High energy particles from cosmic sources

H. Meyer
FB Physik, University of Wuppertal, D42119 Wuppertal, Germany

In this review it will be attempted to briefly cover some of the recent developments in the observation of photons and neutrinos to constrain models on the origin and acceleration of cosmic rays. It appears that EGRET on board of CGRO provides most valuable new data in that context. Data from high energy air-shower arrays and Tscherenkov telescopes add to the picture although not yet strong enough to really decipher the origin of cosmic rays. Searches for high energy neutrinos in underground detectors put further constraints on models in particular on possible origins of the highest energy cosmic rays. Most spectacular is the EGRET observation of a particular gamma ray burst deepening the mystery of the gamma ray burst phenomenon. Further ongoing observations of cosmic ray photons and neutrinos should get us closer to an understanding of the origin of cosmic rays.

1. INTRODUCTION

The origin of cosmic rays remains a largely unsolved problem of particle astrophysics. The flux of cosmic ray particles follows a power law in energy from about 10 GeV to 1 PeV with spectral index 2.75 and still higher energies up to about 10 EeV with spectral index of about 3.15 and for two more decades in energy with a somewhat smaller spectral index again [1]. Below about 10 GeV the flux is rather strongly dependent on solar activity seen in solar spot number through changes in the shape of the magnetic field of the earth and sun and in the space in between. Occasionally the flux of cosmic ray particles at low energies gets sizeable contributions from flares [2], however most of the low energy cosmic ray flux is certainly not coming from the sun or the solar neighborhood. At energies below 1 PeV cosmic rays are generally assumed to originate from inside our own galaxy [3]. Since the total amount of energy stored in the galactic flux is large compared to other forms of energy in the galaxy it has been suggested since more than 60 years [4] that supernovae should be at the origin of galactic cosmic rays. Since supernovae produce strong shockwaves pushing through the surrounding material consisting of either just interstellar matter or matter lost from the star before the supernova explosion it has also long ago been suggested that shockwave acceleration provides the basic physical mechanism for generating high energy galactic cosmic rays [5]. For the energy range below 100 TeV the chemical composition of cosmic rays is rather well determined, mostly using experimental equipment carried above the atmosphere with balloons and also with satellites [6,7]. The relative abundance at energies of about 10 TeV resembles that of the so called primordial abundance, in particular the odd even regularity in mass number. However of great interest are the changes, with a much reduced flux of H and He at high energy and very much enhanced fluxes of Li, Be, B and also for the elements below iron [7]. The flux of electrons (and positrons) is lower by two to three orders of magnitude with spectral index of about 3.2 [7]. The flux of photons has been rather well measured below about 30 GeV with great advances only recently due to the EGRET instrument on board of CGRO [8]. It has confirmed many details of the picture that cosmic rays are of galactic origin [9] adding to it interesting new information on pulsars [10] and the interstellar medium as sources of photons [11]. Almost nothing or very little is known about neutrinos, only the flux from the sun at a level reduced by about a factor of two as compared to expectation has been monitored since about 20 years [12]. Also the secondary flux of neutrinos originating from interactions of primary cosmic rays in our atmosphere has been detected in experiments located deep underground [14]. At energies greater 10 E 15 eV the origin of cosmic rays may have contributions both from galactic- and extra-galactic sources however at energies greater

1 PeV an extragalactic origin seems almost certain [1,14]. Not to much is known about the chemical composition in this energy range in particular in the knee region around 1 PeV [15] where the all particle spectral index changes by about 0.5 and experimental information on the chemical composition of cosmic rays would be of great value. Cosmic rays at the highest energy end of the cosmic ray spectrum are of particular interest since pion photoproduction either in photon fields at the origin of the highest energy particles or in the 3 K photon background very efficiently dissipates the energy of cosmic ray nucleons [16]. This may leave remnants of photons and neutrinos which as a cosmological signal would be of greatest interest to detect on earth [17]. Finally the enigmatic phenomenom of gamma ray bursts mainly in the keV to MeV -range seems to extend, at longer timescales, up into the GeV -range as seen by EGRET [18] and a search for an even further extension into the TeV -range should provide basic new information. In the chapters to follow I would like next (2.) to discuss some experimental issues of air shower physics on the basis of the HEGRA experiment and in (3.) to give a summary on recent developments on galactic cosmic rays and in (4.) on gamma emissions from flat spectrum radiosources followed by a discussion of photon and neutrino remnants (5.) and finally (6.) a brief mention of high energy gamma ray bursts.

2. THE AIRSHOWER ARRAY HEGRA

The HEGRA (High Energy Gamma Ray Astronomy) experiment at the Observatorio del Roque de los Muchachos on La Palma [19] was originally designed (1987) to confirm earlier observations of a cosmic ray signal from Cyg X3. It was considerably extended since and consists now of 252 scintillation counters, 49 angle integrating Tscherenkov stations (AIROBICC) and 17 muon -and electron tracking towers [20]. All these instruments are regularly distributed over an area of about 32 000 m^2. The primary aim is to detect airshowers from cosmic gamma rays, which seems to be a rather difficult if not impossible task based on the experience with bare scintillator arrays [21]. A scintillator array as in HEGRA is now more or less standard technique with accurately calibrated arrivaltime and amplitude (for particle density) measurements on each station. The AIROBICC array however is unique [22] , it covers with 7 x 7 stations the same area as the scintillator array. It detects the Tscherenkov light generated in the airshowers with an acceptance of about 1 steradian. I has very accurate arrivaltime and amplitude measurement with an energy threshold lower by about a factor 2 compared to 40 TeV for the scintillator array. It can be used only at night time when also the moon is down which restricts the observation time to about 15% averaged over one year at La Palma. The Tscherenkov light is not strongly absorbed in the air and therefore a complete picture of the shower development is stored in the information collected by the stations. This allows for superb energy resolution of order 12% or better and as simulations indicate essentially independent of the nature of the primary particle. In contrast the scintillation stations receive only particles that originate in the last 1 radiation length (r.l.) of air just on top of the array and most information on the shower development is lost. The muon detectors have a sensitive area of 16 m^2 and a vertical structure of 6 layers of Geigertubes separated by 20 cm and 4.5 r.l. of Pb each below the first and second layer [20]. Not only are muons identified as straight tracks but also electrons and photons are seen as showers with several samplings along their development in the tower. This significantly adds to hadron shower identification in addition to the muon track information. Therefore in HEGRA when AIROBICC is on, a shower is seen simultaneously by three rather different arrays and we estimate a combined hadron shower rejection factor well above 100, even factors larger than 500 seem possible. If this is sufficient to see photon showers will become known in the near future. Furthermore two Tscherenkov telescopes have been added to the array, with 4 more to be completed 1995/1996. Four of them will be placed in a square of 95 m side-length and the remaining two near the center of the square. The first (rather small) telescope has a polar mounting and a 37 pixel camera, just sufficient to get a significant signal from CRAB [23]. Now the camera has been replaced, the new one having 127 pixel and a somewhat larger acceptance of about 3-4^{o}. The second telescope has 30% more mirror area and a alt- azimuth mount with a 61 pixel camera and serves as a model for the next four telescopes. However all cameras will have at least 127 pixel and the central telescope even 2 to 3 times more. As an unique feature of this arrangement of instruments many cross calibrations are possible and used in HEGRA to fight in particular systematic errors that have plagued other arrays so far. The main aims of HEGRA are an accurate measurement of the energy spectrum of cosmic rays at energies > 20 TeV and up to about 10 PeV well beyond the knee, an attempt to obtain new information on the chemical composition at energies well beyond 10 PeV, detect point sources of gamma rays at energies > 10 PeV and in particular also from more extended sources like supernova remnants, the galactic plane or even the diffuse extragalactic flux and this in order of increasing difficulties. It is worthwhile however to point out that all efforts going into the instrumentation at HEGRA still uses only a few percent (at most) of the information contained in airshowers with intern strong sufferings in hadron rejection power. There is still room for very useful and possibly new technical developments e.g. like realized in the MILAGRO project.

3. GALACTIC COSMIC RAYS

Since the early satellite experiments SAS II and COS B the galaxy is known to be a strong source of GeV photons. Above 100 MeV up to at least 10 GeV most of this photon flux originates from neutral pion production by cosmic ray protons with flux close to what is observed near earth colliding with interstellar protons. The density of the target hydrogen is monitored throughout the galaxy by observations of the 21 cm line and of CO which is assumed to be proportional to molecular hydrogen. In this energy range there is also a significant though small contribution to the photon flux from inverse compton scattering of cosmic ray electrons on ambient photons and finally also from electron bremsstrahlung. This model gives a rather quantitative description of the different photon fluxes from our galaxy [24]. However this requires a cosmic ray flux as observed near earth to penetrate the whole galaxy almost uniformly and does not explain the origin of this same flux. On top of this photon flux there are pointlike sources. Most prominent are the pulsars CRAB, VELA, GEMINGA, 1055-52 and 1706-44 [10], exhibiting the remarkable feature that an increasing fraction of the spindown power loss is converted into GeV gamma rays with increasing age of the pulsars. The pulsars become more and more efficient gamma ray stars. In the GeV range most of the gamma radiation is pulsed with interesting changes in the spectral indices depending on the phase, putting strong constraints on the models for the physical origin of the photon flux [10]. It should be very interesting to predict, on the basis of the observed regularities, possible new gamma ray pulsars not yet discovered. From this list of GeV pulsars only the CRAB has been observed up to much higher energies more than 10 TeV using Tscherenkov telescopes [25]. The imaging of the shape of the airshower as well as a very good pointing resolution in combination with on -source -and off -source observations are the basis for succesfull observations at TeV energies. Airshower arrays including AIROBICC have not yet been able to extract a CRAB signal from the data, putting importing constraints on a possible flux at energies > 20 TeV [25]. The photon emission from Crab is rather succesful explained by SSC model [26], where photons from synchrotron radiation of electrons in the magnetic field of the CRAB nebula are backscattered on the electrons to very high energies. The synchrotron photons are observed at low photon- energies well below a few GeV, however the electrons need to be accelerated to very high energies > 20 TeV with spectral index of about 2. Shockwaves in the nebula are essentially the only way to achieve this remarkable feat. The EGRET source catalogue [8] contains also about 20 sources in the galactic plain not yet identified, some of them may be related to supernova remnants as it is required for the basic mechanism proposed to provide galactic cosmic rays to work. Future deeper exposures of EGRET on particular targets should be of great value for the purpose.

4. EXTRAGALCTIC COSMIC RAYS

One of the most remarkable observations was the detection of point source of GeV gamma radiation consistent with the positions of flat spectrums radio sources [27]. Most of these sources can be found in a radio source catalogue collected in the early eighties by Kühr et al. [28] at a lower flux limit of 1 Jy at 5 GHz. These sources are highly variable on short timescales at all wavelenghts and show similar time variability in the GeV energy range as well. This latter observation implies that continuous monitoring at all wavelengths would be of great value to understand the physical origin of the very high energy output of AGN's in particular in the GeV range. Indeed many of these sources emit more energy in the GeV range than at any other wavelength. One of the sources, Mkn 421, has even been observed in the TeV energy range [29]. The energy spectra of all sources are simple powerlaws with spectral indices ranging from 1.6 to 2.4. Inverse Compton scattering like in the CRAB has been invoked to explain the photon fluxes. The models however have to be streched in their set of parameter to physical limits to get it working and in particular the Mkn 421 observation at TeV energies poses difficulties. A more natural explanation can be obtained in a model that assumes shockwave accelaration of protons in the jets of the AGN's with a strong particle cascade developing which is started off by photoproduction of pions in the ambient photon fields [30]. This mechanism may be responsible for the energy output of AGN's at all wavelengthes down to the radio region. At high energies in the TeV range the photons signaling accelaration of protons and the down-cascading processes may however be roughly absorbed in the infrared photon background by photon - photon pairproduction [31]. Given that AGN's have been observed in GeV photons up to distances of Z > 2, in principle a method to scale distances in the universe on the basis of a well calculated basic process the photon-photon pairproduction becomes a real possibility. This implies that the sources are observed at energies below the infrared absorption and well into the absorption region. This low energy part can only be covered by Tscherenkov telescopes at this stage while the arrays (scintillator or AIROBICC) should be able to smoothly connect on to higher energies. The data will then provide at least very interesting constraints of possible physical models of the energy production in AGN's.

5. REMNANTS OF VERY HIGH ENERGY COSMIC RAYS

The origin of the highest energy, > 1 EeV, cosmic rays has always been of particular interest for our understanding of the sites and mechanisms of acceleration of cosmic rays. The idea that quasars as most energetic objects in the universe are the source of the highest energy cosmic rays has been cast into a well defined model in ref [32]. The EGRET observation of flat spectrum radio quasars as generic GeV gamma ray sources supports this idea (see previous section). In this context it has long been speculated [33] that photoproduction of pions in the ambient photon fields may be the source of very high energy neutrinos and photons. Since quasars already existed very early in the universe and may always have fueled neutrino and photon production, together with a great number of quasars would result in isotropic neutrino- and photon fluxes [34]. They are to be considered as remnants of cosmic rays acceleration to very high energy and truly cosmological in origin. It is of greatest interest that fluxes of neutrino and photon remnants may be high enough to be detectable on earth in the near future. A second line of arguments relates the highest energy cosmic rays to the decay of topological defects [35] or other structures [36] that have originally been formed in the very early universe long before quasars came into existence. Explaining this way the flux of the observed highest energy cosmic rays as a by-product also high energy neutrinos and photons seem unavoidable. The fluxes and energy spectra predicted are of order of magnitude to what results from the quasar origin. The muon neutrinos can be detected with deep underground detectors observing the charged current muons. This way a large volume around the detectors can be sampled. An analysis along these lines has been performed on the basis of neutrino induced muons observed in the FREJUS detector [37]. The background for a possible cosmological neutrino signal comes from atmospheric neutrinos, their flux however can be calculated with sufficient accuracy which also was checked quantitatively recently from FREJUS data [13]. Since the predicted cosmological neutrino spectra cross the atmospheric neutrino fluxes at about 1 to 10 TeV also the neutrino induced muons from neutrinos of cosmological remnants will extend to very high energies. They signal their energy through radiative energy loss which is proportional to the muon energy. In the FREJUS detector the radiative energy loss of muons can be separated from ionisation losses (I) down to about 1/5 of I due to a resolved spatial structure of small showers around the muontrack. This allows to set an energy threshold for radiative losses of about 1 GeV/m for 6 m long tracks to efficiently cut off muons of atmospheric origin while keeping sufficient efficiency for very high energy neutrinos [37]. No events of non atmospheric origin have been observed setting stringent limits on possible neutrino fluxes of cosmological origin. In fact, most of the parameter space allowed for in ref. [17] is inconsistent with the FREJUS limit, also some of the allowed region of ref. [35] is excluded. Recently also a search for photon remnants as predicted in ref. [38] have been searched for [39]. Photons are strongly absorbed by gamma-gamma pairproduction in the universal 3 K photon background with absorption length of order 10 kpc until just below 100 TeV where the universe becomes transparent to photons. They may still be absorbed on the badly known infrared photon background however on much larger length scales though. As a result the photon remnant may survive in the energy region just below 100 TeV. The HEGRA collaboration has performed a search for this isotropic photon flux on the basis of data taken with the AIROBICC and the scintillation arrays. The method is described in detail in ref. [39]. Only a limit on isotropic photon fluxes at > 60 TeV at the percent level of the charged particle flux has been obtained. This however was already sufficient to exclude the predictions [38] of a model based on the annihilation of topological defects and further improvements can be expected in the near future.

6. HIGH ENERGY GAMMA RAY BURSTS

Some of the gamma ray bursts triggering the BATSE set of counters on CGRO have been occasionally observed in the higher energy instruments COMPTEL and EGRET as well [40], extending the energy range of the bursts well into the GeV range. Of particular importance has been a burst on February 17, 1994 which was already strong in the low energy instruments, but it was also observed in EGRET up to about 20 GeV [18]. This GeV photon flux occurred partly very much delayed, after occultation by the earth for about 3700 s the burst was still visible for another 1000 s above 30 MeV and with one 18 GeV photon in this time window. Does this point to the possibility of part of the gamma ray bursts extending even further into the TeV energy range ? Anyway, the observation of high energy tails of bursts with a tendency to lag behind in time is yet one more feature of this enigmatic phenomenom that is very difficult to fit in at this stage of the development of models for the bursts. High energy Tscherenkov telescopes like those in HEGRA will in the near future be alerted by BATSE triggers and search for TeV gamma radiation. The field of view of about 3^o of the telescopes may be just sufficient to match the positional accuracy of stronger bursts. That bursts in cosmic rays should be observed occasionally was actually already mentioned in ref. [4] about 60 years ago although only in the context of a supernova origin of cosmic rays.

ACKNOWLEDGEMENT
I would like to thank the organizers of the meeting L. Bergström and P. Carlson for a very enjoyable workshop. Thanks go to P. Biermann, K. Daum, K. Mannheim, R. Plaga and W. Rhode for fruitful discussions.

REFERENCES

1. D.J. Bird et al., P.R.L. **71** (1993) 3401; N. Hayashida et al., P.R.L. **73** (1994) 3491.
2. G. Kanbach et al., A&A (1993)
3. P.O. Lagage, C.J. Cesarsky, A&A, **118** (1983) 223
4. W. Baade, F. Zwicky, Proc. Nat. Acad. Science, **20** (1934) 259
5. P.L. Biermann, Proceedings of the 23 ICRC, Calgary (1993)
6. S. Swordy, Proceedings of the 23 ICRC, Calgary (1993)
7. B. Wiebel, University of Wuppertal report WUB 94-08 (1994)
8. C.E. Fichtel et al., Astrophysical Journal Suppl. **94** (1994) 551
9. P. Sreekumar et al.,P.R.L. **70** (1993) 127
10. P.L. Nolan et al., ApJ. **409** (1993) 697; D.J. Thompson et al., ApJ. **436** (1994) 229
11. D.L. Bertsch et al., ApJ. **416** (1993) 587
12. P. Anselmann et al., Phys. Lett. **B327** (1994) 377
13. K. Daum et al., to appear in Z. f. Physik C (1995)
14. P.L. Biermann, P.A. Strittmatter, ApJ. **322** (1987) 643
15. P.L. Biermann, T.K. Gaisser, T. Stanev, P.R. D in press, MP f. R preprint (1994) 611
16. K. Greisen, P.R.L. **16** (1966) 748; G.T. Zatsepin, V.A. Kuzmin, P.Z.E.T.Fiz. **4** (1966) 114
C.T. Hill, D.N. Schramm, P.R. **D 31** (1985) 564;
17. F. Halzen et al., P.R. **D 41** (1990) 342. R.J. Protheroe, this proceedings.
18. K. Hurley et al., NATURE **372** (1994) 652
19. F. Aharonian et al., Proceedings of the 23 ICRC Calgary (1993)
20. H. Meyer, Wuppertal preprint WUB 94-23 (1994)
21. E. Lorenz, Nucl. Phys. **33** A,B (1993) 113.
22. A. Karle et al., MPI preprint PhE / 94-29 (11/1994) to be published.
23. R. Mirzoyan et al., MPI preprint PhE/94-24 (10/1994) to be published.
24. I. Bloemen at al. A&A **154** (1986) 25
25. For a summary of the observations see A. Karle et al MPI-PhE/95-01
26. O.C. de Jager, A. Harding A&A **396** (1992) 161
27. C. von Montigny et al. ApJ 1994 in press
28. M. Kühr et al A&A Suppl. **45** (1981) 367
29. M. Punch et al. Nature **358** (1992) 477
30. K. Mannheim A&A **269** (1993) 67
31. F.W. Stecker et al. ApJ **390** (1992) L49
32. P.L. Biermann, P.A. Strittmatter ApJ **322** (1987) 643
33. V.S. Berezinsky, A.Y. Smirnov Ap. and Space Sci. **32** (1975) 461
34. F. Halzen et al Phys. Rev. **D41** (1990) 342
35. G. Sigl et al. FERMILAB-Pub-94/080-A
36. P. Bhattacharjee and G. Sigl FERMILAB-Pub-94/387-A
37. W. Rhode et al. to be published
38. F. Aharonian et al. Phys. Rev. **D46** (1992) 4188
39. A. Karle et al MPI-PhE/94-28
40. M. Sommers et al. ApJ **422** (1994) L63