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Gamma Astronomy from Space and from Ground

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Abstract.
Ground based observations has come of age with the advent of the Whipple imaging telescope 10 years ago. The decade that followed has been a period of consolidation, with several detectors of performance comparable to that of the Whipple, mostly HEGRA and CAT in the Northern hemisphere and Cangaroo and Mark-6 in the South. A few important results have been obtained, but the number of firmly established sources remain quite scarce.

EGRET has collected an impressive amount of data mostly concerning the blazars, but it has left many questions open, and many of the observed sources remain unidentified. The new decade will bring in major progress, with the new satellites AGILE and GLAST and with large arrays of telescopes in both hemispheres. In the same time, new ground based techniques are under study either for better angular coverage or lower energy threshold. Finally, new sites are setting in, which have to find their part to play in this context.

Key words: Gamma Astronomy, Space Astronomy, Atmospheric Cherenkov Detectors

1. Introduction

The High energy gamma astronomy is usually identified with the the domain extending from about 50 MeV and above. This corresponds to the HE and VHE domains - for High Energy and Very High Energy - first proposed by T. Weekes (Weekes 1988) and slightly readjusted by Hoffman et al (Hoffman 1999). The HE domain, from 30 MeV to 30 GeV is covered by satellite observatories, SAS-II, COSB and, for the last decade, EGRET. The scientific objectives were quasi uniquely related to the study of cosmic rays which have remained a very intriguing phenomenon for nearly a century, and particularly since Pierre Auger demonstrated by his coincidence experiment that their spectrum extends to TeV energies and above. A series of satellites, from SAS-II to COSB had been devoted to the intriguing question of how cosmic rays could be accelerated to multi TeV energies. This was still the main goal for EGRET and this remains a major issue for the new generation of space and based ground detectors. Indeed much has been learnt about the cosmic ray population but the way they get their energies remains an open question. In the mean time "serendipitous" (a word often used by astrophysicists) discoveries were made from space. Seven pulsars emitting up to GeV energies. Mostly, a first extra galactic source was seen by COSB, 3C279, a radio source from the Cambridge catalogue, a major discovery indeed, followed by a large collection of nearly 100 such objects by EGRET.

Also at the onset of the last decade, the ground based detectors entered in the arena of active Gamma Astronomy, extending the field to the TeV domain. The first evidence of a cosmic point sources came from the observation of the Crab nebula, with a spectrum now extending up to about 50 TeV. Extra galactic sources were observed soon after, such as two rather close Bl-Lac objects of the Markarian catalogue of active galaxies, Mrk-421 and Mrk-501. Both Space and Ground programs must now develop with new equipment, and merge into a new branch of Astronomy.

2. Scientific issues

2-a. Galactic observations

The cosmic rays

The image of the Galaxy as observed from EGRET has been often shown. Through the production of π^0's, the Galaxy is seen as a passive source of γ-rays, distributed along the Galactic disc, with enhancements near the Galactic centre and in the vicinity of known molecular clouds. Attempts to detect from the ground the corresponding diffuse image have not yet been convincing.

The ongoing 2D and 3D modelisations of A.W. Strong and I.V. Moskalenko (Strong 1998, & 2001), with the use of all available data, in particular on CR constituents at moderate energies, tend to give of the CR distribution and transport within the Galaxy a renewed image. Instead of the previously estimated $E^{-0.7}$ rate of escape of the leaky box model, the data fit better with the theoretical Kolmogorov power law of $E^{-1/3}$. To convolute with the well established $E^{-2.7}$ CR distribution, the acceleration process should obey a $E^{-2.4}$ power law, which is severely at variance with E^{-2} expected from 1st order Fermi acceleration mechanisms within the terminal shocks of super novae remnants (SNR) (e.g. Drury 1994). Against the still widely admitted SNR hypothesis, another difficulty is that the distribution of CR wihich results from the numerical model of Strong et al. is extending at larger radial distances than that of the SNR's obtained from EGRET.

Nevertheless, the most promising sites of SNR collisions with dense molecular clouds - as viewed by radio and X-rays - have been scrutinised by EGRET and major efforts have been pursued from the ground, e.g. the observation of Cassiopeia-A by HEGRA (Aharonian 2001). A few positive indications have been obtained, but the general trend is the lack of a convincing support to the SNR hypothesis.

There is room for new hypothesis concerning the mechanisms and sites of CR accelerations. Suggestions have been made for the contribution from bubbles in the Galaxy or from terminal shocks within the Galactic halo of Galactic hypernovae (Dar 2001). The greatly improved angular resolution of GLAST with respect to EGRET opens new hopes of progress. The improved sensitivity of ground based detectors might bring an essential accompaniment.

The pulsars and plerions

The Pulsars.

The hypothesis of collapsed stars into neutronic matter had been suggested by F.Zwicky shortly after the neutron discovery by Chadwick, as early as 1933 (Zwicky 1934), that is quite a long time before pulsating stars were discovered in radio waves (1968). There is more than one thousand detected pulsars in the Galaxy and there must be many more neutron stars having exhausted their rotational energies in the form of radio waves and/or harder radiations. The neutron stars are formed by the collapse of a star of a few solar masses undergoing a (class II) supernova. The collapsed magnetic field may reach 10^{15} gauss, and its fast rotation generates a colossal electromagnetic engine.

In principle, this machinery is essentially characterized by three parameters : the intensity of the magnetic dipole, the speed of rotation and the angle in between their respective axis. The mass and diameter happen to be about the same for all neutron stars, that is ≈ 1.4 solar mass and $\approx 20km$, and their interaction with the inter stellar medium is weak. Should not it be a nice show case of a fully calculable e.m. machine? Instead, there exists a wide dispersion of behaviours and there are several classes of models.

The main difficulty is that ultra relativistic effects occur such as the generations of intense e^+ and/or e^- plasma which are not easily dealt with (although the theoreticall tools exist). This plasma tends to screen the accelerating electric field everywhere but in two regions: a small region in the vicinity of the magnetic poles (Daugherty 1996) and a larger region at some distance from the star surface, near the light cylinder (Cheng 1986, Chen 1993). Accelerated electrons or positrons closely follow the magnetic field line. They can escape the magneto-sphere as there are open field lines in both regions and they will eventually energetize the super nova remnants (whenever the neutron star has remained well inside the SNR). γ-ray emission can proceed through curvature emission, synchrotron and inverse Compton.

The polar cap is a constrained model, the outer gap affording more flexibility, and the two models are not fully exclusive. Although few pulsars only have been seen at GeV energies - by EGRET - critical pro or co observation is expected from the determination of the energy cutoff of the most energetic emissions. The focus is now on two cases PSR 1706 and PSR 1951 as exposed by O. de Jager (De Jager at this meeting). Both are observed by EGRET and the expected cutoff in the frame work of the polar cap model should occur in the no man's land energy band. This should be solved by GLAST, if it is not taken care of in the mean time by HESS for PSR 1706 and by MAGIC or even sooner by CELESTE for PSR 1951.

The Plerions.

Some pulsars remain within the the supernova remnants. They give rise to a "plerion" such as that of the Crab, a complex showing emissions at many wavelength, from radio to high energy γ-rays. Pulsed activities can be attributed to the pulsar proper, while unpulsed emissions are seen as activities recycled within the nebula, possibly including a re-acceleration process within a terminal shock of the electrons ejected from the pulsars. An unpulsed emission, seen in the MeV domain by COMPTEL (aboard C-GRO) and extended by EGRET up to a few GeV according to de Jager et al. (de Jager 1992 & 1996), is attributed to the synchrotron radiation of electrons within the nebula. However, this production is not confirmed in the re-analysis of EGRET data by Fierro et al. (Fierro 1998). The emission observed from the ground in the TeV domain is unpulsed. In term of the spectral energy distribution (EdN/dlogE) it constitutes an enhancement interpreted as the inverse Compton process. First observed by the Whipple group, it extends up to 50 TeV in the case of the Crab nebula as shown by Cangaroo.

The MHD model of Kennel and Coroniti (Kennel 1984), as worked out by O. de Jager and A.Harding (de Jager 1992), gives an essentially parameter free description of the Crab plerion, with a terminal shock which could be identified with the torus of $\leq 0.5pc$ size seen at other wavelength, e.g. by the Hubble Space Telescope (HST) and more recently by Chandra X-ray satellite. This elegant description of the two bump structure of the plerion γ-ray activity will become more convincing when data will be added in the intermediate energy gap from 1 to 200 GeV essentially void of measurements. The expected precise data from GLAST as well as from the new ground based detectors would be highly welcome.

The X-binaries and the micro-quasars

As early as 1964, the study of compact binaries with a very massive partner was proposed by Zel'dovitch and Novikov (Zel'dovitch 1965) and independently by Salpeter (Salpeter 1964), as a mean to probe the immediate vicinity of collapsed stars. These suggestions have contributed to the onset of the X-ray astronomy with the explicit goal to observe the X-ray thermal emission from postulated turbulent accretion phenomena. Such an X-ray intense emission was first detected from Cygnus X-1 in 1970, by Uhuru, an early X-ray satellite.

Since then, X-ray binaries have appeared as superb laboratories for gravitational physics and for plasma physics.

The most recent class of such objects is that of micro-quasars, characterized by the occurence of jets as for the extra galactic quasars. This is an ideal opportunity to study accretion disc and jet formation phenomena possibly upto the HE and UHE domains.

Ultra high energy emissions from Cygnus X-3 and Hercules X-1, were claimed by ground based experiments in the 1980s and this is summarized in the review article by Weekes (Weekes 1988). These events have no doubt contributed to the interest in high energy and ultra high energy gamma Astronomy. However, no such flare from any one of these sources have been seen in more recent years, although the detectors now available are more sensitive. There is place for doubts about the former claims, but the possibility of rare transient phenomena cannot be excluded. A permanent watch program from ground would hardly be justified. A better strategy would be to rely on a quasi permanent survey at GeV energies that the large acceptance of the GLAST detector will permit.

The unidentified sources of EGRET

A large fraction of the EGRET sources are unidentified in the sense that they have no evident counterpart in other wavelength, whether radio, optical or X-rays.

In the issue of Nature of March 2000, I.Grenier and N.Gehrels et al. (Grenier 2000; Gehrels 2000)) differentiate two subgroups of unidentified EGRET sources:

- a rather bright population lying within the Galaxy (they are closely packed along the Galactic equator on the Atoff projection);

- a population which coincides with the near molecular clouds which constitute the Gould belt.

This second population is particularly intriguing. The Gould belt is a ring like structure, of $\approx 0.3-0.4 kpc$ in radii and tilted at 20^o to the Galactic plane. The sun lies into the void of this local bubble, at about half of its radius. This torroidal structure, expanding since $\approx 35Myr$ ago (at a speed of $\approx 100km/s$), is constituted of dense molecular clouds, rich in young massive stars, of O and B types. The opacity of these clouds hides less brillant objects such as black hole binaries, pulsars, plerions and supernovae remnants, letting some γ rays through. GLAST, with its enhanced sensitivity and improved angular resolution, should afford the first opportunity to study, from near, a large collection of energetic sources. The finer localization of the sources will facilitate their studies at other wavelength. The ground observations might greatly improve our understanding of these objects, a goal which cannot be pursued independently from the space survey.

Hunting for exotic objects within the Galaxy

The excess of gravitational mass in galaxies and clusters of galaxies over their "visible masses" have been noted long time ago (by F.Zwicky in the fourties). At least a part of the "dark matter" must have only weak interaction with ordinary matter. This could be due to the WIMPs, the "weakly interacting massive particles". Attempts to a unify the fundamental interactions, electromagnetic, weak and strong, together with gravity, into a global theory of matter call for the existence of new particles. A class of such unification scheme, the Super-Symetry theories, predicts the existence of a "neutralino", stable against self decay but with a probability for pair annihilations into radiation or into hadronic or letonic matter. Depending upon (two) free parameters, cross sections can be computed for processes such as $\chi\chi \rightarrow \gamma\gamma$ or $\chi\chi \rightarrow Z^o\gamma$ (where Z^o is the so-called weak neutral boson). Recent calculations of these processes displayed a channel about 10 times more favourable than the previously assumed dominant one (Bergstroem 1998). Independently of their cross section, the annihilations should occur in proportion of the density to ~~the~~ square, that is with an enhanced contrast with respect to that of the dark matter distribution. They could show up as compact sources of energetic γ-rays, at the centre of stars or of star clusters or at the centre of galaxies or of clusters of galaxies (Baltz 1999).

The sensitivity of present set-ups, in space or on the ground, is barely at the level of testing the most optimistic predictions. The new detectors will improve the chances of sorting out a signal or at least, to constrain the theories more significantly. In case the neutralino would first be discovered with the use of high energy colliders, their manifestation in the cosmos would still be an important issue.

2-b. Extra galactic observations

The Blazars

The breakthrough of the high energy gamma astronomy has come from the discovery of the emission from a well defined class of Active Galactic Nuclei (AGN), the blazars. Nearly hundred such sources have been seen by EGRET (von Montigny 1995; Mukerjee at this meeting).

The AGN's are understood as super massive black holes, lying at the centre of certain galaxies, which undergo a phase of active accretion, probably resulting from a perturbation of the whole galaxy (e.g. due to a collision with another galaxy). The accretion proceeds through the formation of a disk of matter which is the siege of turbulences manifested by thermal emission in X-rays. The formation of jets along the rotation axis is a very frequent feature although its dynamics is rather obscure. These jets can extend to Mpc distances. They contain discontinuous blobs near their basis whose apparent speed can exceed the light velocity. The relativistic boost entails an apparent flux enhancement as $\gamma^3_{Lorentz}$, associated with a focussing of the emission within an angle $\theta(radian) \approx 1/\gamma_{Lorentz}$, typically 5^o for $\gamma_{Lorentz} \approx 10$. Through this same relativistic boost effect ("the relativistic "Doppler effect"), the γ-rays energy is increased as $\gamma_{Lorentz}$ and the observation clock is speeded up by a factor $\gamma_{Lorentz}$.

The term blazar was forged from that of BL-Lacerda (Bl-Lac) which is a member of this class now interpreted as AGN's having one of their two jets oriented towards us. Essentially all the identified EGRET sources above a galactic elevation of 10^o were associated with blazars previously observed in X-rays or in radio.

Only a few blazars have been clearly seen from the ground. They are sources of the Markarian catalogue, Mrk421 and Mrk501, which were not seen by EGRET or just lying at the limit of sensitivity. This led to the feeling that the GeV and the TeV domains of observation were addressing different phenomena. This view does not prevail anymore. Instead, a unification of the field of blazars is emerging under the phenomenological scheme developed by the group of Milan (Fossati 1997). Blazars display a very wide spectrum, from radio to X-rays or γ-rays. A double peak structure is viewed with comparable amplitudes in SED (EdN/dlogE) as synchrotron emission followed by a inverse Compton emission. This presents a striking analogy with the double peak of the Crab nebula emission. Both structures could possibly be produced to a unique population of high energy electrons propagating within a magnetised plasma. The inverse Compton could in fact occur on the very photons from the synchrotron emission process, resulting in the so-called 'self-Compton' mechanism (the SSC).

The few blazars observed from the ground represent extreme cases of the class of high energy X-ray blazars. Altogether, the ground based observations has brought a major enlightenment on the large class of blazars, (and to the even larger class of AGN). This enlightenment is multifold:

- the strikingly fast variability of these sources, occasionally doubling the flux in less than one hour (Gaidos 1996), could not be established in the HE domain for which the efficient detection area is small (as it coincides with to the size of the detector). This fast variability establishes that the site of emission is very compact and must lie close to the black hole, just at the basis of the jet, possibly in a nascent blob;
- the variability has permitted establishing the simultaneity of the flaring in X-ray observed by Beppo-Sax and that of the flaring in γ-ray, of Mrk501 on March 16 1997 establishing the common origin and the common locus of the emissions contributing to both peaks. This is a significant hint in favour of the synchrotron and inverse Compton double manifestation of a unique population of electrons;
- the fact that within the overall class of AGN's, energies of tens of TeV can be reached brings in a major information for theories of emission within a jet. Our personnal bias is

that the purely electro-dynamical models, e.g. the MHD model of G.Pelletier et al.(Henri 1999) are more readily capable than any hadronic model to account for the high energies together with the fast variablities.

Energy limit of VHE Astronomy for the deep Universe

A limit to the accessibility of blazars to ground based observations is set by the opacity of the distant Universe to UHE γ-rays due to their interaction on the extra galactic diffuse light ($E_\gamma E_{IR} \approx 2m_e^2$ for $\gamma_\gamma \gamma_{IR} \rightarrow e^+e^-$). The CMB radiation at 2.7^oK sets a cut-off of $E_\gamma \approx EeV = 10^{15}eV$, similar to the GZK cut-off affecting protons of above $10^{19}eV$. The 10 TeV γ-rays are likely to be affected by the diffuse infrared light from star origin. Both Mrk421 and Mrk501 happened to be at very small redshifts, namely $z \approx 0.03$. However there are no sign of cut-off on the smooth energy spectra of neither of them, and this has been used to set an upper limit of $\approx 5nw/m^2sr$ on the infra red extragalactic light (IR) at wavelength of $\lambda \approx 10\mu m$ (Renault 2001). Results from direct diffuse light measurements are hard to assert because of the intense foreground from Galactic (zodiacal) light. Evaluation via the counting of red galaxies by the ISOCAM detector aboard the ISO satellite affords a lower limit which lies at a few nw/m^2sr under the realistic assumption that most if not all the light originates either directly from stars or through its recycling by interstellar dust. This would set for $10TeV\gamma$-rays an optical depth of the order of $z \approx 0.1$, which is about the redshift of 1ES1426, a blazar actively searched for by ground based observatories (e.g. J. Finley at this meeting). These considerations contribute to set the focus of interest on the low energy part of the ground based observations, i.e. in the TeV region and below, a region of overlap with space observations and for which the ground based will remain unique for variability studies.

For the deep Universe, the Astronomy of e.m. radiation has a limit in energy, around a few TeV.

Hunting for other extra galactic objects

The sudden and short duration bursts of keV γ-rays, had become a particularly puzzling question after BATSE, aboard the C-GRO satellite, had established - from their highly isotropic angular distribution - the cosmological origin of these gamma ray bursts (GRB). The Beppo-SAX satellite, combining γ and X-ray detectors, could first uncovered a part of the mystery by the means of the optical counterpartallowing the pointing of optical telescopes. The cosmological origin is confirmed by the association of some of them with galaxies of large redshifts. Afterglows of several days have also been seen.

The attempts to build models of production (e.g. Piran 1999 & 2000; Daigne 2000) follow similar patterns than for Blazars. A large consensus is for the formation of a relativistic jets, but with a much higher Lorentz factor, upto $\gamma_{Lorentz} \approx 10^3$. The burst would be related to inner shocks within the jet, while the after glow would be due to the terminal shock against the intergalactic medium. Whether the progenitor is a merger of two dense objects as was first conjectured, or to the collapse of a very massive star, an 'hyper-nova', is a matter of debates. There is still very much to learn.

As for Blazars, the high energy gamma astronomy is likely to bring essential contributions. But the space instruments suffered from drastic drawback up to now of the dead time of spark chambers, forbidding the detection of a burst as a series of γ-rays closly packed within a few seconds. GLAST will have solved this difficulty by the use of a fast detector for the tracker. Some information might come also from the ground based observatories, with the same impediment of IR cutoff as for blazars and that of the few minutes of time delay to rotate the telescopes.

The search for WIMPs from extra galactic sites such as the centre of clusters of galaxies have been advocated. This rather exotic topic may seerve to illustrate the general idea that a large increase in sensitivity in the field of High Energy Gamma Astronomy could well be the starting point for new avenues.

Before we turn to the instrumentation, let's insist on that Gamma Astronomy is constituting the last step in energy, at least for the deep Universe. By now, it is in the process of merging with the other astronomies from radio to infrared and visible light and X-ray. Its interest is that, standing at the extreme, it offers critical constraints on our understanding of major physical phenomena.

3. The instrumentation, from then to now

3-a. Space Detectors

From COSB to EGRET and again for GLAST, the detector concept is unchanged. This is based on a two stage detection, measuring first the γ direction and then its energy. The direction measurement exploits essentially the of first γ-ray conversion in an electron positron e^+e^- pair in thin converter plates with x-y measuring planes. This is the tracker.

The γ-ray energy is measured by cascading the incident γ-ray into a dense and 'active' material and suming the ionization losses. This is the calorimeter.

Besides, a veto against charged cosmic rays is achieved by a shield of scintillator tiles. There is no such a possibility of veto for ground detectors.

The Tracker

The angular resolution within the tracker is limited by the multiple scattering affecting the e^+ and e^- of the primary pair within the conversion layers which thus must be very thin, typically of about a few percents of a radiation length. $\delta\theta_{x,y}(radian) \approx 13.6 MeV/E\sqrt{L/X_o}$ where L is radiator thichness and X_o is the radiation length of the material. The e^+ and e^- tracks must be measured before they get scattered through further conversion layers down-stream. The basic scheme is that of an alternation of conversion plates immediately followed by the x & y measuring planes, then comes a drift space which constitutes the level arm for the direction measurement.. This concept presents serious constraints. Even with conversion layers as thin as 3% of a radiation length, the resolution is rather poor below say 100 MeV ($\delta\theta_{x,y} \approx 0.13^o$), and still, the basic pattern must be repeated about 30 times, in order to reach a total depth of one radiation length so as to convert most of the cosmic γ-rays.

For COSB and for EGRET, the tracker was constituted of thin lead plates within a wire chamber working in the spark mode. The gas for the chamber had to be renewed regularly and the high voltage pulse had to be fed onto it at each event, implying a dead time for recharge. The fact that EGRET could be maintained in a running condition for about 10 years in space, is a superb achievement.

For GLAST as well as for AGILE, instead of wire chambers, silicon crystal detector with etched strips will be used. With this technique there is no need for consumable, and there is essentially no dead time (apart that for the event readout). The pitch can be much smaller than the distance between wire ($0.2mm$ instead of $10mm$), so that the drift space can be reduced as well. TThis results in a more compact device offering a much larger angular acceptance. The difficulties to be mastered are numerous. The basic silicon elements are small, they must be assembled in mosaics. The total area to cover is about 100 m^2 ($\approx$ 20 x and y layers, times 1.6 x 1.6 m^2). For a minimum ionizing particle, the output signal is weak requiring amplifiers. With the detector subdivided into 16 square "towers", this is about 1 million channels to handle and to read-out, a premiere in space technology.

The Calorimeter

The calorimeters which have been used in this field of space physics have been constituted with scintillating crystals. They are sensitive in the whole volume (as oppose to sampling techniques making use of alternate absorber and scintillating materials) which is appropriate especially for γ-rays of low energy. The burden here, for a space program, is the weight, typically a 10 X_o depth is adoptedcoresponding to 1 ton per m^2, while 20 X_o would be appropriate in order to fully contain the showers up to 10 GeV.

For energetic showers, the loss due to leakage can be detected and partly corrected for, if the longitudinal profile of the showers can be measured. This is obtained in the case of GLAST by a subdivision of the calorimeter into 8 successive layers, affording 8 longitudinal samplings. Needless to say that although free from systematic bias, the resolution at high energies will be rather poor.

The arrangement of the calorimeter in layers is furthermore exploited to confer to the calorimeter some hodoscopic capability. Each layer is subdivided in parallel logs, of about 3 cm width, disposed in alternate x and y directions from layer to layer.

Due to a strict limitation in weight to 60 Kg, AGILE will make use of a very thin calorimeter of 0.2 radiation length, still allowing to measure energies upto 200 MeV.

Alternatives for future space program

From the consideration above, the improvements for the coming generation of space detectors is not based on new principles but merely on more recent and more adequate techniques. The weight constraint from the calorimeter has not been much eased, except by a better exploitation of its area thanks to the larger angular acceptance of the tracker above it. As for the tracker itself, its improvement, directly borrowed from the accelerator experiments, relies on multi cell solid state detectors associated with progresses in integrated electronics and and on line computers. Altogether, no new physical process is at stake. Needs for further major steps - mostly in sensitivity and angular resolution - have already been expressed. Futuristic avenues are being investigated such as pair creation within a huge gaseous drift chambers, or the successive detections of two or more Compton scatterings in solid cystal detectors.

3-b. Ground Based Detectors

The Imaging Techniques
As is well known the results beyond the 5 σ statistical criteria was obtained with the use of a large single dish detector, the Whipple 10m, equipped with a camera of 37 pixels. The imaging presents the double virtue to afford a measurement of the source position and also to select out the showers from cosmic ray hadrons.

The main successes along the last decade came from "imagers", with Cangaroo and M5-6 in the Southern hemisphere, and CAT and HEGRA in the Northern hemisphere and, not the least, the Whipple telescope with its 100 pixel camera. Much work has been done to fully exploit the imaging method, in particular with the CAT telescope exploiting with an high resolution camera an optics of negligible aberrations and small anisochronicity. Software procedures have undergone much progress, starting the shape analysis of Michael Hillas, followed by the super-cut method of Michael Punch and, more recently, the χ^2 fit to templates of Stephane LeBohec. This template procedure developed for a high resolution camera, and applied to CAT data, was capable of distinguishing top from bottom on each shower image, and to fully determine the source position, of each shower.

To push the imaging strategy to its extreme possibilities with present techniques is the ambition pursued by MAGIC. With a 17 m diameter bowl equipped with adaptable mirrors, and exploiting the most recent photodetection techniques, the claim is this detector should be able to increase the sensitivity by a factor 2 or more and to lower down the minimum detectable energy to ten GeV. The first light is envisaged for 2002, but the running-in of this sophisticated instrument will take some time. With a time delay of about 5 years, the MYSTIC project of the Bhabha institute should emerge. Inspired from MAGIC, but conceived with two bowls, MYSTIC is safe from excessive muon triggers (a strategy already envisaged by MAGIC but not funded)

The Sampling Techniques with Multi-telescope rays
The first confirmation of this signal from the Crab nebula came from the use of an array of small telescopes each one being equipped with a single photomultiplier. The Themistocle array could extend the spectrum to even higher energies, but with a far smaller sensitivity than that of the Whipple imager.

Nevertheless, the multi telescope approach has been further studied, either on its own, i.e. with single pixel cameras, or in conjunction with imaging. These developments are illustrated respectively by the solar plants and the HEGRA imaging telescope array.

The HEGRA five telescope array has been running in the Canary Islands since 1994. The simultaneous observation of images of the same showers permit the stereo reconstruction of the shower trajectory, and thus of its direction which is identical to the source position. This is similar to the achievement of CAT with the template method. But another and major advantage is the double (or multiple) image provides an enhanced rejection against hadron showers and single muon images which remains the main sources of background for the single telescope imaging technique. This further reduction of the continuum affords much improvement in sensitivity.

Both the HESS project which first telescope is now under construction in Namibia, and the VERITAS project to be built near the Whipple site, take advantage from the

CAT and HEGRA developments (with the use of 10m diameter mirrors or larger). The distances between telescopes are such that a shower can be normally seen by at least two of them, and the quality of the optics as well the fine resolution of the cameras will permit the shape analysis initiated by CAT. These new arrays should reach an energy threshold of 50 GeV and possibly less, and the sensitivity should be improved by about a factor 10 with respect to existing equipment.

We may quote here the TACTIC device, now in a running-in phase at Mt-Abu. TACTIC has four telescopes of mirror area similar to HEGRA (only one equipped with a full scope imaging camera).

The solar plant projects

In several places in the world exist solar plants, some of which are based on the central collection of the solar light reflected by many heliostats each one with mirrors of the size of the Whipple dish. All the reflected light is focussed at a central position on top of a tower where it is trapped into the solar plant furnace. The Cherenkov light from an air shower can be trapped just as well, since the angular extension of a shower is about equal to that of the sun. But for shower detection, more information is needed than the mere sum of all reflected photons. A clean separation between photons from each heliostat can be achieved if, in place of the furnace, a secondary optics is set looking at the field as was first suggested by T. Tümer. Near the focal plane of this optics, each heliostat has its own individualized image, a locus attained by any light ray originating from its surface, so this is where to collect the light reflected by this heliostat. Such a device is equivalent to a set of telescopes with a single pixel photodetector as for Themistocle (but with large mirrors).

Two similar size projects are in a running in phase, CELESTE, in the French Pyrénées on the same site as CAT, and STACEE at Sandia in New Mexico. CELESTE is the most advanced of the two, with a well established signal above 50 GeV from two independent cosmic sources, the Crab nebula and Mrk-421 (in an active phase at a level superior to the Crab). This is the first observation of a cosmic sources in the present energy gap lying from 20 to 200 GeV.

The detector of the Tata institute, which is now running at the site of Pashmari, presents some similarities with CELESTE or STACEE (although it is not based on a pre-existing solar plant).

In case the method is proven to be powerful for the exploration of the unobserved energy domain, the most natural extension that can be envisaged would be to make use of the site of SOLAR-II at Barstow in California, a possibility presently investigated by the group of T. Tümer who is carrying preliminary observations.

While the scientific objectives are essentially the same, with a complementary approach, there remain a large diversity of ground detectors while a same basic method has been used in space for decades. This is partly due to the fact that actors are more disperse and more numerous in the ground based projects. But it is due also to the higher complexity of the physical process, and the severe competition of hadrons and muons against γ-rays. Nevertheless, a general scheme is probably emerging, combining imaging and sampling.

Large Acceptance Ground based Detection

A severe drawback inherent to the Cherenkov techniques, alike for any optical methods, is its small angular acceptance of a few degrees at most. As a result, large surveys are very costly in observation time so that most studies aare limited to sources from existing catalogues. To by pass this shortcoming, use must be made of the shower chaarged secondaries, electrons and of energetic secondary photons which can be materialized. Detection must take place before the shower has exhausted its development. High altitudes sites are necessary in order to be still sensitive to reasonably low energy showers. The Tibet-II scintillation array at 4300 m above sea level, has seen the Mrk501 flare of 1997 with ≈ 3 TeV threshold (Amenomori (2000). On this same site and presently in its installation phase, the ARGO project - based on RPC detectors - is aiming at a drastically reduced energy threshold (Bacci 1999). In the mean time, a water pool detection at Los Alamos, the MILAGRO project (Yodh 1999) is in its running-in phase. The field of VHE Astronomy would be enriched - if not deeply renewed - by the advent of large angular acceptance detectors.

4 . Conclusion

Our purpose in these pages has been to establish that space and ground based astronomy are closely associated partners of a now mature gamma ray astronomy. For the deep Universe, VHE with its domain limited to 30 TeV, constitutes the endpoint of the e.m. astronomy while higher energies are observed in CRs up to the GZK limit of $10^{19} eV$. A programm based exclusively on UHE Galactic γ-rays would be risky. On the contrary, the topics are very numerous including hints for new phenomena in the intermediate energy region which will soon be covered from the ground and from space. Far from a sterile competion, this double approach is rich of promises with complementary information, the space allowing large surveys while the ground will have a better sensitivity to the highest energies and to time profiles - or light curves - of transient phnomena.

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