Photons from the Universe
New Frontiers in Astronomy

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This century has seen a dramatic increase in observational possibilities of the physics of the universe. Several of the very recent new developments with emphasis on the particle physics aspect and in particular $\gamma\gamma$ interactions are briefly discussed in this talk.

1 The universal photon background

At any point between galaxies in the universe one encounters a field of photons ranging in energy from the long wave end of the radiospectrum at $10^{-12}$ eV to at least $10^{11}$ eV and possibly $10^{20}$ eV which is the upper end of the cosmic ray spectrum observed at earth. To a large extend astronomy is based on the observation of local deviations from this universal background and was based over millennia on photons in a very narrow energy interval at about 1 eV accessible for detection by the human eye. Since the 1940th the radio range was explored and after 1960 the X-ray, the MeV and GeV range, and the infrared and extreme ultraviolet mostly using instruments launched by rockets and operating outside the earth atmosphere. The photon energy range to be explored with these new experimental possibilities expanded by many orders of magnitude and entirely new processes in the universe became available as tools of astronomy. As one result of the observations it now becomes possible to construct the universal photon flux for all wavelengths up to about 100 GeV photon energy. To achieve this one has to eliminate the local foreground flux of photons with the galaxy obviously as the most prominent local enhancement visible over the whole energy spectrum. In the infrared region only upper limits are available, due to the brilliance of our very local environment in this energy range. The universal photon background was given about 10 years ago by Ressell and Turner. Since then, new information became available, at almost all wavelengths and an attempt has been made to update the compilation in. This is shown in figure as photon flux in units of $cm^{-2}s^{-1}sr^{-1}$ and figure as energy flux per unit decade in eV. The highest flux originates from rather early in the universe at a black body temperature of presently $\approx 2.7^o K$. It is a pure Planck spectrum exact to a very high degree, with dipole distortion due to the motion of the solar system and remaining nonuniformities at the $10^{-5}$
Figure 1: Flux of the diffuse extragalactic background radiation.

level indicating seeds of structure formation in an expanding universe.

In the radio range the source of photons is synchrotron radiation of relativistic electrons in ambient magnetic fields mostly from normal radio galaxies with a sizeable contribution from a small subclass of galaxies with a highly active nucleus (AGNs). The AGNs are also contributing a dominant part of the X-ray region as well as in the MeV - GeV range, which has only very recently been revealed from observations using the Compton Gamma Ray Observatory (CGRO). Beyond 100 GeV the photon background is not yet known; shown here is a theoretical estimate based on a universal flux of cosmic rays at energies $> 10^{19} eV$ that interact and cascade in the universal photon background. This cascade starts with single pion photoproduction of protons on photons from the $2.7 K$ field and develops with short cascade length until all photons have energies $\ll 100 TeV$ where the interaction length becomes very large again. The energy range between 100 GeV and 100 TeV is at present the frontier region of astronomy with photons (TeV - astronomy).
For energies $> 100$ TeV the density of the photon background does not allow to look beyond our own galaxy (see figure 3). Here neutrinos may step in and at energies $> 10^{19}$ eV even protons depending on the structure and strength of magnetic fields in and beyond our local cluster. It thus appears that the energy range $> 100$ GeV is a true domain of high energy physics in the universe where processes usually studied in the laboratory at particle accelerators are used to reveal the nature of extreme objects and environments in space, with the very early universe at temperatures $> 100$ GeV as the most prominent and singular spot in spacetime.

2 The process $\gamma \gamma \rightarrow e^+ e^-$ in the universe

Soon after the discovery of the positron the cross-section for the fundamental process photon + photon $\rightarrow$ electron + positron was calculated. For an incoming photon of energy $E$ colliding with a target photon of energy $\varepsilon$ at an
angle $\Theta$ the threshold energy $E_{th}$ is given by

$$E_{th} = \frac{2 \cdot m_e^2}{\varepsilon(1 - \cos \Theta)}$$

and in units relevant for TeV astronomy:

$$E_{th} \approx \frac{1}{2} \left[ \frac{1 \, \text{TeV}}{\varepsilon} \right] \text{eV}$$

(1)

The total cross-section for the process is given as

$$\sigma_{\gamma\gamma} = \frac{3}{16} \sigma_0 (1 - \beta^2) \left[ (3 - \beta^4) \ln \frac{1 + \beta}{1 - \beta} - 2\beta(2 - \beta^2) \right]$$

(2)

with

$$\beta \equiv \left( \frac{1 - 2m_e^2}{E \varepsilon(1 - \cos \Theta)} \right)^{\frac{1}{2}}$$

and

$$\sigma_0 = 6.65 \cdot 10^{-25} \text{cm}^2$$

the Thompson cross section.

The cross-section rises rapidly after threshold with a peak value of about 200 mbarn at about $2 \cdot E_{th}$ and then it falls off approximately as $1/E$. This behavior of the cross section folded with the $2.7^\circ K$ Planck spectrum then results in the deep absorption trough at about 2 PeV shown in figure 3 taken from [3]. At about 1 eV light from stars dominates and absorbs most strongly at about 1 TeV while the far infrared part of the $2.7^\circ K$ photons should cut off all photons at about 150 TeV. The transparency in the window (1 - 150) TeV is very uncertain, as the universal photon flux in the range from $6 \cdot 10^{-3}$ eV to $6 \cdot 10^{-1}$ eV is not measured yet and can be estimated only from rather involved models of dust- and star formation throughout the lifetime of the universe. Several such calculations have become available recently and can be used to calculate a Gamma Ray Horizon see figure 3 and 13. It is obvious that considerable uncertainty is present on how deep into space high energy photon sources can be revealed. Interesting structures in the universe are
Figure 3: The $\gamma$-ray horizon for photons of energy $>10^{11}$ eV (solid line). It is based on a photon background density as shown by the dashed line (and right hand scale). The region of optical and infrared photons is described here by a model calculation.

nearby galaxies at say 1 Mpc that could not be seen above 100 TeV while below 100 TeV the local cluster and beyond is probably accessible, although the uncertainty on how far one will be able to see is presently very much open. One of the very challenging tasks of TeV astronomy is the exploration of the $\gamma$-ray horizon and various ideas on possible sources at the horizon have been published recently.

3 The pair–Compton cascade

As can be seen from figure 3 the absorption of $>100$ TeV photons by the ubiquitous 2.7$^\circ$K photon background has a characteristic length of $\sim10$ kpc, which is short compared to intergalactic distances. The resulting pair electrons have a similarity short Compton scattering length and therefore an intergalactic pair–Compton cascade develops as long as there are photons left in the cascade with energy $>100$ TeV. The $e^+e^-$ pairs 'see' intergalactic magnetic fields, or stronger fields near galaxies which results in measurable delay phenomena of bursts, the creation of so called pair halos near the source, or changes in the power law spectra due to pile up of cascade photons. This will serve as great tools to explore intergalactic magnetic fields at values $<10^{-11}$ G that
are hardly accessible by other experimental means.

4 Active galactic nuclei (AGN)

Galaxies with an active nucleus have been known for long time and have been the subject of countless investigations. A particularly interesting feature is the high variability of the emission from the nucleus. In the radio and the optical sizeable polarization has been detected, which points to synchrotron radiation at the source. At radio frequencies thanks to interferometry between antenna far apart even up to intercontinental distances spatial resolutions at better than 1/1000 of an arcsec can be obtained. These observations resolved the AGN emission into a succession of 'blobs' seemingly moving with superluminal velocity (v>c) across the sky. If the train of 'radioblobs' consists of relativistic plasma (emitting the radio photons) with Lorentzfactors ≫1 moving towards us at small angle < 10° in a jet like fashion, consideration of Lorentz transformation gives for the transverse velocity (β) of the blob

$$\beta = \frac{\beta_j \sin \Theta}{1 - \beta_j \cos \Theta} \approx \frac{2}{\Theta} \quad (\text{for } \Theta \ll 1 \text{ and } \beta_j \rightarrow 1) \quad (3)$$

with \(\beta_j\) the velocity of the blob and \(\Theta\) the viewing angle. This explains the apparent superluminal motions observed in many jets of AGN. As a further consequence the observed luminosity \(L_{obs}\) of the source is considerably enhanced over the restframe luminosity \(L\) according to

$$L_{obs} = D_j^2 L \quad (4)$$

with

$$D_j = \frac{1}{\gamma_j (1 - \beta_j \cos \Theta)} \quad \text{and} \quad \gamma_j = \left(\frac{1}{1 - \beta_j^2}\right)^{\frac{1}{2}}$$

The AGN should in fact not only have a jet pointing towards the observer but a balancing jet receding in the opposite direction. The same relativistic transformation effect responsible for the high brilliance of the jet towards us renders the receding jets hardly observable. At larger inclination angle however both jets become visible. Small changes in the viewing angle for the jet moving towards us may be responsible for the large and somewhat stochastic
nature of the intensity variations as it may result from moving plasma at relativistic velocity along helical paths. There is indeed evidence for this from radio observations.

It is assumed that the jets originate from a central black hole of mass $10^8$–$10^{11}$ solar masses. The black hole accretes matter from a flat disk spinning at relativistic speed at its inner edge not far from the horizon of the black hole. This setup may be surrounded by a huge dust torus connecting up with stars and interstellar matter of the host galaxy. Different viewing angles then produce a large variety of observational phenomena for the AGNs.

The energy flux versus wavelength for AGN is rather flat within 1-2 orders of magnitude from the radio range over more than 20 orders of magnitude into the GeV range. It renders AGN as prominent contributors to the universal photon flux in the universe at almost all energies (see figure 1). The most notable exception is of course the $2.7\degree K$ microwave background that originates from the big bang.

5 AGN at GeV-Energies

Launched in spring 1991 the Compton Gamma Ray Observatory (CGRO) has provided the first all sky survey in the high energy (up to 100 GeV) gamma ray range using the EGRET instrument. As a result many new sources have been discovered and in addition the diffuse gamma emission from the galaxy and from extragalactic space have been determined rather accurately. Among the sources the identification of 65 AGN at the $>(4-5)\sigma$ level stands out as a great discovery. Several of these AGN have - when flaring - the highest energy flux in the GeV region, they all show dramatic variability in flux, and the spectra are rather flat with power law indices on average about 2. They constitute a fraction $>10\%$ of all known flat spectrum AGN, out to a distance of $z=2.5$. The contrast in amplitude is large about an order of magnitude, seemingly larger then at the other wavelengths. Since EGRET provided only rather moderate sensitivity it is not unreasonable to assume that mostly the peaks of the emission have been seen and future missions with higher sensitivity and also better exposure (e.g. GLAST) may detect all flat spectrum AGN’s. These sources also may provide a sample of candidates for “Beacons at the Gamma Ray Horizons” if the energy spectra could be followed to higher energies. The more distant ones should hit the horizon at ten’s of GeV (see figure 3). It is therefore of great importance to increase the sensitivity of GeV-TeV gamma ray instruments to finally detect the absorption feature in the energy spectra due to the universal photon background in the universe.
6 The new frontier - TeV energies

At TeV energies the flux of photons is low, the strongest steady source in the sky is the CRAB nebula which gives only $0.4 \times 10^{-11}$ photons/cm$^2$sec at 1 TeV. Large collection areas are required, of the order of a few $\times 10^4$ m$^2$, certainly impossible for space based experiments at present. One therefore is confined to experiments on earth’s surface. The key feature of the presently most successful technique makes use of the air as a Cherenkov medium, with changing index of refraction and nicely transparent to the Cherenkov photons. The air is about 23 r.l. thick thus confining the electromagnetic shower generated by the incoming TeV photon. For stability of observational conditions clear air is needed preferentially at an elevation of order 2500 m and above the cloud level. The Observatorio del Roque de los Muchachos (ORM) on La Palma is such a location and has been chosen by the HEGRA collaboration for the deployment of an extended airshower array for TeV observations (see figure 4). Details of the installations and properties of the detectors can be found in [21]. Of particular importance are the Air Cherenkov telescopes with large
detection area of about 30,000 m$^2$, good separation power of photon- versus hadron showers and $\sim 1/10^8$ angular resolution. Like optical telescopes good observations are possible only in clear nights and low moon light. The field of view of the telescopes is about 4° and at any given setting essentially only one source can be observed. Several telescopes combined (presently 4 of the 6 installed at ORM on La Palma) give improved gamma hadron separation and also angular resolution at the expense of some fraction of the detection area. The first source definitely detected in the TeV-range has been the CRAB nebula, the remnant of the AD 1054 supernova that also houses the 33 msec CRAB pulsar. As a mechanism for the generation of TeV photons in the nebula it is assumed that electrons are accelerated to very high energies of order $10^8$ GeV. The electrons produce synchrotron radiation in an ambient magnetic field of the order of tens of $\mu$T. The synchrotron photon spectrum reaches up to a few GeV and is detected by EGRET. Compton upscattering of the synchrotron photons by the primary electrons is taken responsible for the very high photons up to tens of TeV. There must however exist in the CRAB nebula an efficient mechanism to accelerate the electrons to energies $\gg$ TeV with shock wave acceleration usually assumed as such a mechanism. More sources of similar structure are to be expected in the galaxy and indeed TeV photons from SN 1006 and from 1706-44 as similar supernova remnants have been observed using the Air Cherenkov technique at a site in Australia.

In a follow up observation of EGRET sources the Whipple collaboration discovered TeV photons from one of the closest extragalactic sources in the EGRET sample the Markarian galaxy Mkn 421 at a redshift of $z=0.031$ ($\sim$ 300 Mill.ly.) This observation was confirmed by HEGRA. In addition a similar galaxy, Mkn 501 at $z=0.034$ was detected as a rather weak source and again confirmed by HEGRA. Both galaxies have an active nucleus and belong to a subclass of AGN’s, the so called Bl Lac objects named after the first found galaxy of this type at a distance of $z=0.069$. The active nucleus of Bl Lacs is at the center of an elliptical galaxy that has only narrow emission lines of width $< 5\AA$. In May 1996 the Whipple telescope was lucky enough to detect two very bright and extremely rapid flares from Mkn 421 (missed by HEGRA because of daylight at La Palma). Most of the time both Mkn 421 and 501 are near the detection limit of the telescopes however not inconsistent with the typical behavior of the flat spectrum AGN’s, that seem to change continuously their emission intensity e.g. in the radio or optical region. When Mkn 501 became observable again this spring it was seen in a state of rapid flaring (see figure) much brighter than 1996 and frequently much more intense than the ‘standard candle’ CRAB, indeed up to 10 times the CRAB flux was observed making Mkn 501 the most intense TeV gamma ray source in the sky.
Furthermore the energy spectrum was observed to extend well beyond 10 TeV with a seemingly unabsorbed power law with spectral index $\sim 2.5$ similar to the CRAB\textsuperscript{30}. As an immediate consequence, given the distance of Mkn 501, it became clear that the universal infrared background must be very much lower than the upper limits obtained so far and likely very close to the lower end of recent theoretical estimates\textsuperscript{12,13}. This opens up the possibility to really detect the universal infrared background through observation of the absorption in the spectra at some tens of TeV. The position of Mkn 501 can now be found with TeV photons at the level of 0.01°, better than arcmin, which is considered as a sort of entrance ticket to real astronomy. Mkn 501 is observed to continue flaring at a high level and is meanwhile being detected by several instruments using the Air Cherenkov technique\textsuperscript{31}.

7 Terra Incognita at >100 TeV

As shown in chapter\textsuperscript{2} photons with energy >100 TeV get readily absorbed in the 2.7°K microwave background and as a result the horizon out to which one can see into the universe comes down to galactic distances. Only a faint
halo of isotropic 'skyshine' is expected to remain from photons created at $>100$ TeV. However we get knowledge of phenomena of energy at least six orders of magnitude higher since airshowers up to $10^{20}$eV total energy (with a few events beyond) have been observed. At very high energies $> 10^{19}$eV when charged particles (say protons) would become stiff enough to keep direction in intergalactic magnetic fields they may reveal sources in our local universe out to about 50 Mpc, since on longer distances protons would be absorbed through photon pion production in the 2.7°K photon background. This possibility of 'proton astronomy' may soon be explored, when the two 'Auger' arrays of size several thousand $km^2$ become operational. As a further possibility we should be aware that proton acceleration to very high energies $>100$ TeV in e.g. AGN should not only produce $\pi^0$ via photo pion production which may have – as one of the possibilities – been observed with 10 TeV photons from Mkn 421 and Mkn 501. It implies charged pion production as well and therefore we obtain from $\pi, \mu$ decay a muon- and electron neutrino flux of TeV energies. If detected it surely tells of a similar photon flux, while the reverse is not necessarily true since photons could have primary electrons as the only source. Therefore it is of great importance to detect $>100$ TeV neutrinos from distant sources to cover the highest energy window inaccessible to photon detection. A rather promising project (AMANDA) to detect the very high energy neutrinos is under construction using the ice of Antarctica at the south pole station. Last antarctic summer several strings of photomultipliers $\sim 400$ m long have been successfully lowered to a depth beyond 1500 m of ice. This setup should safely detect neutrinos originating from cosmic ray interactions in earth atmosphere and it may come close to detect (with some luck) extragalactic neutrinos. This would open up yet another new window into the universe with entirely new information on the most violent processes in the universe.

8 Bursts of $\gamma$-rays

An enigmatic astrophysical phenomenon, the so called $\gamma$-ray bursts were serendipitously discovered in the early 70th in the course of verification of the nuclear test ban treaty. Short bursts of $\gamma$-rays in the keV-MeV range were observed ranging in time from msec to min. Nothing else was seen at the $\gamma$-burst position that could reveal the nature of phenomenon. A big surprise came with the CGRO which had with BATSE a dedicated all sky monitor for $\gamma$-ray bursts on board. It detected bursts at a rate of about one a day, more than 1500 by now. The distribution on the sky was found to be completely isotropic (at the $< 2\%$ level; see figure) while the intensity distribution is inhomogeneous, less frequent at low flux. The simplest hypothesis places them at cosmological
distances corresponding to a redshift $z \sim 1$ which implies an energy budget of $\sim 10^{48}$ erg/sec at the source. Recently a new attempt was made to find counterparts with the deployment in space of the “Beppo-Sax” X-ray satellite. It allows for arcmin localization of $\gamma$-ray bursts in the lower X-ray band within hours. A burst on 28/Feb./97 was the first case where a fading counterpart was observed in the X-ray range by Beppo-Sax as well as in the optical band using the William Herschel 4.2 meter telescope at ORM on La Palma. Very recently on 8/May/97 again an optical counterpart was detected at first getting brighter and than fading again. This burst for the first time gave a lower limit on the distance of $z \geq 0.835$ observing absorption lines features in the spectrum using the KEK telescope on Mauna Kea, Hawaii. More such observations might finally reveal an underlying mechanism, the present observations being fully consistent with a nonisotropic relativistically expanding plasma as the source of $\gamma$-ray bursts. This resembles similarity with radio blobs in AGN jets however many more accurate pointings and counterpart detections are needed to find a clue.
9 Closing Remark

This century has seen a dramatic extension of knowledge about the universe in particular exploring observational possibilities in e.g. the radioband, the X-ray range and very recently up to the TeV photons. Entirely new information should come from very high energy neutrino observation. A further leap into new territory is sure to come once gravitational waves will have been detected. Exciting times at new frontiers in astronomy are ahead of us.

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