I RETROSPECTIVE

As we enter a new century of high energy astrophysics, it behooves us to consider briefly how far we have come and far we have yet to go. It is some 47 years since Galbraith and Jelley mounted a ten inch mirror in a garbage can with a photomultiplier at its focus and under the impossibly damp skies of the Berkshires detected the first Cherenkov light pulses from air showers [1]. Within a decade the broad outlines of the atmospheric Cherenkov technique, as it applied to the search for very high energy gamma rays, had been defined and significant experiments built to pursue these searches. Reading again these early papers [2] [3] [4] one cannot but marvel at the prescience of the authors and the courage of the exponents who were taking on what must have seemed an impossible task. It is amazing how much was anticipated in these classic papers and how much is ”rediscovered” by later exponents of the technique with large teams of experimenters, sophisticated telescopes, and vast simulations. Using simple, but elegant, telescopes, analytical models, and considerable foresight, much of what was later to become the basis of the multi-million dollar observatories now in operation was anticipated. The early pioneers of the field, W. Galbraith and J.V. Jelley of the Atomic Energy Research Establishment, Harwell, England, N.A. Porter of University College, Dublin, Ireland, A.E. Chudakov and V.I. Zatsepin of the Lebedev Institute, Moscow, U.S.S.R., were the giants on whose work all future progress depended; their names should be inscribed large within the High Energy Astrophysics Hall of Fame! It is but an accident of nature that these early experiments failed to detect significant signals from supernova remnants and quasars since their sensitivities were remarkably close to subsequent detection levels.

To consider the state of high energy astrophysics in 1960 is to appreciate their courage in undertaking very high energy gamma-ray experiments at that time. In fact ”high energy astrophysics” per se did not exist as a discipline at that time. Although the seminal papers containing estimates of fluxes of 100 MeV and TeV gamma-rays to be expected from cosmic sources were already in print [5] [6], they were, with hindsight, hopelessly optimistic. One can only hope that contemporary estimates of TeV fluxes of neutrinos from cosmic sources are on a more solid base!
Gamma-ray astronomy at any energy was in its infancy with no sources detected. X-ray astronomy did not exist and was not even seriously considered. Since cosmic rays were both the prime motivator to look for gamma-ray sources and the chief source of information as to what properties such sources might have, the conventional wisdom was that the dominant energy spectrum would be that of the cosmic radiation, i.e. a differential exponent of -2.7. Such an exponent did not bode well for the chances of detecting very high energy gamma-rays. Since space gamma-ray telescopes could be shielded with active detectors to exclude the charged cosmic radiation, the chances of detecting a signal in a non-shielded ground-based detector seemed vanishingly small. Optical detection methods which depended on an unstable atmosphere and on the detection of a weak optical signal against a background of natural and man-made light sources did not seem promising. Only a fool or someone with great courage would choose to pursue such techniques in the face of such uncertainty.

The eventual detection of a mixed population of very high energy (VHE) gamma-ray sources is a vindication of these early efforts and a tribute to the pioneers.

II GAMMA-RAY ASTRONOMY’S GREAT FAILURE!

Although GeV-TeV gamma-ray astronomy has had a number of outstanding successes (the detection of blazars, the GEV component in solar flares, the GeV-TeV component of GRBs, pulsars, shell and plerionic supernova remnants, the galactic plane, to mention but a few), the single great motivator, the conclusive solution to the problem of the origin of the cosmic radiation, is still elusive. It was this problem more than any other that led to the development of high energy gamma-ray astronomy, both in space and on the ground, but in some ways, at least observationally, we are no closer to identifying the source than we were 40 years ago. While we can celebrate the contributions of gamma-ray studies to pulsar phenomenology, to limiting the infrared background, to the study of jets in extragalactic sources, we cannot yet proclaim with any confidence "Gamma-ray astronomers find the Origin of the Cosmic Radiation".

As pointed out previously [7] every gamma-ray source detected to date can be explained as a source of cosmic electron acceleration and interaction; there is no source that can be conclusively attributed to hadron acceleration. The $\pi^0$ bump is only observed in the galactic plane and there we observe the propagation, not the source, of the cosmic rays.

The title to this section is deliberately provocative and hopefully will be obsolete before this volume is off the press. The number of sensitive ground-based telescopes now on-line, or shortly to come on-line, ensures that a vast number of new candidate sources are under ever increasingly sensitive scrutiny and may soon supply the vital data necessary to solve this problem.
FIGURE 1. Map of the sky at TeV energies in galactic coordinates showing 13 discrete sources (from R.W.Lessard, private communication)

III WHAT THE IMAGING A.C.T. HAS DONE FOR ASTROPHYSICS:

A Existence of Sources

The outstanding contribution of the imaging atmospheric Cherenkov technique (IACT) must surely be that it has elevated ground-based gamma-ray astronomy techniques above that critical threshold where sources are detected with some credibility. In short the IACT has confirmed that there is a gamma-ray sky at energies above 200 GeV (Figure 1), that the upper energy limit of space gamma-ray telescopes is an instrumental limit, not an astrophysical one, that there are a variety of different kinds of source populations, that there are both galactic and extragalactic sources, both steady and variable sources, and both point-like and extended. Furthermore the energy spectra extend to 50 GeV where the flux sensitivity of the IACT is not large so that the construction of new telescopes that are sensitive above this energy is now justified.

Half of the reported sources are galactic. These include plerions, shell SNRs in which the progenitor particles are probably electrons and an X-ray binary. The extragalactic sources are all blazars. All but one are X-ray-selected BL Lacs; this population is quite different from the population of EGRET-detected blazars.

Although a large fraction of the sky has not been surveyed with high sensitivity, there are a number of objects for which significant upper limits have been established. These have the effect of severely limiting some classes of models and thus contribute to high energy astrophysics in a negative sense. These non-sources include shell-type SNRs, in which the progenitor particles are hadrons, the galactic plane and various pulsars.

The energy range covered by atmospheric Cherenkov telescopes extends from 50 GeV to 50 TeV. Thus far, the IACT has only been used down to 200 GeV but
TABLE 1. Source Catalog c.2000 (Heidelberg)

| Source               | Type  | z     | Discovery | EGRET | Grade |
|----------------------|-------|-------|-----------|-------|-------|
| **Galactic Sources** |       |       |           |       |       |
| Crab Nebula          | Plerion | 1989 | yes       | A     |       |
| PSR 1706-44          | Plerion? | 1995 | no        | A     |       |
| Vela                 | Plerion? | 1997 | no        | B     |       |
| SN1006               | Shell  | 1997 | no        | B−    |       |
| RXJ1713.7-3946       | Shell  | 1999 | no        | B     |       |
| Cassiopeia A         | Shell  | 1999 | no        | C     |       |
| Centaurus X-3        | Binary | 1999 | yes       | C     |       |
| **Extragalactic Sources** |          |       |           |       |       |
| Markarian 421        | XBL   | 0.031 | 1992      | yes   | A     |
| Markarian 501        | XBL   | 0.034 | 1995      | yes   | A     |
| 1ES2344+514          | XBL   | 0.044 | 1997      | no    | C     |
| PKS2155-304          | XBL   | 0.116 | 1999      | yes   | B     |
| 1ES1959+650          | XBL   | 0.048 | 1999      | no    | B−    |
| 3C66A                | RBL   | 0.44  | 1998      | yes   | C     |

it is possible to reach as low as 50 GeV using Solar Arrays. By observing at low elevations the IACT can reach energies as high as 50 TeV.

B Source Catalog

It is a matter of some disappointment (given the number of new observatories now in operation) that the source catalog (Table 1) shows no changes since the one assembled at the time of the Snowbird Workshop [7]. In particular the credibility rating of sources has not changed.

C Time Variability

One of the extraordinary contributions of VHE gamma-ray observations to high energy astrophysics has been the revelation of the variability of blazars on a wide range of time-scales. This has truly opened a new window to the study of these objects and has been a major incentive to improve and extend the observations.

**Short-term Variations:** The dramatic flare from Markarian 421 observed by the Whipple group on May 15, 1996 [9] is still the best instance of a rapid time variation (doubling time < 15 minutes) from an AGN (Figure 2). The observation of such short flares from more distant AGN may have some important consequences for cosmology and quantum gravity [10].

**Longterm Monitoring:** The ability of VHE telescopes to provide longterm monitoring of variable sources is a little appreciated property of ground-based ob-
D Multiwavelength Observations

For an understanding of the mechanisms at work in AGN jets, multiwavelength campaigns are required. These are notoriously difficult to organize since many traditional observatories require advanced notification and approval and do not readily respond to Targets of Opportunity. VHE observatories have the advantage that they are usually controlled by the principal investigators, do not have rigid observing schedules, and have only a small number of known sources (regrettably!).

The correlation of X-ray and VHE observations has been reported in a number of
instances (cf. [13] and references therein). One such instance is shown in Figure 4.

X-ray observations of sources with non-thermal spectra have proved particularly useful in identifying candidate VHE supernova remnants. Hard X-ray observations hold the promise of identifying a new class of extreme blazars which will have detectable and variable TeV emission. The launch of EXIST, the first hard X-ray survey instrument, in the next decade will extend this symbiotic relationship.

### E Energy Spectrum

The ability of the IACT to measure energy spectrum in the TeV region has steadily improved and is comparable or better than that achieved in space gamma-ray telescopes. Energy resolutions of single telescope systems are quoted as 35% and for the HEGRA array as low as 10-15%. It is reassuring that observations made
by different experiments using different methods of analysis are in good agreement (Figure 5).

IV STATUS OF VHE OBSERVATORIES

The IACT continues to be the favored method of detecting gamma-rays in the 100-10,000 GeV energy range although there are several overlapping techniques at the low and high energy ends of this range. The principal observatories who have reported results using this technique at recent workshops are listed (Table 2). Sadly at this meeting we learnt that both the Durham and 7TA observatories, after the successful detection of several sources, have ceased operations. Also listed (Table 3) are several atmospheric Cherenkov observatories which do not use imaging; the Potchefstroom experiment has also recently ceased operation.

In the interval between the death of EGRET and the launch of GLAST it is interesting to explore the lowest energies that can be achieved from the ground. Although it is unlikely that ground-based observations can be really competitive below 50 GeV, there is a window of opportunity between 10 and 100 GeV before the next generation of space telescopes come into operation. Even relatively simple telescopes could elucidate such problems as pulsar spectral cut-offs, AGN absorption in intergalactic space, gamma-ray bursts, etc. The simplest approach is to use large mirror collection areas and these are provided by the relatively crude optics of large solar collectors using heliostats. The four experiments listed in Table 4 use
existing solar farms (large fields of heliostats pointing, and roughly focussing, light to a central tower). STACEE uses a facility that is still in operation for experimental solar energy work whereas the other three use facilities that are no longer in use.

The energy threshold of particle air shower detectors (Table 5) has gradually been reduced to the point where there is now overlap with IACT experiments. The Tibet experiment has been in operation for some years whereas MILAGRO has just come on-line.
TABLE 4. Atmospheric Cherenkov Solar Array Telescopes c. June 2000

| Group   | Countries       | Location       | Heliostats | Threshold | Ref. |
|---------|-----------------|----------------|------------|-----------|------|
| STACEE  | Canada-USA      | Albuquerque, USA | 32 (48)    | 180       | [28] |
| CELESTE | France          | Themis, France | 40 (54)    | 50±10     | [29] |
| Solar-2 | USA             | Barstow, USA   | 32 (64)    | 20        | [30] |
| GRAAL   | Germany-Spain   | Almeria, Spain | (13-18)x4  | 200 GeV   | [31] |

TABLE 5. Non-Atmospheric Cherenkov VHE Telescopes c. June 2000

| Group   | Countries        | Location     | Telescope   | Altitude | Threshold | Ref. |
|---------|-----------------|--------------|-------------|----------|-----------|------|
| Milagro | USA             | Fenton Hill, NM | Water Cher. | 2.6      | 0.5       | [32] |
| Tibet HD | China-Japan    | Tibet        | Scintillators | 4.5      | 3         | [33] |

V NEXT GENERATION TELESCOPES

The next few years will see the completion of several new "next generation" IACTs which will significantly improve the scientific potential of the discipline. These major observatories will probably dominate the field for the next decade and they represent a major transition from the traditional "small science" which characterized the early years of the IACT to multi-national facilities which will serve a larger community as guest investigators. Three of the facilities: CANGAROO-III [34], HESS [35], and VERITAS [36], build on the IACT array concept that has been demonstrated by HEGRA and are very similar in concept; the first two will be in the southern hemisphere, the third in the northern hemisphere. MAGIC is a single large imaging telescope which will use several new technological approaches [37]. Some of the most important parameters of these telescopes are listed in Table 6. A new addition to the list of new IACTs is MACE, an Indian look-alike of MAGIC; its parameters were described at this meeting.

Sensitivity: New experiments are often characterized by their energy thresholds and flux sensitivities. The definitions of these quantities are not trivial and often cause confusion. Energy threshold, usually defined as the maximum in the differential response curve for a Crab-like spectrum, is particularly misleading since
TABLE 6. MAGIC, HESS, CANGAROO-III and VERITAS

| Parameter       | MAGIC | HESS | CANGAROO-III | VERITAS |
|-----------------|-------|------|--------------|---------|
| Base            | Munich| Heidelberg | Tokyo       | Arizona |
| Country         | Germany| Germany | Japan        | U.S.A. |
| Partners        | Spain, Italy | France | Australia   | UK, Ireland |
| Science         | AGNs, Bursts | SNR | Gal. Sources | AGNs, SNR, Bursts |
| Location        | La Palma | Namibia | Woomera   | Arizona |
| Elevation       | 2.3 km  | 1.8 km | S.L.       | 1.4 km |
| # of tel.       | 1     | 4 (16) | 4          | 7       |
| Pattern         | -     | Square | Square     | Hexagon |
| Spacing         | -     | 120m  | 100m       | 80m     |
| Design          | Parabola | Davies-Cotton | Parabola | Davies-Cotton |
| Aperture        | 17m   | 12m   | 10m        | 10m     |
| Focal length    | 20m   | 15m   | 8m         | 12m     |
| OSS             | Carbon fiber | Steel | Steel     | Steel |
| Facets          | 60cm square | 60cm circ. | 80cm circ. | 60cm hex. |
| Material        | Al-milled | Ground-glass | Composite | Glass |
| Supplier        | Italy | Czech/Arm. | Japan     | USA |
| PMTs            | EMI    | Phillips | Hama.     | Hama.? |
| Cabling         | Fiber  | Coax | Coax       | Coax |
| Electronics     | FADC   | -   | -         | FADC |
| # of pixels     | >800   | 800 x 4 | 512 x 4  | 499 x 7 |
| First light     | 2001   | 2002 | 2003       | 2005 |

the event selection can be biassed to give a very low energy threshold but with very small collection area.

Figure 6 gives the integral flux sensitivity for various existing experiments as well as the predicted sensitivity for GLAST and VERITAS [39]. This figure has been widely reproduced. However integral flux sensitivities presuppose knowledge of the source spectrum and are not useful for sources with steep spectra which fall off near the energy threshold. The flux sensitivity for VERITAS is in close agreement with that derived for HESS [38] as would be expected. However the sensitivity quoted for CANGAROO-III [34] is much better, particularly at lower energies; this prediction needs to be reconciled with those of VERITAS and HESS since the array parameters are not that different.

Schedule: Of major concern to all those interested in VHE astronomy is the roadmap of HE and VHE experiments in the next decade. Although all proposed launch and construction completion dates are inevitably optimistic, it is hoped that the future depicted in [7] is not grossly inaccurate. The solar telescopes are already reporting results. The MAGIC web page proudly, if somewhat optimistically, gives a countdown to first light in 2001. Concrete has already been poured for the HESS foundations and one CANGAROO telescope is in place and taking data. Although the first of the next generation projects to be announced, VERITAS, has yet to break ground, first light in 2005 is still feasible. The space telescopes, reported elsewhere in these proceedings, seem to be well on schedule. The scheduled
completion date for MACE, the Indian MAGIC look-alike, is 2003.

Although AMS [40] and AGILE [41] will partially fill the HE gap left by the demise of EGRET, they will not provide a significant boost in sensitivity. In the next few years the most exciting new results may well come from the solar telescopes as they explore a new energy domain. Prior to the launch of GLAST [42] there will be a spate of new results forthcoming from the new generation of IACT arrays.

Acknowledgements: Research in very high energy gamma-ray astronomy at the Smithsonian Astrophysical Observatory is supported by the U.S. Department of Energy. I am grateful to Tony Hall, Deirdre Horan, Jim Gaidos and Rod Lessard for helpful comments on the manuscript.

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