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III. HIGH ENERGY γ-RAYS AND BURSTS

The atmospheric Cherenkov technique in γ-ray astronomy: the early days†

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1. Introduction

At this meeting papers were given by Turver & Weekes and Sreekantan about the current status in the detection of ultra-high-energy γ-rays in the energy range 10^{11}–10^{13} eV, by means of the atmospheric Cherenkov technique.

There are two objectives of this short contribution. The first is to describe briefly the early history of the subject, and the second to outline the basic physics involved, which will reveal how the technique is essentially quite different from those used in the other energy bands in the γ-ray spectrum.

The technique depends on the detection of the Cherenkov light produced by the vast swarm of charged particles, mainly electrons and positrons, generated in the atmosphere as a result of primary high-energy γ-rays entering the top of the atmosphere. This cascade of particles, known as an extensive air shower (e.a.s.) is initiated by pair-production, and the growth of the shower takes place via successive steps of bremsstrahlung and further pair-production.

In an e.a.s. there are coexistent components of nuclear particles and mesons, and the detailed development of an e.a.s. is extremely complicated.

The Cherenkov technique is the only one that is available for studies of γ-rays of such high energy. It is unique in that it is ground-based, directional, and relatively simple and cheap, at least compared with any satellite experiment. Its great potential lies in the fact that the effective collecting area is that of the pool of light on the ground rather than that of the detector itself, a factor that can easily be 1000 or more. In all other techniques in γ-ray astronomy, the photon has to react directly within the detector, which has of necessity a restricted area.

The one serious limitation is that there is no simple way of distinguishing between the γ-induced e.a.s. and the far more abundant proton-induced e.a.s. except by the fine angular structure expected from γ-ray sources.

2. Reminiscences of early days in the field

Blackett (1948) had suggested many years ago that Cherenkov radiation in the atmosphere, from the general flux of cosmic rays (c.r.), would contribute a fraction of *ca.* 10^{-4} of the total background light of the night sky at a dark site. But, as the c.r. could not be turned off, and the contribution was so small, there was clearly no way of detecting this effect.

It was many years later, when Blackett was visiting A.E.R.E., Harwell, that he casually mentioned this paper to W. Galbraith and myself, when we were working together in the

† Although lack of time prevented oral presentation of Dr Jelley's paper, the organizers are delighted to be able to include the paper by this distinguished pioneer in γ-ray astronomy.

cosmic-ray group under W. J. Whitehouse. During this brief visit, neither Blackett nor we ourselves mentioned the e.a.s. as a possible source of Cherenkov radiation.

However, a few days later, it occurred to us both that an e.a.s. might well produce very strong pulses of light, because a very large number of particles, especially electrons and positrons, would arrive almost simultaneously, the duration of this burst being extremely short, *ca.* 10 ns.

In great excitement we therefore set up an experiment with equipment of extreme simplicity. In those days, not long after the war, there were countless shops in Lisle Street and High Holborn in London crammed with ex World War II optical and electronic equipment. We soon purchased some 25 cm $f/0.5$ parabolic signalling mirrors. We mounted one of these at the bottom of a dustbin, standard stores issue, and clamped an EMI photomultiplier, itself a relatively new device, to a retort stand inside the dustbin, with its photocathode placed at the focus of the mirror. Coupling this to the fastest amplifier available at the time (0.03 μs rise-time) and pointing the contraption to the zenith sky, at a dark site near Harwell, we were rewarded with success on the very first night.

Large single light pulses were observed at once, at a rate of between one and two per minute; these were bandwidth limited, distributed randomly in time, possessed a fairly broad zenith-angle dependence, and had a pulse-height spectrum similar to the numbers against energy spectrum of c.r. primaries.

After simple control experiments, with the lid on the dustbin and a small filament lamp inside, we soon showed that these were indeed light pulses from the sky. The claim that these pulses were associated with e.a.s. was soon substantiated, when a few nights later we observed coincidences between the light flashes and shower particles detected on a small e.a.s. array which was in operation at the same site (Cranshaw & Galbraith 1954). This original experiment was described in detail by Galbraith & Jelley (1953).

Looking back, we realize what a blind experiment it was, as we had little idea of what intensity we should expect. Furthermore, it was fortunate for us that the rate was just a few per minute. Had it been say only one per hour, we might well have not seen them, as we were observing the pulses visually on a 'scope, and had they been at say a few per second, some meticulous optical astronomer might well have noticed them in a wide-field telescope.

We soon demanded greater sensitivity and larger fields of view. In that carefree past we were rapidly able to procure 60 and 90 cm diameter mirrors. Quite soon, at our instigation, numerous 1.5 m ex-Army searchlights were rolling down the roads from surplus equipment depots in Coventry, and shortly afterwards some even crossed the Irish Sea.

These experiments, and references to much of the other early work can be found elsewhere (Jelley 1967). Many developments followed in rapid succession, and the field was taken up in various countries, by N. A. Porter's group in Dublin, by a group in the U.S.S.R., and by one or two groups in the United States.

As far as this conference is concerned the interest of course is in the upper energy regions of the γ-ray spectrum, and hence it is partly the directional properties of the technique that attract special attention. It may therefore be of historical interest that in 1954 the author took a small 'light receiver' to the Royal Greenwich Observatory, at Herstmonceux. This was strapped to the barrel of their 6-inch (15.24 cm) refractor and was used to search for c.r. from the Crab nebula. With T. Gold, the then Assistant to the Astronomer Royal, several nights of observations were expended on this project, of which we were tolerably hopeful of success at the time.

Naive as it may seem now, it must be remembered that at that time the significance of the role of the galactic magnetic field on primary c.r. protons was not fully appreciated, and there was no knowledge whatsoever of the ratio of the intensity of the γ-ray component of the c.r. to the primary charged-particle component. Moreover, this pre-dated by fourteen years the discovery of the Crab pulsar, with its *ca.* 10^{12}Oe† field on the surface of the neutron star, and *ca.* 10^{8}Oe field at the velocity-of-light circle. Apart from these local fields at and around the pulsar even the weak fields in the interstellar medium would be sufficient to curve the paths of even the very-high-energy charged primaries.

3. The characteristics of atmospheric Cherenkov radiation produced by the e.a.s.

The refractive index of air at sea level is $n = 1.00029$, so that for relativistic particles, for which we can put $\beta = 1$, the Cherenkov cone angle $\theta_C = 1.3°$, the production rate for light in the wavelength band 350–550 nm is very small, *ca.* 30 ph m^{-1}, and the energy thresholds are high, 21 MeV for electrons and 4.3 GeV for muons.

The effective angular distribution of the light produced in an e.a.s. is governed more by the Coulomb scattering of the particles in the shower than by the Cherenkov angle. At sea level the r.m.s. scattering angle for electrons of energy E/MeV is $\langle\theta_s\rangle_{r.m.s.} \approx 21/E$ rad, so that for a typical electron energy of 100 MeV, $\langle\theta_s\rangle \approx 12°$ i.e. *ca.* $9\theta_C$. The angles θ_s and θ_C are functions of E and the altitude h in the atmosphere, so that the typical radius of the pool of light, which in effect splashes down on the ground, the splash lasting *ca.* 10 ns, is *ca.* 100 m.

Although the efficiency of production of Cherenkov light in air is very low, the energy of an optical photon is also low, *ca.* 3 eV, so that the number of photons is extremely high, and it is this that contributes to the success of the technique. For example, take a shower of primary energy $E_0 \approx 10^{15}$ eV. Such a shower has *ca.* 10^5 particles at sea level and produces *ca.* 3×10^{10} quanta. The effective radius of the distribution of particles in the e.a.s. is only *ca.* 10 m, in contrast with the 100 m quoted above for the radius of the light pool, so that in this example the flux of Cherenkov radiation is *ca.* 10^6 quanta m^{-2} and the corresponding ratio of the flux of light photons to particles is very high, *ca.* 3000. It is from these considerations that we deduce that the effective collection area for detecting a primary γ-ray is so large.

So far we have discussed mainly the question of the light pool on the ground, but what of the appearance of the flash of light on the celestial sphere, as viewed from the ground? If we take a point source of γ-rays from some celestial object, the e.a.s. which this source produces will arrive randomly in time, and the cores of the showers will all be parallel to each other but will have random lateral displacements with respect to the optic axis of the light receiver.

After a run in which several shower flashes have been obtained from this source, we would have a group of images on the celestial sphere not coinciding with, but positioned around, the source of γ-rays. Photographs have indeed been obtained of Cherenkov images from e.a.s. against the celestial sphere (Hill & Porter 1961). In agreement with theoretical predictions, the images are found to be comet-shaped, and of a size determined by the expected Coulomb scattering; these images, integrated over time, appear broadly on a circle the centre of which coincides with the γ-ray source.

The one basic problem with the technique is the vast background of pulses produced by the isotropic primary c.r. charged-particle flux. In all other γ-ray techniques these are readily

† 1 Oe = $10^3(4\pi)^{-1}$ A m^{-1} ≈ 79.58 A m^{-1}.

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excluded by anti-coincidence shields. The potential of the Cherenkov technique rests primarily on the fact that the angular resolution of the installations is so good and the expectation that all high-energy γ-ray sources will be in effect point sources.

As stated earlier, this technique has provided the astronomer with a tool for searching for sources of γ-radiation at energies that cannot be reached by any other method. For those with further interest in the earlier applications of the technique to γ-ray astronomy I refer to a paper by Jelley & Porter (1963).

References (Jelley)

Blackett, P. M. S. 1948 *Emission spectra of the night sky and aurora*. Rep. Gassiot Committee of the Royal Society of London, p. 34.

Cranshaw, T. E. & Galbraith, W. 1954 *Phil. Mag*. **45**, 1109.

Galbraith, W. & Jelley, J. V. 1953 *Nature, Lond*. **171**, 349.

Hill, D. A. & Porter, N. A. 1961 *Nature, Lond*. **191**, 690.

Jelley, J. V. 1967 *Progress in elementary particle and cosmic ray physics*, vol. IX, ch. II, p. 41. Amsterdam: North Holland.

Jelley, J. V. & Porter, N. A. 1963 *Q. Jl R. astr. Soc*. **4**, 275.

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