.7°) dominates the X–ray spectrum from the jet of 3C 273 (see Fig. 5.3).

Their model moreover predicts a strong angular dependence of the photon spectrum with respect to the jet direction. The emission of radiation from the counter jet (produced by secondary electrons at an angle $\alpha \approx 145°$ to the line of sight) should be much less than the one from the jet pointing towards us because of much smaller Lorentz factors of secondary electrons produced backwards.

Conclusions.

- 3C 273, is the closest and the only one extragalactic source observed from radio up to high energy γ–rays. From its compact highly variable core emerges one sided jet (observed from radio up to at least X–rays) with evidences of superluminal motion in the central part.
- The variable X-ray spectrum can be in general described by a power law with index from –1.2 up to –1.5. The γ–ray spectrum was reported by COS B and SAS 2 experiments as stable and can be fitted by the power law with index -2.5 ± 0.6. At MeV and TeV energies only exist the upper limits.
- To explain γ–ray emission from 3C 273, two basic mechanisms were proposed: the first, synchrotron self Compton model (Jones, 1979; Königl, 1981; Jones and Stein, 1990) and in the second γ–rays are produced in decay of π° which are created in particle–particle interaction. This second mechanism was applied in two different models: spherically symmetric γ–ray production in central core (Protheroe and Kazanas, 1983; Giovannelli *et al.*, 1984) and in the model postulated the origin of γ–rays in extended, optical part of the jet of 3C 273. If the lack of correlations between different parts of photon spectrum from 3C 273 and stable flux of γ–rays is confirmed, the model of γ–ray production in the jet of 3C 273 seems to be the most probable.

5.4 Centaurus A (NGC 5128)

Centaurus A (NGC 5128) is the nearest 'active' galaxy at a distance of $\sim 5Mpc$. It appears to be the result of merger of elliptical galaxy with small spirall galaxy (Baade and Minkowski, 1954). The compact nucleus seen in radio, infrared and X–rays (big amount of dust makes optical identification impossible) is characterised by variability from years to a few days (e.g. Kellermann, 1974; Kaufmann and Beall, 1980; Terrell, 1986). Moreover, the emission from the nucleus shows the large intrinsic polarization of $\sim 9\%$ (Bailey *et al.*, 1986).

The inner jet–like features and very big extended lobes are observed in radio, optical and X–rays. Structures observed in these three energy bands correspond to each other (e.g. Feigelson *et al.*, 1981; Brodie and Bowyer, 1985). The detailed observations of Cen A, applying VLA array, show complicated structure with a few knots (Burns *et al.*, 1983)

The Cen A is also a very strong source of infrared emission ($\sim 2 \times 10^{10} L_{\odot}$) produced by grains in the disk of the galaxy. Grains are thermally heated by a massive young stars (Mashall *et al.*, 1988).

The soft X–ray spectrum from Cen A was observed by TENMA satellite (Wang *et al.*, 1986) with total luminosity $\sim 2.6 \times 10^{42} erg/s$. Only the variability in intensity but no changes in the spectral shape were reported. Moreover, narrow iron line between $6 - 7keV$ was reported.

For review of Cen A see Ebneter and Balick (1983) and observations of the jet, see Feigelson *et al.* (1981).

γ–ray emission from Cen A.

The soft γ–ray photons from the direction of Cen A were observed in a few experiments. The continuum emission (from hard X–rays to soft γ–rays) was described by power law spectrum with spectral index: –1.9 between 40–1000keV by Hall *et al.* (1976); –1.6 between 10–140keV and –2. between 140–2300keV by Baity *et al.* (1981);–1.59 between 100–500keV by Gehrels *et al.* (1984). Above results are consistent in the limits of errors.

In the higher energy region, Von Ballomoos *et al.* (1987) detected this source with 4σ significance level and found that spectrum between 0.7–20MeV can be described by power law with spectral index –1.4. However, extrapolation of this spectrum to higher energies is clearly above the observations of γ–rays by SAS 2 satellite between 35–100MeV (Bignami *et al.*, 1979) and COS B between 50–200MeV (Pollock *et al.*, 1981) which yielded the upper limits of 10^{-10} $photons\ cm^{-2}\ s^{-1}$ and 2.5×10^{-11} $photons\ cm{-2}\ s^{-1}$, respectively. Moreover, 3σ upper limits derived by O'Neill *et al.* (1989) are a factor of 2 below the results reported by Von Ballmoos *et al.*. If these observations are true, strong variability of the flux in MeV range seems to be sure. For collected results in this energy range, see Fig. 5.4.

The detection of broad emission lines with 3.3σ was reported at the energy 1.6MeV and 4.5MeV (Hall *et al.*, 1976). However these lines were not observed by next experiments and only upper limits were derived.

The observation of extragalactic sources at very high photon energies is extremely difficult because of expected very small fluxes and

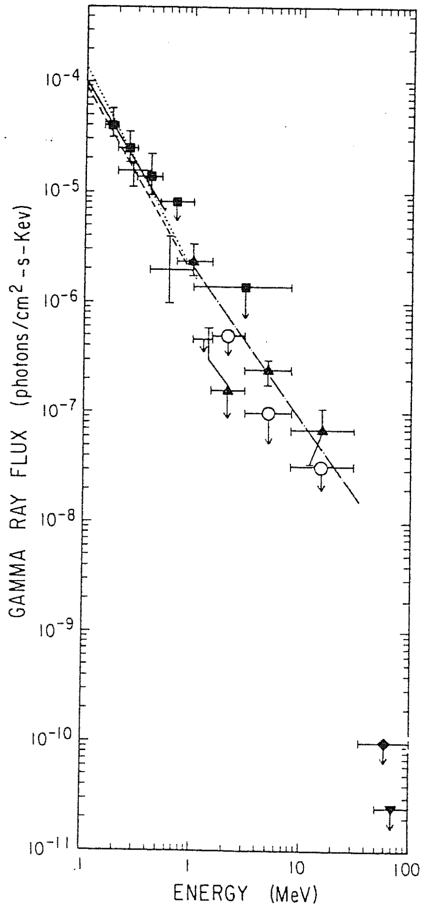

Figure 5.4: *The photon spectrum from the direction of Cen A; different points correspond to different experiments, for references see O'Neill et al., 1989)*

lack of periodicity (very useful to reduce the background). The only one statistically significant detection of Cen A (with 4.1σ) was reported by Grindlay *et al.* (1975). The detected flux was $(4.4 \pm 1.0) \times 10^{-11}$ $photons\ cm^{-2}\ s^{-1}$ for energies $> 0.3TeV$. Recently, derived 3σ upper limit of 7.8×10^{-11} $photons\ cm^{-2}\ s^{-1}$ at energies $> 0.3TeV$ (Carraminana *et al.*, 1990) is apparently compatible with the flux reported by Grindlay *et al.* (1975).

At energies $> 1PeV$, there exist only an upper limit of 10^{-14} $photons\ cm^{-2}\ s^{-1}$ derived by Clay *et al.* (1984) with 2.7σ significance level. However, one should expect a large attenuation of γ–rays with energies $0.1 - -10PeV$ on 2.7K black–body radiation because of the distance to Cen A (4–6Mpc).

Concluding, in spite of the small distance to the Cen A (in comparison to other active galaxies) our knowledge about its γ–ray emission is poor. Only soft γ–ray emission seems to be well documented. Sporadic positive observations in higher energies (2–20MeV; TeV; PeV) are not confirmed and at least strongly suggest variability of this source.

Possible models of γ–ray emission from Cen A.

It is widely believed that black hole is a central engine of Active Galactic Nuclei. In the case of Cen A, from the upper limit on the annihilation e^+e^- line, Baity *et al.* (1981) estimated the lower limit on the dimensions of the central source equal to $\sim 10^{13}cm$. From the other site, the upper limit was estimated from the 6 months variability observed in X–rays (Feigelson *et al.*, 1981) or even 10 days (Terrell, 1986) is equal to $\sim 5 \times 10^{17}cm$. This sizes strongly support existence of $10^7 - 10^9 M_\odot$ black hole in the center of Cen A.

The most popular model of γ–ray emission from Cen A apply comptonization mechanism. Two such detailed scenarious were suggested:

- Thermal comptonization – Von Ballmoos *et al.* (1987) suggested the heating of the plasma during accretion onto the nucleus up to the electron temperatures $\sim 5MeV$. The power law photon spectrum in X and γ–ray regions can be formed in multiple scattering of low energy photons (e.g. infrared). For such relativistic electrons, the emerging photon spectrum is slightly bumpy because of small number of scatterings (see, Pozdnyakov *et al.*, 1977; Górecki and Wilczewski, 1984). Similar model was earlier proposed to explain spectrum of Cen A in radio and X–ray regions (Beall *et al.*, 1978; Beall and Rose, 1980).
- Nonthermal comptonization – synchrotron photons produced by relativistic electrons are next comptonized by them to the γ–ray

range. Nonthermal distribution of electrons can be produced by shock formed during an accretion onto a massive black hole (e.g. Protheroe and Kazanas, 1983). Similar model was suggested also by Grindlay (1975) to explain the observation of TeV photon emission from Cen A. In his model, comptonization occurs in two different regions A and B with parameters; diameters: $\sim 9.7\times10^{-3}pc$ and $2.2 \times 10^{-1}pc$, Lorentz factors: $30 < \gamma_A < 3 \times 10^3$ and $10^2 < \gamma_B < 9 \times 10^6$, respectively.

In general, the bump in the photon spectrum from Cen A between 0.7–20MeV can be also originated by the number of unresolved emission lines (Lingenfelter *et al.*, 1978). However lines at 1.6MeV and 4.5MeV reported by Hall *et al.* (1976) were not confirmed by other experiments.

Conclusions.

- Cen A is the closest 'active' galaxy ($\sim 5Mpc$) with features typical for elliptical and spiral galaxies. It has two–sided extended radio lobes observed from radio up to X–rays. The central core with diameters of $\sim 10^{13} - 10^{18}cm$ is probably a black hole of mass $10^7 - 10^9 M_\odot$.
- The emission in hard X–rays and soft γ–rays is well documented and spectrum in this region can be described by power law with spectral index -1.8 ± 0.2. Results of observations in higher energies reported by: Bignami *et al.* (1979), Pollock *et al.* (1981), Von Ballomoos *et al.* (1987) and O'Neill *et al.* (1989), if all true, suggest variability of Cen A in this spectral range. The only one statistically significant detection (4.1σ) was reported at TeV energies (Grindlay *et al.* 1975).
- Comptonization models seems to be the best candidates to explan the spectral features of Cen A. Two more detailed propositions were suggested: comptonization by thermal electrons (Beall *et al.*, 1978; Von Ballomoos *et al.*, 1987) and comptonization of synchrotron radiation by nonthermal electrons (e.g. Grindlay, 1975).

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Chapter 6

Perspectives of γ–ray astronomy

The γ–ray astronomy is still in its early stage of development. Its present status can be compared to the first results of X–ray observations in 1960's, when at the beginning only a few sources were known but after increasing detector's sensitivity by an order of magnitude, the number of discovered sources increased very rapidly. Similar jump is expected after launching a new generation of satellites (e.g. GRO) and improving sensitivity and angular resolution of ground–based telescopes in VHE and UHE γ–ray range (e.g. HERCULES project).

In the low energy γ–ray range, three new detectors will be launched on the board of GRO satellite at the end of 1990:

- BATSE – is designed to monitor continuously a large segment of the sky for detection and measurements of the γ–ray bursts. It works in the energy range 0.05–20MeV with maximal energy resolution 7.3% at 0.66MeV and time resolution of $<$ 1milisecond.
- OSSE – consists of 4 identical shielded and collimated scintillation detectors, each with a $3.8° \times 11.4°$ field of view. It works in the energy range of 0.1–10MeV, has an angular resolution of 8% at 0.66MeV and source sensitivity of 2×10^{-5} *photons* cm^{-2} s^{-1} (line emission) and 3×10^{-5} *photons* cm^{-2} s^{-1} (continuum emission).
- COMPTEL – is a wide field–of–view (1 steradian) double Compton telescope. It works in the energy range of 1–30 MeV with energy resolution $\sim$ 8% and angular resolution 7.5 arcmin. Its sensitivity is $30 - 3 \times 10^{-6}$ *photons* cm^{-2} s^{-1} (line emission) and 5×10^{-5} *photons* cm^{-2} s^{-1} (continuum emission).

For more detailed description of these detectors see e.g. Schönfelder (1989) or Ryan (1989). They should be able to detect MeV photons

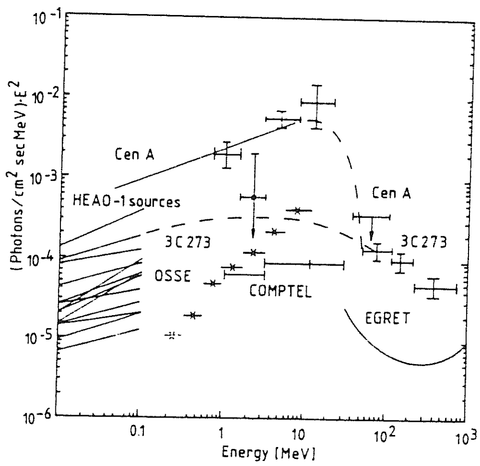

Figure 6.1: *Sensitivities of detectors on the board of GRO satellite in comparison to reported fluxes from 3C 273 and Cen A, (from Schönfelder, 1990)*

from at least few extragalactic sources (see, Fig. 6.1 for comparison of their sensitivity with the flux of photons from 3C 273 and Cen A).

Also the Europien Space Agency consider to build a new generation of a γ–ray telescopes with plan to send it in the mid of 1990's. The main goal of this telescope (called GRASP) will be the spectroscopy and accurate positioning of γ–ray sources in the energy range 0.015–100MeV with angular resolution of $\sim$ 1arcmin and sensitivity up to $\sim 10^{-5}$ *photons* cm^{-2} s^{-1} (see Bignami *et al.*, 1988).

A few more telescopes working in this energy range are planned to be launched in the near future (or are under studies). For example: GRANAT (0.02–2MeV) and HETE (0.006–1MeV) will search for γ–ray bursts, others like: SPECTRA–2 and NAE (Nuclear Astraphysics Explorer) are planned for investigating γ–ray lines. This last project (NAE) should have sensitivity of 10^{-6} *photons* cm^{-2} s^{-1} (about one order of magnitude better than GRO detectors) in order to detect line emission from type I supernova explosion in the Virgo cluster (see Gehrels and Candey, 1989). The achievement of sensitivity below the projected for NAE seems to be very difficult by using standard Ge detectors because of very big amount of Ge needed (100 times more than for NAE). The better solution seems to be the limitation of the background radiation by more precise shielding and by decreasing the field of view of the telescope. In the proposition called Lunar–Based Gamma–Ray Spectrometer (LBGS), the use of lunar soil for shielding of the Ge detector could be applied (see, Gehrels and Candey, 1989).

As the most promising new technologies in MeV energy range are considered gas and liquid detectors including high pressure Xenon and liquid Argon or Xenon detectors. They have many desirable properties like: a high detection efficiency, higher Z number than Ge and comparable energy resolution to the Ge detectors. Potentially much higher energy resolution (of the order milli–eV) could be achieved by phonon detectors. However, this technology is still under study and no practical γ–ray detectors are working yet.

In spite of highly successful COS B mission during 1970's, there have been no new observational results in the high energy γ–ray range for the least ten years. Planned for this time Soviet satellite GAMMA–1 (similar parameters like COS B) had a big delay and probably will be launched this year. It has angular resolution of the order 15arc-min (Akimov *et al.*, 1985), although application of the coded aperture limits their collection area and only effective observations of known bright sources will be possible.

The really new generation of γ–ray telescopes will start EGRET instrument on the board GRO satellite (see e.g. Kanbach, *et al.*, 1988). The sensitivity of this detector will be of 10–20 times better in comparison to COS B. It will work in the energy range 20MeV– 30GeV with energy resolution of 15%. The extension of observations to several tenths GeV is extremely important for testing the results of γ–ray observations obtained by Cherenkov methods on the Earth. Positions of the sources can be determined to about 10 arc–min at the higher energies and extended features $> 0.5°$ should be distinguishable from point sources.

If GRO satellite discovers many γ–ray sources, the next generation of γ–ray telescopes (with higher angular resolution) will be necessary in order to identify them with knowing objects in other wavelengths. Three approaches have been suggested to achieve higher resolution and sensitivity:

- Gas Cherenkov telescopes – two similar projects were proposed (Goret, 1985; Koch *et al.*, 1989). The last one (more ambitious), propose to use the External Tank of the Space Shuttle as a very large gas Cherenkov telescope. It will register photons with energies $> 200 MeV$. The counting rate will be about 40 times better than EGRET detector on the board of GRO. Such telescope will be specially useful in investigating short time variabilities in high energy γ –ray range.
- Coded aperture telescopes – practical solution of this type was proposed by Frye *et al.* (1985). The angular resolution of a few arc–min could be achieved over a field of view of 25°, but detection of e^+e^- pairs created by γ–ray photon will be by drift chamber detector. Such detector can work above 20MeV, how-

ever background radiation induced by charged particles in coded mask reduces effective observations for only the brightest sources.

- calorimeters – new generation of such instruments will be able to measure the γ–ray spectrum from 10GeV to 100TeV (Yodh, 1985). Detector of this type called ASTROMAG (large superconducting magnet) is planned to be placed on the Space Station Freedom in the late 1990's. His energy and angular resolution will be much better than EGRET telescope (sensitive area $\sim$ 7 times greater) and can extend γ–ray observations up to 1TeV (Eichler and Adams, 1987).

The new technique for improving sufficiently the angular resolution of observations in high energy region was proposed by McBreen (1984). He suggests application of strongly correlated emission of radiation by e^+e^- pairs (channeling radiation) if they propagate at a small angle to a major cristal axis (or plane). The precision of 5 arcseconds for 10GeV γ–ray photon can be achieved in this method. However, such detectors can be applied only for earlier discovered sources and should be very useful in deep investigating of an energetic processes in the extragalactic sources (e.g. to distinguish which part of 3C 273 is responsible for γ–ray emission, central core or jet?).

The VHE/UHE γ–ray astronomy is expected to be a very quickly developing branch in the near future (see Fig. 6.2). Since the most (or maybe all?) very high energy γ–ray sources are probably variable and requires continuous monitoring, the big number of new telescopes distributed all over the Earth is very important. Also observing programs by different experiments should be arranged to obtain more complete and independent results which is not easy because of the dependence of the Cherenkov observations on the weather conditions.

General parameters of new working detectors are basically very similar to these ones starting VHE γ–ray astronomy about 25 years ago. However the improvement of the observations expected in the next few years will go in following directions. First, the observation of sources on southern hemisphere is very important because most of the potential VHE/UHE candidates (binary systems) is distributed on this part of the sky. Two new experiments are prepared at the south pole: ACT (see Morse, 1990) and SPASE (see Hillas, 1989). The advantage of such location are ideal in several respects:

- the long polar night permits almost continuous Cherenkov observation (1700 hours/year) – ACT telescope;
- the very high altitude of the Pole (695$g\ cm^{-2}$ atmospheric overlay) allows air showers to be detected easy to below 100TeV –SPASE

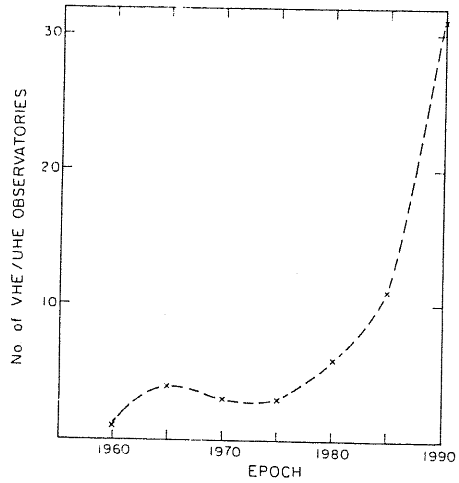

Figure 6.2: *Growth of the number of VHE/UHE γ-ray observatories with time (from Weeks, 1988)*

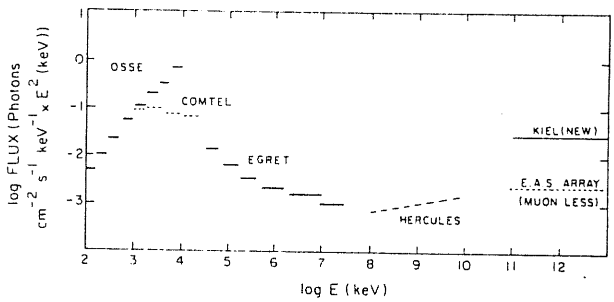

Figure 6.3: *The predicted sensitivity of the next generation of the VHE/UHE γ-ray telescopes with comparison to detectors on board of GRO satellite (from; Weeks, 1988)*

telescope;

– for such location, data analysis simplifies.

Second, the efforts are going to the improvement in angular resolution and sensitivity of the telescopes. Some new experiments, under construction or starting, will have angular resolution of $0.2° - 0.5°$ (Gibbs *et al.*, 1988; Goret *et al.*, 1988; Heintze *et al.*, 1989). Cawley *et al.* (1990) propose application of a new detector consistent with 109 close-placed photomultiplier tubes to the Wipple telescope. It should improve telescopes sensitivity by a factor of 10 and angular resolution up to $\sim 0.1°$. Another project, called HERCULES (see, Hillas and Lamb, 1987), could localize a source to less than $0.1°$. For comparison of its sensitivity with other γ-ray telescopes see Fig. 6.3.

A big step forward in this field is expected with the realization of TEMISTOCLE experiment (see for details; Fontaine, 1990). The authors plan to achieve accuracy of arrival direction of showers of the order of $\sim$ 1arcmin analyzing the shape of the front of the air shower.

Third, improvements in methods distinguishing γ–rays from the hadronic background is expected by application of the new results of particle physics in numerical simulations of the showers.

Forth, development of new techniques covered the 10–100TeV region which is now not available for Cherenkov and air shower observations.

Apart from previously mentioned new developed and planned experiments, specially interesting seems to be the Cherenkov telescopes like JANZO on the southern hemisphere and U. of Durhum telescope at Dungway, and air shower arrays like GREX at Haverah Park, Kiel array on Canary Islands, Cygnus array in New Mexico PEGASAS array in Tibet (for details see Weeks, 1988) or SINGAO array (see De Palma, 1990).

The reported excess of muons from the direction of Cyg X–3 observed by NUSEX and SUDAN underground experiments have stimulated studies of new, much bigger underground detectors. To currently working, IMB, Kamiokande, Homestake and Baksan, a few more ambitious are under studies: MACRO, Lake Baikal and DUMAND.

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Chapter 7

Summary and Conclusion

This thesis is divoted to the new branch of astronomy which analyses the most energetic part of the electromagnetic spectrum. In spite of many observational problems (new technique had to be developed), the first results were very promising and even stimulates research in other parts of photon spectrum, cosmic ray astrophysics and neutrino astronomy.

The main problems mentioned in this thesis can be classified under the following items:

1). γ–ray observations –technical equipment

The main observational differences in in the γ–ray energy range compared to lower energy photons concerns very low photon fluxes from cosmic sources, impossibility of focusing of γ–ray radiation and necessity of moving detectors outside the Earth atmosphere or at least at high altitudes. For this reasons, γ–ray telescopes are completely different than instruments of optical astronomy and even different techniques have to be used in different parts of γ–ray energy range.

In low energy range (see section 2.1), scintillation detectors (NaI(Tl)) and semiconductor detectors (Ge(HP)) are used. The energy resolution of Ge (HP) detectors is quite high (of the order of $\sim 1keV$) but they are not able to localize in space the arrival directions of photons. Only mechanical collimaters can be used. However they reduce the detectors sensitivity. The continuum low energy γ–ray spectrum can be also measured by detectors based on Compton effect. The arrival direction of photons can be estimated within a few degrees which is a big disadvantage in searching for γ–ray point–like sources. Effects like periodicity, variability or other special features have to be used in identification of source in other wavelengths.

In high energy range (see section 2.2), the γ–ray telescope consists of the spark chamber (conversion of photon into e^+e^- pair, derivation of photon direction), anticoincidence system (rejection of charged particles) and scintillator (measurements of photon energy). The angular resolution of these detectors depends on the photon energy and is typically of the order of 1°. Photons with higher energies can be in general also detected by this technique. However to achieve a reasonable counting rate of photons, very big detection area are required which up to now is only a topic under investigation.

The information about very high energy photons ($> 10^{11}eV$) can be obtained indirectly from analysis of the electromagnetic cascades initiated by photons in the Earth atmosphere (see section 2.3 and 2.4). In the energy range $10^{11} - 10^{14}eV$, the photon energy and arrival direction can be derived from measurements of the Cherenkov light emitted by secondary particles of the cascade. However this technique is strongly dependent on the weather conditions and needs special electronics able to measure very short light pulses. If the photon energy is $> 10^{14}eV$, the secondary particles of the cascade can be rejestred directly on the ground level by very big detector arrays distributed on the surface up to several tenths of km^2. The arrival direction of primary photon with these two techniques can be estimated within 1°.

The main problem of γ–ray measurements is how to distinquish these cascades initiated by photons from these initiated by cosmic charged particles ($\sim 10^4$ per one photon). In the low and high energy ranges this problem is solved by applying anticoincidence systems screening central detector against charged particles.In the VHE and UHE photon energy range the problem is much more complicated. In practice, the selection of showers initiated by photons rely on numerical simulations of both γ–ray and hadronic showers. Only statistical parameters of showers (like lateral distribution, muon content, age parameter or content of ultraviolet radiation) can be applied in distinguishing between very high energy photons and charged particles. However this process makes detection of photons unsure specially if small statistics of events is available.

2). γ–ray observations – results

In the low energy γ–ray range, emission lines were reported from the Solar flares, γ–ray bursts, Galactic Center, SS 433 and even from extragalactic object Cen A (see chapter 4, 5 and section 2.2). The continuum low energy emission was detected from some pulsars (e.g. Crab, Vela), Cyg X–1, Solar flares, two Seyfert galaxies NGC 4151 and MCG8–11–11 and radio galaxy Cen A. However in many cases the results of observations are not confirmed and identification with specific sources is not sure because of very poor angular resolution of detectors.

In the high energy γ–ray range, 24 point–like sources were seen in COS B data although only a few of them were identified with known object (see for details chapter 4 and section 2.3). The typical error box of these "sources" is of the order of 1° and some of them are expected to be local interstellar clouds irradiated by cosmic rays. The identification of these point–like features in other wavelengths (were angular resolution of observations is much better) is very important from the viewpoint of theoretical analysis of their structure and γ–ray production processes. Also 15 γ–ray excesses were found in data from SAS 2 satellite. They were connected with extragalactic objects but the statistical significance of these results is very poor and new more precise observations are needed. The most probable extragalactic identification in this energy range seems to be the quasar 3C 273 found in COS B data.

The situation in the very high and ultra high photon energies is much more complicated (see sections 2.4,2.5; for details of Crab observation section 4.6 and Cyg X–3 section 4.7). There are uncertainties about the validity of some observational results (see Tab. 2.1). Most of the sources were reported only in $\sim 3\sigma$ significance level which is very strange why a wide variety of objects (pulsars, X–ray binaries, AGNs) placed at different distances have similar apparent magnitude? Pessimists are trying to explain this fact as a result of statistical fluctuation of background radiation and suggest that most of the sources are real. Another problem is that many results are not confirmed by other groups. Optimists are explaining this fact by variabilities of the sources in very high energy range.

Even when the sources are accepted as detected, it is not possible to conclude that particles that emit are γ–ray photons. Some reported parameters of air showers assumed as initiated by γ–rays are very untypical (e.g. muon contents).

in conclusion, several sources were reported as emitters of high energy photons. However the number of unanswered questions is very big and only new, much precise observations made simultaneously by different groups can solve them. Also very important is calibration of the photon detection technique applying analysis of the air showers by direct detection of VHE/UHE γ–rays in cosmic space (planned detector ASTROMAG will cover part of VHE region).

3). Mechanisms and models of γ–ray production

Different processes are responsible for the production of γ–ray emission in different parts of this photon energy range (see chapter 3). In low

γ–ray energy range, the emission lines are caused by annihilation of particles and antiparticles or by nuclear reactions and nuclear deexcitations (see section 3.2). The continuum photon emission is caused by processes involving acceleration of electrons (synchrotron radiation, bremsstrahlung, inverse Compton scattering of softer photons or e^+e^- annihilation in flight).

The higher energy photons are originated in interaction of relativistic heavy particles (protons, nuclei) with background matter and radiation via production of charged pions or deexcitation of excited nuclei. Moreover, processes of inverse Compton scattering of synchrotron radiation, curvature radiation and bremsstrahlung can be important in sources of relativistic electrons with significant magnetic field.

The low energy γ–rays are usually produced by thermal processes. Models applying them can describe γ–ray emission from γ–ray bursts (section 4.3) or active galactic nuclei (chapter 5). The production of more energetic photons reguires acceleration of particles to very high energies. Such nonthermal mechanisms are postulated in the case of γ–ray emission from pulsars (see e.g. section 4.6), X–ray binaries (see e.g. section 4.7) or black hole candidates (see section 4.4).

The first positive γ–ray observations stimulated calculations of simple models (spherical symmetry) applying different mechanisms (synchrotron, inverse Compton, bremsstrahlung, π° decay). Recent works concentrate on the analysis of γ–ray emission by optically thick high temperature plasma in which propagation effects on the emerged photon spectrum are taken into account. Moreover, there are some efforts to take into consideration geometry of the source. Analysis of such models is necessary since most of the γ–ray sources have probably non–spherical structure. However detailed calculations are very complicated (because of more than one–dimensional problems) and only numerical modeling is possible.

Summarizing, our general knowledge about mechanisms of γ–ray production is quite satisfactory although detailed modelling of γ–ray sources have very often troubles in explaining all observed features. Further work taking into account multiwavelength behaviour of γ–ray sources is strongly needed.

4). Perspectives of γ–ray astronomy

A big step forward (at least in detection technique) is expected in the next few years (see chapter 6). To investigate the low and high energy γ–ray range, new telescopes (e.g. GRO, GAMMA–1, GRANAT, etc...) will be launched with sensitivity and angular resolution of the order of one magnitude better. Also new detectors, even with better parameters, are under study or planned (e.g. GRASP, SPECTRA-2, NAE, ASTROMAG). Analysis of a huge stream of data will need specialized groups of scientists and will take many years since most of this work cannot be done automatically.

In the very high and ultra high photon energy range, the number of working telescopes all over the World is rising very quickly (see Fig. 4.2). This is very important from statistical reasons, higher chance of simultaneous observations and covering the south hemisphere (on which up to now equipment was much poor). Also the parameters of working telescopes will improve sufficiently (e.g. HERCULES project will achieve sensitivity of the order of one magnitude better and angular resolution less than $0.1°$; TEMISTOCLE experiment will have angular resolution of $\sim 1 arcmin$). New underground detectors are under studies (e.g. MACRO, Lake Baikal, DUMAND). These projects will be very important in investigation of muon contents in the air showers initiated by VHE/UHE photons. Up to now, there are controversial reports in this subject which makes unsure the identification of showers initiated by γ–rays.

The purpose of my thesis was to review the recent results of γ–ray observations of cosmic point–like sources and to show the main theoretical efforts trying to understand these results. In particular, I have concentrated on different machanisms of γ–ray production and on models of γ–ray sources. Special atention was payed to γ–ray production in inverse Compton, bremsstrahlung and hadronic processes. Also more detailed description of models for Cyg X–1, Cyg X–3, Geminga and quasar 3C 273 was included.

Appendix A

In this appendix we derive in details the spectrum of muons produced in the decay of charged pions.

The kinematics of the production of muons with energy E_μ at an angle α_μ with respect to the direction of motion of the relativistic proton is shown in Fig. A.1. The number of muons produced in the above process is given by:

$$dR = \frac{d^3\sigma(p_\pi, \cos\theta_\pi, \phi_\pi)}{dp_\pi d(\cos\theta_\pi) d\phi_\pi} P(\gamma_\pi, E_\mu, \cos\theta_\mu, \phi_\mu) dp_\pi d(\cos\theta_\pi) d\phi_\pi dE_\mu d(\cos\theta_\mu) d\phi_\mu \tag{A1}$$

The energy and angular distribution of muons in the observer's frame from the decay of pions with momentum p_π (Lorentz factor γ_π) is Described by:

$$P(\gamma_\pi, E_\mu, \cos\theta_\mu, \phi_\mu) = \frac{1}{4\pi} J_1 \delta[\gamma_\pi(E_\mu - \beta_\pi p_\pi \cos\theta_\mu) - E_\mu^*] \tag{A2}$$

where: $J_1 = p_\mu / p_\mu^*$ is the Jacobian of the transformation of distribution of muons from the rest frame of pions to the observer's frame; $E_\mu^* = (m_\mu^2 + m_\pi^2)/2m_\pi$ and $p_\mu^* = (m_\pi^2 - m_\mu^2)/2m_\pi$ are the energy and the momentum of muons in the pion rest frame while E_μ, p_μ are in the observer's frame; β_π is the relative velocity of pions. All angles are defined in Fig. A.1.

Substituting A2 into A1, we obtain the angular dependent spectrum of muons (per unit energy, solid angle, volume and time):

$$\frac{dR}{dE_\mu d(\cos\alpha_\mu) d\phi_\pi dV\, dt} = \frac{Ap_\mu}{4\pi p_\mu^*} \times \int\int\int \frac{d^3\sigma(p_\pi, \cos\theta_\pi, \phi_\pi)}{dp_\pi d(\cos\theta_\pi) d\phi_\pi} \delta[\gamma_\pi(E_\mu - \beta_\pi p_\mu \cos\theta_\mu) - E_\mu^*] J_2 d(\cos\theta_\mu) dp_\pi d\phi_Y \tag{A3}$$

where the angle $\cos\theta_\pi$ is expressed via spherical trigonometry (see

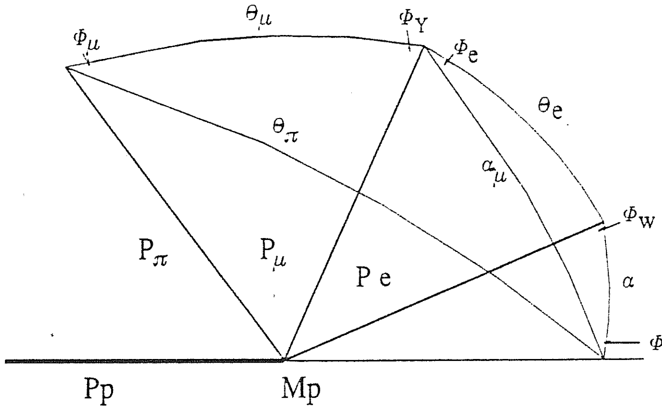

Figure A.1: *The kinematics of the angular dependent spectra of secondary electrons in proton-proton interaction ($p + p \longrightarrow \pi^{\pm} \longrightarrow \mu^{\pm} \longrightarrow \nu^{\pm}$) is here shown (from Bednarek and Calvani, 1990)*

Fig. A.1) by:

$$cos\theta_{\pi} = \cos\theta_{\mu}\cos\alpha_{\mu} + \sin\theta_{\mu}\sin\alpha_{\mu}\cos\phi_{Y}$$

and jacobian

$$J_2 = \frac{d(\cos\theta_{\pi})d\phi_{\mu}}{d(\cos\alpha_{\mu})d\phi_{Y}} = 1.$$

A - is described in section 3.7 (Eq. 3.3). The integration over $\cos\theta_{\mu}$ in A3 is done analitically using the properties of Dirac's δ–function. After changing variable of integration from p_{π} to γ_{π} we obtain:

$$\frac{dR}{dE_{\mu}d\Omega_{\mu}dV\,dt} = A\frac{m_{\pi}^2}{2\pi(m_{\pi}^2 - m_{\mu}^2)}\int\int\frac{d^3\sigma(p_{\pi},\cos\theta_{\pi},\phi_{\pi})}{dp_{\pi}d(\cos_{\pi})d\phi_{\pi}}\frac{1}{\beta_{\pi}^2\gamma_{\pi}}d\gamma_{\pi}d\phi_{Y} \qquad (A4)$$

where:

$$\cos\theta_{\mu} = \frac{(E_{\mu} - E_{\mu}^{*}/\gamma_{\pi})}{\beta_{\pi}p_{\mu}} \qquad (A5)$$

from the Lorentz transformation. m_{π}, m_{μ} are the masses of the charged pions and muons respectively.

Let us discuss now the integration limits. The minimum and maximum values of the Lorentz factor γ_{π} of the pions that can produce muons with energy E_{μ} are calculated for the cases when $\cos\theta_{\mu} = 1$ (minimum) and $\cos\theta_{\mu} = -1$ (maximum). They are given by:

$$\gamma_{min} = \frac{(E_{\mu}^{*}E_{\mu} - p_{\mu}p_{\mu}^{*})}{m_{\mu}^2} \quad ; \quad \gamma_{max} = \frac{(E_{\mu}^{*}E_{\mu} + p_{\mu}p_{\mu}^{*})}{m_{\mu}^2} \qquad (A6)$$

In order to perform the numerical integrations, we distinguish two cases: (i) The energy of the muon emitted at the angle α_{μ} in the

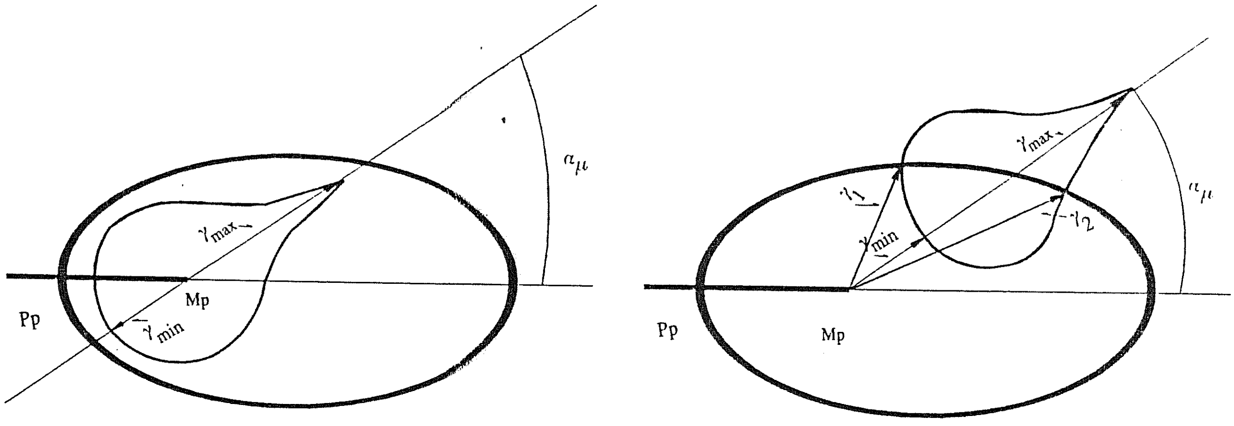

Figure A.2: *The maximal ellipsoid of momentum of pions produced in p + p interactions is shown together with the function describing the production of muons with fixed energy in the pion momentum phase space. Case a) is for* $m_\mu \leq E_\mu \leq E^*_\mu$ *and case b) for* $E_\mu > E^*_\mu$ *(from Bednarek and Calvani, 1990)*

observer's frame is less than the energy of the muon in the pion's rest frame ($m_\mu \leq E_\mu \leq E^*_\mu$).

Since the cross–section for pions production in p + p interactions is given for $\gamma_p \geq 2$ (see Tan and Ng, 1983), the function W describing possible values of pion Lorentz factors (see A5) which can produce muons with energy $m_\mu < E_\mu \leq E^*_\mu$ is inside the function V describing the

maximal ellipsoid of momentum of pions produced in p + p interactions (see Fig. A.2). The limits of integration (in A4) are given by:

$$\gamma_{min} \leq \gamma_\pi \leq \gamma_{max} \qquad \text{and} \qquad -\pi \leq \phi_Y \leq \pi.$$

(ii) The energy of the muons emitted at the angle α_μ in the observer's

frame is greater than the energy of the muon in the pion rest frame: $E_\mu > E^*_\mu$. This case is shown in Fig. A.2.

Three possibilities arise now depending on the relative values of γ_{min}, γ_{max} (A6) with respect to the maximum value of the Lorentz factor of the pions γ_α produced in p + p interaction at the angle α_μ (see Fig. A.2, where:

$$\gamma_\alpha = \frac{M + K\sqrt{M^2 + K^2 - 1}}{1 - K^2}. \qquad (A7)$$

$M = E^*_{max}/m_\pi \gamma_S$; $K = \beta_S \cos \alpha_\mu$; E^*_{max} is the maximum energy of pions produced in p + p interaction in the center of mass of the colliding protons (see Tan and Ng, 1983); γ_S, β_S are the Lorentz factor and relative velocity of the center of mass of the colliding protons, $\gamma_S = \sqrt{(E_p + m_p)/2m_p}$ (E_p– energy of relativistic protons). The three cases are: (a) $\gamma_{min} \geq \gamma_\alpha$. No muons with energy E_μ at an angle α_μ are produced. (b) $\gamma_{min} \leq \gamma_\alpha < \gamma_{max}$. The limits of integration (in A4) are:

$\gamma_{min} \leq \gamma_\pi \leq \gamma_1$ with $-\pi \leq \phi_Y \leq \pi$, and $\gamma_1 \leq \gamma_\pi \leq \gamma_2$ with $-\phi_0 \leq \phi_Y \leq \phi_0$

The values of pions Lorentz factors γ_1 and γ_2 are obtained by solving w.r.t. γ_π the equation

$$\cos\theta_{max} = \cos(\theta_\mu \pm \alpha_\mu) \qquad (A8)$$

where:

$$\cos\theta_{max} = \frac{\gamma_\pi \gamma_S - E^*_{max}/m_\pi}{\gamma_\pi \beta_\pi \gamma_S \beta_S}$$

while $\cos\theta_\mu$ is given by (A5).

The angle ϕ_0 is found from:

$$\cos\phi_0 = \frac{\cos\theta_{max} - \cos\theta_\mu \cos\alpha_\mu}{\sin\theta_\mu \sin\alpha_\mu}$$

(c) $\gamma_\alpha \geq \gamma_{max}$. The limits of integration are: $\gamma_{min} \leq \gamma_\pi \leq \gamma_{max}$ with $-\pi \leq \phi_Y \leq \pi$.

For the particular values $\alpha_\mu = 0°$ and $\alpha_\mu = 180°$, the integrand function in A4 does not depend on ϕ_Y and this integration can be performed analitically.

Appendix B

We present here a short description of the calculations needed to obtain the angular dependent spectra of secondary electrons (positrons) from the decay of muons which are produced in the reactions: p + p $\rightarrow \pi^{\pm}$ + anything; $\pi^{\pm} \dashrightarrow \mu^{\pm} + \nu_{\mu}$. The decay of muons in three particles ($\mu^{\pm} \rightarrow e^{\pm} + \nu_e + \nu_{\mu}$) was described by Lee and Yang (1957) in the case of negligible electron rest mass w.r.t. the muon rest mass. In the following derivation we assume that $E_e >> m_e$.

The number of electrons emitted at the angle α per unit energy, solid angle, time and volume is described by:

$$\frac{dP}{dE_e d\cos\alpha d\phi^e_{\mu} dV dt} = \iiint \frac{dR(E_{\mu}, \cos\alpha_{\mu})}{dE_{\mu} d\cos\alpha_{\mu} d\phi^e_{\mu} dV dt} J_1 \frac{dN(E^*_e, \cos\theta^*_e)}{dE^*_e d\cos\theta^*_e d\phi^*_e} J_2 dE_{\mu} d\phi_W d\cos\theta_e \quad \text{(B1)}$$

where the two fractions in the integrals are described in section 3.7 (Eq. 3.4); $J_1 = p_e/p^*_e = 1/\gamma_{\mu}(1 - \beta_{\mu}\cos\theta_e)$ is the Jacobian of the transformation from the muon rest frame to the observer's frame of the distribution of secondary electrons; p_e, p^*_e are respectively the momentum of electron in the observer's frame and in the muon rest frame and $J_2 = d\cos\alpha_{\mu} d\phi_e / d\cos\alpha d\phi_W = 1$ is the Jacobian of the transformation of the solid angles; $\cos\alpha_{\mu}$ is given via spherical trigonometry by: $\cos\alpha_{\mu} = \cos\theta_e\cos\alpha + \sin\theta_e\sin\alpha\cos\phi_W$. All angles are defined in Fig. A.1. Substituting then into Eq. B1 the distribution of secondary electrons in the muon rest frame (Lee and Yang, 1957), the Jacobians J_1 and J_2 and changing variable of integration from E_{μ} to γ_{μ}, we obtain:

$$\frac{dP}{dE_e d\cos\alpha d\phi^e_{\mu} dV dt} = \frac{2E_e}{\pi m_{\mu}} \times \iiint \frac{dR(E_{\mu}, \cos\alpha_{\mu})}{dE_{\mu} d\cos\alpha_{\mu} d\phi^e_{\mu} dV dt} \varepsilon\left[(3 - 2\varepsilon) + (1 - 2\varepsilon)\cos\theta^*_e\right] d\gamma_{\mu} d\phi_W d\cos\theta_e \quad \text{(B2)}$$

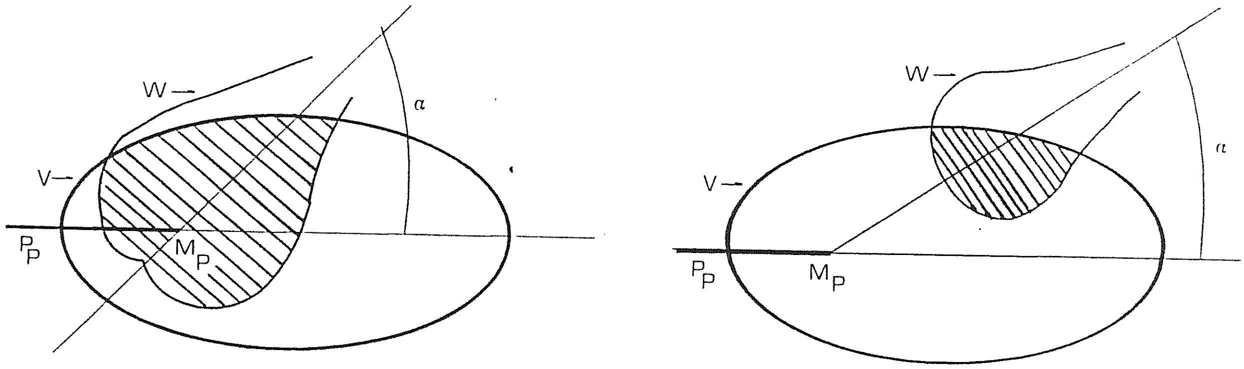

Figure B.1: *The maximal ellipsoid of momentum of muons produced from pions decay is shown together with the function discribing the production of electrons with fixed energy in the muon momentum phase space. Case a). is for $E_e \le E_e^*$ and case b) for $E_e > E_e^*$ (from Bednarek and Calvani, 1990)*

where: $\varepsilon = 2E_e\gamma_\mu(1-\beta_\mu\cos\theta_e)/m_\mu$; $\theta_e^* = \arctan[\sin\theta_e/\gamma_\mu(\cos\theta_e - \beta_\mu)]$; E_μ, γ_μ, m_μ are the energy, Lorentz factor and rest mass of the muon.

In order to perform the numerical integration, one has first to fix the integration limits. This is straightforward, although quite involved. In general there are two different relevant cases: 1) $E_e \le E_e^*$ (see Fig. B.1) and 2) $E_e \ge E_e^*$, where $E_e^* = m_\mu/2$, see Fig. B.1. In both of them the integration is performed over the common part of the two three-dimensional functions in the momentum space describing respectively, the ellipsoid of maximal muon momentum (function V) and the permitted values for muons momentum which can produce electrons of energy E_e (function W). The relative positions of function V according to fixed function W depends on the electron energy and many different cases are possible. Two of such configurations are shown in Fig. B.1 where the hatched area denotes the volume of integration.

B.1 References

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