Čerenkov Radiation from the Night Sky, and its Application to γ-Ray Astronomy

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1. INTRODUCTION

Professor Powell (1) has described the primary cosmic-radiation (2) as a "thin rain of charged particles". This cosmic radiation (CR), which has now been studied exhaustively for nearly fifty years, has many remarkable features. One of these is the overall constancy of its intensity, and another, the high degree of isotropy, particularly at the higher energies. The CR is also remarkable for the high concentration of energy in individual particles, for the vast range of energies involved, and for the large fraction of the total energy of the Galaxy which is in this form.

By far the greatest proportion of CR particles arriving at the top of the atmosphere are protons, and the remainder consist of α-particles (helium nuclei) and heavier nuclei having a mass spectrum which, to a first approximation, is not very dissimilar to that of the cosmic abundances of the elements. The energy spectrum extends from $\sim 10^8$ eV to $\sim 10^{19}$ eV, a range of eleven decades. The lower limit is set by terrestrial and probably interplanetary magnetic fields, while the upper limit appears at the moment to be set by the very low frequency of events at this energy. The flux-energy spectrum for the primary CR obeys a power-law of the general form

$$N(>E) = kE^{-\gamma} \tag{i}$$

in which γ varies from about 1·4 to 2·1 over the range 5×10^9 eV to 10^{18} eV respectively.

For many years it was anticipated that electrons would be found in the primary CR, but measurements have shown (3) that their contribution to the total incoming flux is < 0·6 per cent. Mesons and hyperons do not exist in the primary CR owing to their short lifetimes, and the same applies also to neutrons.

The other possible components in the primary CR are γ-rays and neutrinos (4). These two have one important feature in common, namely that they are unaffected by magnetic and electrostatic fields. Therefore, and in anticipation of the next section, CR γ-rays and neutrinos will arrive at the Earth undeflected from their points of origin; thus, with suitable directional equipment, the sources of such radiations, if they exist, may be derived. Neutrinos and their relevance to "Neutrino Astronomy" have been discussed elsewhere (5).

In the above discussion we have spoken exclusively of the *primary* CR at the top of the atmosphere. The radiation, as actually received on the ground, or even at extreme mountain altitudes, is but a secondary image of the unadulterated radiation coming in through the Earth's exosphere. The incoming primary protonic and nucleonic radiations produce high-energy nuclear interactions at altitudes around 30 km, i.e. at heights just attainable with large balloons. Among the products of these interactions are mesons, the longer lived forms of which survive to sea-level. Among the decay products of these mesons are electrons and γ-rays. The "thin rain" at sea-level is therefore a jumble of particles of many kinds, with μ-mesons and electrons dominating. If the primary particles have sufficiently high energy, $\sim 10^{12}$ eV or above, a large number of secondary particles will be produced and will survive to sea-level. Such a splash of particles caused by a single incoming primary is called an Extensive Air Shower (58) owing to its large lateral extent.

Until recently, the main aim of CR physics has been the interpretation of the complex phenomena involved and their relation to the incoming primary radiation. To be entirely free from the effects of the atmosphere, to study the primary CR, it is essential to carry the recording instruments in satellites. Even then however, effects of "albedo" occur (6), and secondary or scattered CR particles are found coming up to the satellite from below, from the atmosphere.

In general, for the CR astronomer, the atmosphere is a deterrent, as it masks and distorts the primary radiation. However, in the application of the technique to be described in this paper to γ-ray astronomy, the atmosphere is absolutely essential; it is in effect part of the detection system.

Before discussing the general topic of γ-ray astronomy, some remarks ought to be included on the present status of the theory of origin of the CR, the acceleration mechanisms required and the general astrophysical background to the subject. Fortunately, however, these topics have but recently been discussed in the pages of this Journal (7), by Dr M. C. Johnson, to whose review the reader is referred.

It is now universally accepted that the absence of any anisotropy of the charged-particle CR is a direct consequence of the presence of weak magnetic fields which extend over vast regions of space. Indeed the very existence of particles of high energy implies the presence of such fields, if we are to accept the basic acceleration mechanism proposed by Fermi (8), or the variants of this theory (9).

The evidence for interstellar and cosmic magnetic fields stems from a number of sources. First, there are general electrodynamical considerations such as the equipartition of kinetic and magnetic energy in ionised gas clouds (10), the polarization of starlight (11), and the oriented and filamentary structures in bright emission nebulae (12) and other astronomical objects such as the Crab Nebula (13).

The most convincing evidence for magnetic fields stems from Radioastronomy and the realisation that much of the non-thermal radiation observed arises from the so-called synchroton mechanism* (10, 13), in which electrons radiate by circulation on spiral paths in a magnetic field.

There is now also direct evidence for magnetic fields, obtained from the Zeeman splitting of the 21-cm hydrogen line (14) and the recent Australian work on Faraday rotation (15, 16, 17).

2. γ-RAY ASTRONOMY

In view of the accumulated evidence for extensive magnetic fields, and the observed high degree of isotropy of the CR, attempts to search for "point sources" of charged particles have virtually been abandoned, except perhaps at the highest energies, i.e. at $>10^{18}$ eV.

It is against this background that thoughts have turned to looking for extra-terrestrial γ-rays, with considerations by what mechanisms such γ-rays might be produced and in what celestial objects. These considerations, which include tentative estimates of the likely fluxes and energies to be expected, have led to conclusions which suggest that a variety of objects may be likely "point" sources of γ-rays.

Since the mean life of a charge-particle CR stored in an interstellar or galactic magnetic field is in general large compared to the time for a single orbit, each such particle has manyfold opportunities of traversing a given region of space. However, for γ-rays, which travel in straight lines from their point of origin, the situation is different, for they have but one chance of being intercepted.

For these reasons it follows that even if γ-rays are produced in nuclear processes with a frequency equalling that of protons and other CR particles, the γ-ray fluxes at the Earth will be expected to be small.

Incoming primary γ-rays, like their more common relatives, the protons, can also produce extensive air showers, observable at sea-level, providing the initial energy is high enough, i.e. $>10^{12}$ eV.

Morrison (18) was the first to propose a search for extra-terrestrial γ-rays, and to realise the implications of such a search, were it fruitful,

* Sometimes referred to as Magneto-Bremsstrahlung, especially in the Russian literature.

both to astrophysics and to cosmical nuclear physics. There are a great variety of mechanisms by which such γ-rays might be produced (**19**) and we will here restrict ourselves to those processes which yield γ-rays in the energy region above the threshold of the Čerenkov technique, i.e. $> 10^{12}$ eV, and which have a reasonable probability of occurrence. The two basic processes which interest us most are the γ-rays from the decay of fast π°-mesons in flight, and γ-rays from the Coulomb-field Bremsstrahlung*(**21**) of fast-moving electrons colliding with nuclei in gas clouds in interstellar space.

The chain of events associated with the first of these processes, for the collision of a fast CR proton p_1 with the nucleus of a stationary hydrogen atom p_2 in a typical gas cloud, may be written:

$$p_1 + p_2 \begin{cases} \nearrow \; \pi^{\pm} \xrightarrow{10^{-8}\,\text{sec}} \mu^{\pm} \xrightarrow{2\times 10^{-6}\,\text{sec}} e^{\pm} \\ \searrow \; \pi^{\circ} \xrightarrow[10^{-16}\,\text{sec}]{} 2\gamma \end{cases} \tag{ii}$$

The charged and neutral π-mesons are produced in approximately equal numbers, and so the numbers of γ-rays and electrons (positive and negative) produced are comparable. If the above process takes place in a magnetic-field region, the electrons will generate the radio-frequency emissions observed by the radio-astronomers. This in turn saps the kinetic energy of these electrons to such a degree that they will not survive long enough to reach the Earth, which probably explains the absence of electrons in the primary CR.

The second, or Bremsstrahlung, process referred to above is written simply

$$e + p_2 \rightarrow p_2 + e' + \gamma$$

It is the chain of processes (ii) which Shklovskii (**10**) and others (**20**) have proposed may occur in a number of celestial objects, of which the Crab Nebula is of special interest. From what celestial objects may we then expect to find high-energy γ-rays? First, we might expect that the strong radio sources, at least those with a non-thermal spectrum, would also be emitters of high-energy γ-rays. Into this class falls the Crab Nebula, for which there is especially strong evidence for an associated magnetic field, owing to the discovery of polarized optical continuum radiation (**13, 22, 23**) which, it is deduced, is also synchroton radiation.

* This process, which is familiar in Nuclear Physics, is that in which an electron radiates as a result of its deflection in the strong electric field close to the nucleus of an atom.

Also in this class is the unusual radio emitter, the Galaxy M 87, which has a "jet" protruding from its nucleus, and again polarized continuum radiation (**54**). Other possible sources of γ-rays are the radio source Cassiopeia A, remnants of other super-novae with the filamentary structure suggestive of a magnetic field, and remote peculiar galaxies such as Cygnus A.

Of these the Crab Nebula is the radio source of greatest interest to us, for a number of reasons. It is a super-nova of relatively recent origin, 1054 A.D., it is close to us in our own Galaxy, being only about 1,000 parsecs away, and sufficient is known from its radio and optical emission for reasonable limits to be placed on the values of the local magnetic field, $\sim 3\times 10^{-4}$ Gauss (**10**), the energy of the electrons involved $\sim 10^{11}-10^{12}$ eV, and the flux of these electrons. It is with these data that estimates have been made (**24**) of the probable flux of γ-rays from the Crab Nebula, which estimates have however been considered by others (**25**) to be over-optimistic.

Besides these particular radio sources, a variety of other celestial objects have also been proposed as possible seats of origin of γ-rays, for example magnetic variables (**26**), flare stars (**27**) and the T-Tauri stars (**28**). In view of our rather scanty knowledge of the physical processes going on in these and other objects, it is not unreasonable to investigate at least some of these possibilities. There is one important proviso, and that is that in view of the recent measurements with the satellite Explorer XI (**6, 29**), the *general* flux of γ-rays is so low that one is unlikely to find such radiation from any type of object which is relatively common in the sky.

3. TECHNIQUES FOR THE DETECTION OF PRIMARY γ-RAYS

The problems involved in the detection of the lower energy γ-rays, produced by electron-positron or proton-antiproton annihilation at rest, are radically different from those encountered in the region $10^{12}-10^{13}$ eV. This paper is primarily concerned with the latter, but a brief description of the results of low energy surveys is given here.

Measurements at balloon altitudes, with nuclear emulsions and other detectors, have shown no evidence for primary γ-rays, but have reduced the upper limit for the intensity at 70 MeV or greater to about 7×10^{-3} cm^{-2} sec^{-1} sterad^{-1}, which is about 10^{-3} of the nuclear flux. A small number of events have however now been observed (**6**), with satellite Explorer XI. A preliminary analysis shows no marked directional tendency. The flux observed is considerably below that expected from the creation rate of antiprotons given by Hoyle and Burbidge (**30**), but there are many uncertainties in the astrophysical quantities involved in this estimate.

At energies above about 10^{12} eV the flux of γ-rays expected is so small that direct detection by experiments carried in balloons or satellites is difficult, though a nuclear emulsion experiment (**31**) has succeeded in setting a limit of about 2×10^{-7} γ-rays cm^{-2} sec^{-1} sterad^{-1}. This is less than that predicted (**24**) for the Crab Nebula alone. As with nuclear primaries at these or higher energies, the extensive air shower offers an alternative means of detection.

When a high energy cosmic ray proton enters the Earth's atmosphere, it interacts with a nucleus of oxygen or nitrogen. Amongst the products of these nuclear interactions are neutral π mesons, which decay very rapidly, each into two γ-rays. These initiate, by successive pair production and Bremsstrahlung, a cascade of electrons and photons. The nuclear products of the interaction, protons, neutrons and charged mesons, continue downwards, themselves producing further nuclear interactions, and further γ-rays. The electron-photon cascade is therefore fed continually from the nuclear cascade in its passage through the atmosphere. The number of particles in the cascade reaches a maximum at an altitude determined by the primary energy and by the height of the first interaction. For primary protons of $\sim 10^{14}$ eV, the maximum occurs at an altitude of about 6 km, at which height $\sim 10^4$ electrons are observed. At sea level this number is reduced by ionization loss to about 10^3. The nuclear component is absorbed somewhat more slowly, and appears at sea level mainly as μ-mesons, resulting from the decay of charged π-mesons. The number of μ-mesons is usually only 10–20 per cent of the number of electrons, and the number of nuclear-active particles, protons, π and K mesons, only about 1 per cent.

Because of multiple Coulomb scattering, the electron component is spread laterally over distances of about a hundred metres from the axis of the shower, but the whole cascade, travelling essentially at the velocity of light, arrives at ground level almost simultaneously, the particles being contained in a disc, normal to the original direction of the primary, and a few metres thick. A shower may therefore be detected by arranging a number of Geiger or scintillation counters in a lattice, with spacings of several tens of metres separation, and demanding that several of the detectors be struck simultaneously. This criterion eliminates the background of continuous cosmic radiation from low energy primaries, and the effective collecting area will be of the order of the lattice area. Large extensive air shower arrays have areas ranging from 0·5 km^2 up to 10 km^2. By using fast timing techniques, the time of arrival of the shower disc at different detectors, and hence the primary direction, may be determined to an accuracy of one to five degrees.

Primary γ-rays will also produce showers, but these will contain essentially no nuclear particles, since the photonuclear cross-sections are small. They will also develop somewhat more rapidly, be attenuated more rapidly than nuclear induced showers, and have a different lateral structure. In principle, therefore, the detection of showers with no nuclear particles offers the possibility of resolving a small flux of primary γ-rays from the background of protons and light nuclei. In practice, this is difficult, since nuclear particles form only a small fraction of the total number of particles, and very large shielded detectors are required to establish that they are absent from the shower. Furthermore, at the energies of 10^{12}–10^{13} eV for which γ-rays are expected, the number of particles remaining at sea level is very small, and it is necessary to work at high mountain altitudes.

An air shower array of this kind has however been constructed, and is being operated successfully at Mount Chacaltaya (5200 metres) in Bolivia, by collaborating groups from M.I.T., Tokyo, La Paz and Minnesota (**32**). It responds to showers of minimum energy of the order 10^{13} eV, and consists of a system of five fast timing scintillation detectors, a shielded scintillation detector of area 60 metres^2, seventeen detectors each of 1 metre^2 area for measuring electron densities, seven detectors for measuring energies of the electrons, a large cloud chamber and a neutron detector. It is possible to detect a γ-ray primary not only by the absence of particles in the large shielded detector, but also by detailed examination of the structure of the shower. The angular resolution in arrival direction is $\sim 5°$. Showers probably induced by primary γ-rays have now been detected (**56**) and appear to occur at a rate about 3×10^{-4} of the nuclear induced showers, which are observed at 100/hour. No point sources of γ-rays have been observed although there may be an excess from low galactic latitudes (private communication).

Whilst an air shower array of this kind is extremely effective, it has the disadvantages of complexity, high cost, and the necessity of working at great altitudes. An alternative approach, which is simpler, and can be operated at sea level, is offered by the detection of pulses of Čerenkov light from air showers in the atmosphere. Whilst its use is restricted to clear, moonless nights, it has, for surveys of possible γ-ray sources, some advantages over the detection of particles.

4. THE NATURE OF ČERENKOV RADIATION

When an electron plunges through a transparent dielectric medium at a velocity exceeding the velocity of light within the medium, it sets up an electromagnetic shockwave, producing a faint emission of bluish-white light. This emission, which is known as Čerenkov Radiation (**36**) after its discoverer, is in some ways analogous to the mechanical shock-wave generated by an aircraft or missile flying at supersonic speed. The effect, which was first discovered by Mallet (**33**) and later, independently, by Čerenkov (**34**), was interpreted shortly afterwards (**35**) on the basis of classical electromagnetic theory. A simplified account of the basic physics of the process is now presented.

If an electron moves swiftly through a medium, it produces local and transient polarization along the track of the particle. Each element of track thus radiates a minute electromagnetic pulse as the electron goes by. If now the velocity of the particle v_p exceeds the velocity of light in the medium, v_1, it is possible for the radiation from all the elements along the track to interfere constructively, this occurring when the radiation is emitted at a unique angle θ with respect to the direction of motion of the particle. If c is the velocity of light *in vacuo* and n is the refractive index of the medium, one can write $v_p = \beta c$ and $v_1 = (c/n)$. The condition of constructive interference, or coherence, is easily shown, by Huygens' principle, to be given by:

$$\cos \theta = (1/\beta n) \qquad \text{(iii)}$$

which is known as the Čerenkov Relation. This relation is easily derived from the simple construction in Figure 1(a) which shows, in one plane, the distances travelled by the particle, and by the light, in a small time interval Δt. It will at once be seen that two special conditions may arise. First, there is a "threshold velocity" for the particles, which is that velocity below which no radiation can take place, this occurring when $\theta \to 0$.

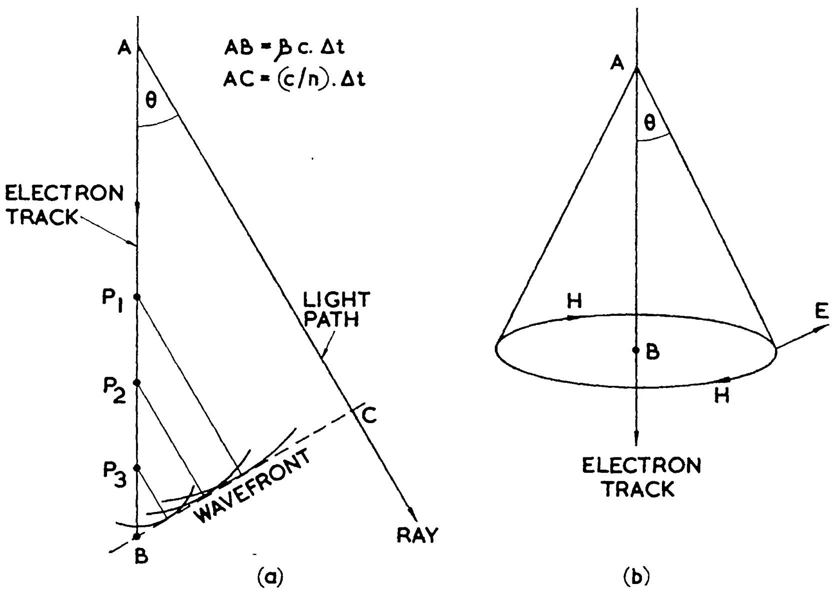


FIG. 1. Huygens' construction to illustrate coherence
(*a*) In a plane containing the track of the particle.
(*b*) The Čerenkov cone, showing the disposition of the electric and magnetic field vectors, E and H respectively.

This condition is $\beta(\min) = (1/n)$. Secondly, at extreme relativistic velocities, i.e. when $\beta \to 1$, there is a "maximum angle" of emission, given by $\theta = \cos^{-1}(1/n)$.

Since the medium is assumed to be homogeneous and isotropic, there is symmetry about the axis of the particle, and the radiation therefore appears on a conical surface whose semi-apex angle is the angle θ, see Figure 1(b).

Since the shock-front is very sharp, the electromagnetic pulse contains a large number of Fourier components, and the spectrum is continuous, extending over the whole range of frequencies ν for which $\beta n > 1$. The radiation yield per unit path is given by

$$\frac{dW}{dl} = \frac{4\pi^2 e^2}{c^2} \int_{\beta n > 1} (1 - 1/\beta^2 n^2)\nu . d\nu \qquad \text{(iv)}$$

where e is the electronic charge. From (iv) we see that the spectral distribution is peaked towards the blue and violet, and $(dW/d\nu) \propto \nu$ or, in terms of wavelength $(dW/d\lambda) \propto 1/\lambda^3$.

Putting in numerical values, for a single ultra-relativistic electron in air at S.T.P., the following figures emerge: $n = 1{\cdot}000293$, $\theta = 1^\circ{\cdot}3$, $E_{\min}$ (corresponding to $\beta_{\min}$) $= 21$ MeV, and $(dW/dl) \approx 0{\cdot}3$ photons cm^{-1}, between $\lambda = 3\,500$ and $\lambda = 5\,500$Å i.e. an energy production of only $1{\cdot}3 \times 10^{-12}$ ergs cm^{-1}.

The only astronomical situations in which Čerenkov radiation in the optical regions of the spectrum are likely to occur are in the atmospheres (and oceans?) of planets, for these are the only regions which provide adequate refractive indices combined with reasonable optical transparency. Čerenkov radiation at radio frequencies can however occur in a plasma, when in the presence of a magnetic field, and in this realm there are many possibilities. This mechanism has already been invoked, for example, to explain one type of solar radio emission (**37**), and also the decametre radio storms on Jupiter (**38**).

5. ČERENKOV PULSES FROM THE NIGHT SKY

It was suggested by Blackett (**39**) that a contribution to the light from the night sky would arise from Čerenkov radiation, produced by single low energy cosmic rays in the atmosphere. The magnitude of this contribution is only $\sim 10^{-4}$ of the total light, and since the radiation has a continuous spectrum, it would be very difficult to isolate, except perhaps by the correlation technique (**40**). An extensive air shower, however, may contain as many as 10^4 particles travelling simultaneously through the atmosphere, and will therefore produce a light pulse which can be detected above the background light of the night sky, by a photomultiplier and fast amplifier. Čerenkov pulses from air showers were first observed (**41, 42**) with a 10 inch, $f/0{\cdot}5$ parabolic mirror, with a 2-inch photomultiplier at the focus. Shower pulses were amplified with time constants of a fraction of a microsecond and photographed on an oscilloscope. Background "noise" was eliminated by biasing the output system at a high level; the noise spectrum falls off more steeply with increasing pulse height than does the spectrum of the shower pulses. The reality of the pulses was established (a) by comparisons between the night sky and a lamp of equivalent brightness and (b) by direct correlation with an extensive air shower array. Spurious pulses may be produced by distant lightning, but these are easy to recognize and reject. No other source of spurious pulses having comparable amplitude or duration has been detected in this or subsequent work.

Since the absorption of light in the atmosphere is very much less than that of charged particles, appreciable contributions to the total signal are made from all altitudes up to ~ 10 km, and this gives rise to a wide lateral spread of light on the ground. A single light detector is sensitive to showers falling over a circle of radius about 200 metres at sea level (**43**), giving an effective collecting area of the order 10^5 metres^2. Moreover, small showers may be detected at sea level, although the number of particles surviving to this depth is negligible. A combination of a 150 cm $f/0{\cdot}5$ searchlight mirror with a single 12 cm dia. photomultiplier can detect showers at a rate of about 700/hour at sea level, with a threshold energy of about 3×10^{13} eV, and a field of view of $\sim 10°$. Only about 10 particles, most of them μ-mesons, would reach sea level in a shower of this primary energy, and the detection of such a small number of particles would prove very difficult.

The light pulse technique therefore offers the advantages of large collecting area and low threshold energy, with detectors operating at sea level. Since the emission of Čerenkov light in air occurs at a small angle to the particle direction (see § 4 above) the light pulses will be concentrated towards the direction of the primary particle. The directional properties of the light at emission are however limited by the Coulomb scattering of the electrons, which is typically 10° from the main shower direction. Nevertheless, the light intensity received by a detector of small field of view is large only when the shower direction is nearly parallel to the axis of the detector, since only then are large contributions made to the total signal from all altitudes.

The angular distributions of Čerenkov light from showers have recently been computed (44) using an I.B.M. 7090 computer, and the I.B.M. 1620 computer at University College, Dublin. As the shower axis falls at increasing distances from the detector, there is a progressive displacement of the peak intensity from the true shower direction. At 100 metres, it is about 0°·7 for a γ-ray shower, and 1°·3 for a nuclear shower. This distortion sets a lower limit to the angular resolution of a directional Čerenkov system. The lateral distributions of the Čerenkov radiation from large showers have also been calculated by a group in the USSR (59). Independent calculations (61) have shown that the lateral distribution of the light will not be centred exactly about the shower axis, unless the shower direction is vertical.

6. PHOTOMULTIPLIER SYSTEMS

The showers detected with the earlier systems had primary energies in the range 10^{15} eV down to $\sim 10^{13}$ eV. Considerable development has been necessary in order to increase the sensitivity so that showers of primary energy as low as 10^{12} eV may be detected, this being the sensitivity required for example in work on the Crab Nebula where there are believed to be electrons having energies around 10^{11}–10^{12} eV (13).

To adapt the Čerenkov technique, with photomultipliers, for a search for γ-rays from selected point-sources, a number of technical improvements have been made. First, since it has now been established (45) that the duration of the Čerenkov flashes is as short as 10^{-8} sec, faster electronics has been used, thereby improving the discrimination between the pulses and the background noise. The noise results from statistical fluctuations in the photoelectron emission from the cathode of the phototube, this emission in turn arising from the steady background light of the night-sky. The faster the amplifier, the less the pile-up of noise pulses within the response time.

Secondly, the field of view of the light receiver is reduced to ~ 10 square degrees, to enhance the discrimination between showers initiated by γ-rays from the direction of the source, and the general isotropic background of charged-particle induced showers. This has several advantages: the reduced field considerably reduces the optical aberrations and also leads to less night-sky background and hence less noise.

It is appropriate here to mention that it has been usual to use military parabolic searchlight mirrors, of diameter 2 to 5 feet, all having an aperture ratio of *f*/0·5. These are, however, hardly adequate for this work, due to the severe coma; it would be preferable to use front-silvered spherical mirrors having an aperture ratio closer to *f*/1.

Thirdly, since the pulse-height distribution for the noise is so much steeper than that for the shower pulses, a considerable improvement in signal to noise, and hence overall sensitivity, is achieved by running two or more identical light-receivers in time coincidence. The outline of such a system, using three 3-foot $f/0{\cdot}5$ mirrors, is shown in Figure 2. The principle of this arrangement is that with the optic axes of the three mirrors

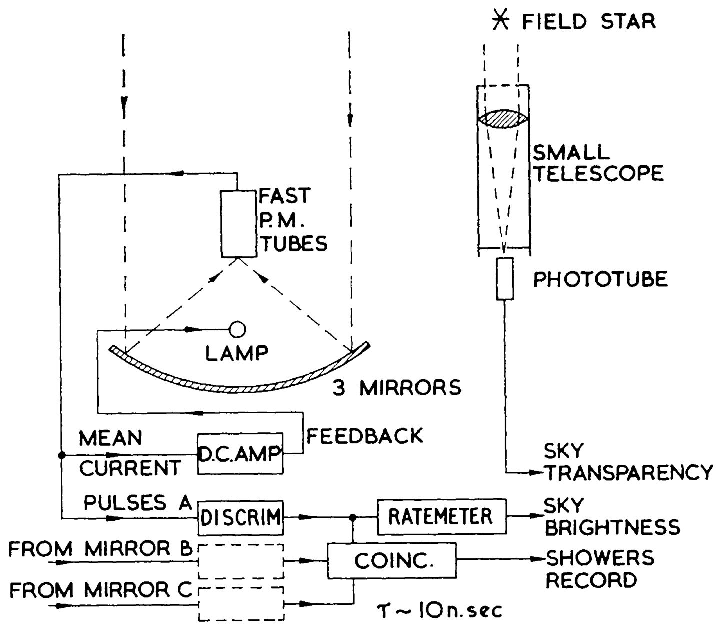
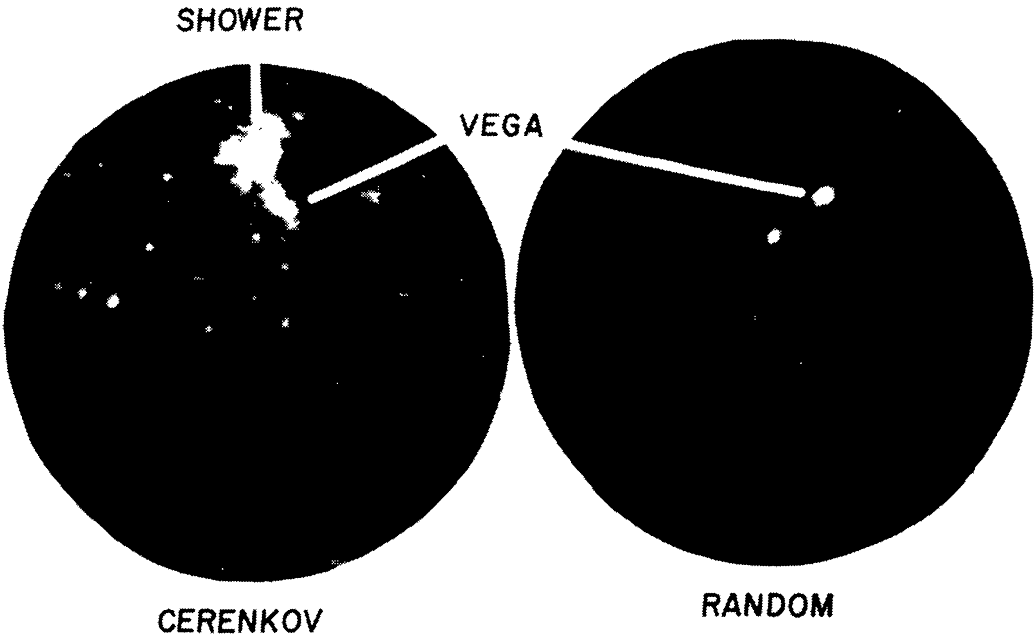


FIG. 2. Schematic diagram of a Čerenkov light receiver system using photomultipliers in coincidence.

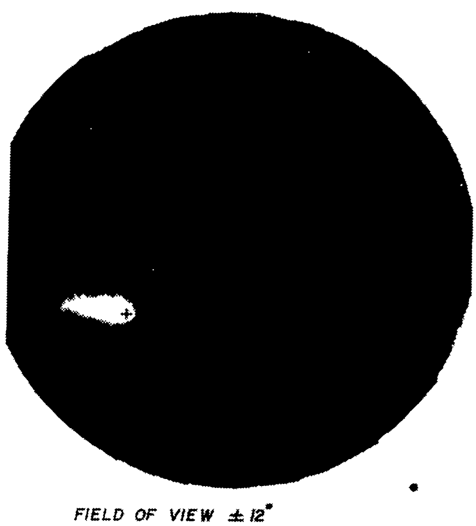
set parallel to each other, the three units will all receive the Čerenkov signal in precise coincidence, while the noise pulses in the three phototubes will be distributed randomly in time.

Considering now some essentially operational problems, it is convenient, for setting and guiding on objects that may be invisible, to mount the light receivers equatorially. Then, by off-setting from a star of known co-ordinates, it is easy to carry out "drift scans", as in radio-astronomy. Since, however, the background light of the night-sky has large spatial variations (**46**), $\sim 2/1$ between the galactic plane and the galactic pole, and the Čerenkov pulses are superimposed on the night-sky noise, it is essential to "stabilize" the apparent brightness of the night sky during drift scans, in order to avoid apparent variations in shower rate as regions of sky of varying brightness drift through the field of view. This is achieved, in the existing system at Harwell, (Plate 12) by adding a little light from a miniature filament lamp, and connecting the lamp in a D.C. servo-loop, so that the total background light remains constant, see also Figure 2. The problem of varying background light is typified in the case of the Crab Nebula, owing to the presence of the second magnitude star ζ Tauri which is but 1° away. In so far as most of the light from the showers of interest is generated at a considerable altitude, it is in

The existing light receiver installation at A.E.R.E., Harwell. The bank of three-foot *f*/0·5 mirrors is mounted equatorially for drift scans.



(*a*) A Čerenkov light flash photographed against the background light of the night-sky, using an image intensifier with phosphor storage, ref. (**52**). *Left*—with the intensifier triggered from a conventional light receiver, showing the patch of Čerenkov light, and the star Vega. *Right*—with the intensifier triggered at random.



(*b*) The image of a larger shower photographed with an improved image intensifier system. This shows the distortion and asymmetry which occurs when the shower core falls some distance from the detector. For comparison the small black dot to the lower right represents the diameter of the Moon, 0°·5.

principle possible to monitor the sky-transparency independently of the general sky brightness, by the simple expedient of recording the light from a bright star in a restricted field of view, as indicated in Figure 2.

Other photomultiplier equipments have already been built, in the USSR, and have been used for drift-scans on selected point sources (**47, 48**). One large installation (**60**), which has been operated for two years in the Crimea, uses twelve five-foot searchlights for studies of selected objects.

7. SHOWER PHOTOGRAPHY WITH IMAGE INTENSIFIERS

Though the photomultiplier systems have a high sensitivity and a good discrimination against night-sky noise, the information content of the recorded signals is small. Furthermore, because of the directional distortion already mentioned, the angular resolution of such light receivers is limited to 3–4 degrees. Moreover, since the angular resolution and the field of view are one and the same thing, only small areas of sky can be observed at any one time. This difficulty has however been partially overcome (**49, 50**) by clustering several phototubes at the focus of a single mirror.

For a long time it has been appreciated that the image intensifier (**51**) offers potentialities in this field, and the photography (**52, 53**) of Čerenkov images against the night-sky is the first step in this direction. Temporarily postponing the technical problems, what are the advantages of this technique? First, with Schmidt optics, it is possible in principle to combine a wide field of view with a high angular resolution. Secondly, photographs already obtained of Čerenkov images suggest that their shapes may be used to give detailed information both on the true direction of the shower and also the coordinates of its point of intersection with the ground, in relation to the position of the equipment. The third feature, and it is really the most important one for γ-ray astronomy of "point sources", is the high angular resolution which may be attained. Though the Čerenkov images are $\sim 2°$ across, and are in general non-circular in shape, it should be possible to determine a shower direction to $\sim 0{\cdot}2°$. Thus, we have, for a true point source, a discrimination (by solid angle) against showers from the general-field CR primaries, of ~ 100 times better than that possible for drift-scans with a photomultiplier system. We should however remember that many of the so-called "point" radio sources have a finite size. The Crab Nebula, for example, has a diameter of 4 min. of arc. It might be added here that a stereoscopic technique, with two separated telescopes, would greatly enhance these potentialities.

There are two basic systems under investigation, one using phosphor storage, and the other, optical delay. The essential features of the first of these and its operation can be understood by reference to Figure 3. The first image-tube forms a continuous record of the night sky on its phosphor screen, the image here being stored for a period determined

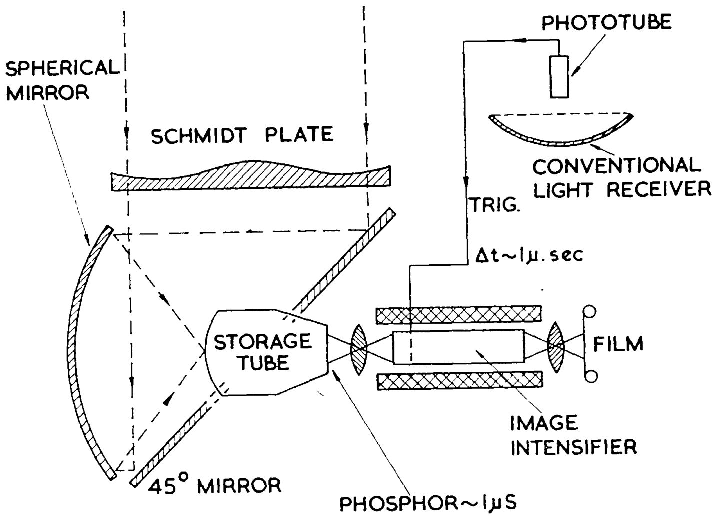


FIG. 3. The essential features of an image intensifier system with phosphor storage.

by the decay-time of this phosphor. The arrival of light from a shower is picked up in an auxiliary simple and conventional light receiver with a photomultiplier, and a pulse from this is then applied to the electronic gate of the second intensifier which is normally biased off. Since, even with present techniques, it is difficult to switch on the second tube in a time shorter than $\sim 10^{-7}$ second, the phosphor on the first tube must have a decay time of at least this order, to store the image. The background light from the sky, viewed at the end of the first tube, depends on the time-constant of its phosphor, so that for this system to have a good sensitivity, it is essential to use exceedingly fast electronics. With this system the minimum photographable light pulse using phosphor storage is therefore nearly two orders of magnitude greater than that detectable with a fast photomultiplier system, corresponding at present to about 10^4 photons incident on the first intensifier, or about 5×10^{14} eV primary energy.

One of the earlier shower photographs taken is shown in Plate 13*a* with a randomly triggered exposure for comparison. The bright star Vega also appears on both exposures. From the known brightness of the star, and the exposure time, an estimate of the number of photons from the shower pulse could be made. In this case it was approximately 5×10^4 photons, rather larger than the threshold. The photograph was taken at the Agassiz Station of Harvard College Observatory, close to sea level, in May 1961. In the whole field of view of 24° diameter, only Vega appeared consistently in photographs at these exposures, other stars appearing only occasionally.

In later work, Hill, Overbeck & White (unpublished) modified the equipment and obtained an improvement both in dynamic range and optical quality. The rate of photographable showers obtained on clear nights was then about 7/hour. An example of one of the larger showers obtained is shown in Plate 13*b*. The distortion of the pattern, expected theoretically for showers falling some distance from the detector, is seen clearly in this photograph. The true direction of the shower lies along the axis of symmetry of the spot at the point marked, and the uncertainty in its position is indicated by the two crossing lines. The small circular spot at the lower right hand corner shows the size of the full Moon on the scale of the picture. Again, although a number of 3rd magnitude stars occur in the field of view, none were sufficiently bright to be recorded.

An alternative arrangement, which would considerably improve the signal-to-noise, abandons phosphor storage in favour of optical delay, see Figure 4. In this system, in which an extra light-path is deliberately

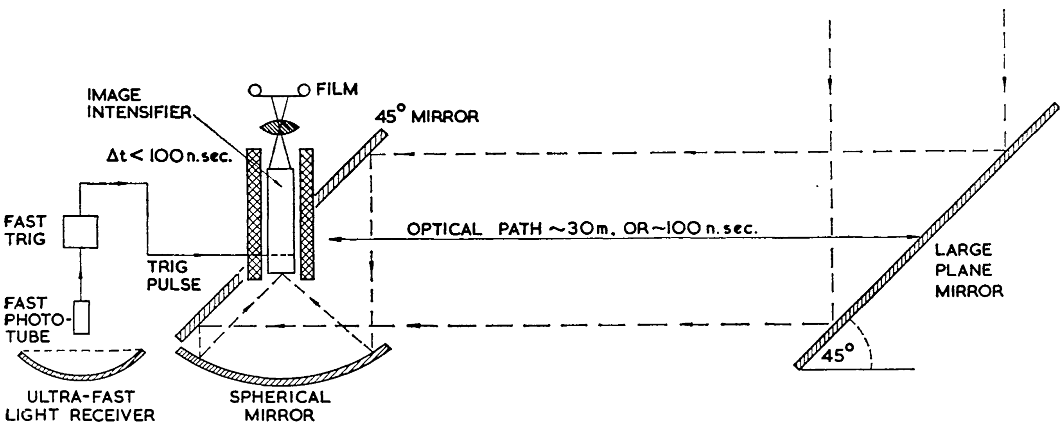


FIG. 4. The essential features of an image intensifier system with optical delay.

introduced before the intensifier, the first image tube is unnecessary, and the trigger pulse must arrive at the intensifier before the light. An electronic delay within the image tube is in principle possible (55) but the problem of developing such a tube has not yet been attempted.

The optical delay method is limited purely by mechanical considerations. The minimum time delay obtainable between arrival of the light pulse at the photomultiplier and the switching on of the intensifier being $\sim 10^{-7}$ seconds, the light reaching the intensifier must therefore pass through an extra path of about 30 metres to be sufficiently delayed. A coelostat can be used for the purpose, but since the minimum acceptable field of view is about 2°, the diameter of the coelostat mirror must be at least 2 metres across, to cover the full field of view. A system under construction in University College, Dublin, uses a square mirror of 150 cm side, mounted on a polar axis but with an adjustment at right angles to the axis so that a single mirror can be used to select a limited band of declinations. Magnetically focussed five-stage intensifiers are used, which have sufficient gain to photograph single photoelectrons emitted from the cathode.

There seems little doubt that some at least of the merits of the intensifier system will be realized in practical systems though there are at present technical problems, one of which is the severe vignetting which arises.

8. PRESENT RESULTS

The only results obtained so far on the likely point sources have been negative. This work (**47, 48**) has been carried out exclusively with photomultiplier systems using the drift-scan technique. Chudakov (**48**) has concluded, from work carried out using a large system of twelve searchlight units, that from the four radio sources the Crab Nebula, Cygnus A, Cassiopeia A and Virgo A(M87), the γ-ray flux at the top of the atmosphere, at energies $\sim 10^{13}$ eV, is $< 10^{-10}$ to 10^{-11} photons cm^{-2} sec^{-1}. From this he deduces that the electrons in the Crab do not come from the processes (ii). There was some suspicion that there was an increase for Cygnus A, over the background, by an amount equal to $(0{\cdot}68 \pm 0{\cdot}28)$ per cent, but this is hardly at the significant level.

In addition to the Bolivian experiment cited (**56**), a French-Polish group (**57**) have statistical evidence for the existence of γ-ray initiated showers at somewhat higher energies, though it is believed that in this work directional information is not available.

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