Radio Pulses from Cosmic Ray Air Showers

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Abstract. The first experiment in which radio emission was detected from high energy particles is described. An array of dipoles was operated by a team of British and Irish physicists in 1964-5 at the Jodrell Bank Radio Observatory in conjunction with a simple air shower trigger. The array operated at 44 MHz with 2.75 MHz bandwidth. Out of 4,500 triggers a clear bandwidth-limited radio pulse was seen in 11 events. This corresponded to a cosmic ray trigger threshold of 5×10^{16} eV and was of intensity close to that predicted. The early experiments which followed this discovery and their interpretation is described.

I BACKGROUND

It is a great honor to be asked to give the opening talk at this, the first workshop on the radio emission from high energy particles. I should stress that my involvement with the field was ephemeral and that although I was the first one to actually see evidence of radio emission from high energy particles, I have made no contribution to the field for 34 years. This invitation motivated me to open my Ph.D. dissertation, probably for the first time since its completion [1], and to realize how lucky I was to be involved, albeit in a junior capacity, with some outstanding physicists in a classic experiment in radiation physics. Since I am now struck by how different the methods used in this simple experiment are from those used by the contemporary student I will belabor the experimental method and stress the historical background as best as I remember it.

Experimental physics in the fifties was still very much conducted in the shadow of post-war politics, economics and experience. The positive contribution of physicists to the war effort ensured that physics research received some support even in those austere times. Still, ingenuity and creative solutions were necessary to accomplish anything meaningful. As a graduate student in the Experimental Physics Department of University College, Dublin, I was fortunate to join Neil Porter's Cosmic Ray group (in 1962) which was building a very high energy gamma-ray astronomy experiment. In those days graduate students really did build experiments, perhaps because little time was spent at computer terminals. Porter had recently returned to Dublin after a stint at the Atomic Energy Research Establishment (AERE), Harwell in England and continued to collaborate with John Jelley at AERE on these cosmic ray studies. It was a measure of the times that our gamma-ray telescope consisted of ex-World War II searchlight mirrors mounted on an old British-naval gun mounting and that major support for the experiment came via a grant from the U.S. Air Force. These were exciting times in high energy astrophysics (as the field came to be called) with the first X-ray sources yet to be discovered and pulsars and quasars still over the horizon. The post-Sputnik explosion in physics research was still in its infancy and its effects had not yet really reached the British Isles.

The discovery of cosmic ray particle cascades, the so-called Extensive Air Showers (EAS) [2] opened a new era of cosmic ray studies with most interest centering on using them to explore the highest energy cosmic rays. The sharply falling spectrum meant that the events of greatest interest were detected infrequently by conventional means (arrays of spaced particle detectors). In the wake of World War II and the availability of radio equipment and expertise, Blackett and Lovell [3] were moved to attempt to detect EAS using radar techniques to detect the ionizing trail left in the wake of the shower. These experiments were unsuccessful (the lifetime of the ions was overestimated) and the technique was not pursued. The feasibility of using simple optical radiation telescopes to detect EAS was demonstrated by Galbraith and Jelley [4] following the suggestion by Blackett [5] that the combined Cherenkov emission from all secondary cosmic rays in the atmosphere might constitute 0.01% of the night-sky light background. Since the Cherenkov radiation was concentrated in the forward direction with a lateral spread similar to that of secondary particles, this technique did not offer too much for the detection of very large EAS, particularly since it was limited to clear dark nights giving duty cycles of $< 10\%$; it did however lead to the development of an effective technique for very high energy gamma-ray astronomy [6]. Jelley [7] proposed that Cherenkov radio emission at radio wavelengths might be detectable but at the microwave frequencies necessary to prevent destructive interference; the predicted signal was small although potentially detectable [8]. The possibility that EAS might be detectable by the fluorescent emission that they caused in the atmosphere was explored, without success, by Greisen [9]; it was later to be revived with great success by the University of Utah group [10].

In 1962 G. Askaryan published a short paper in Russian in which he suggested that the particle cascade resulting from the interaction of a high energy particle in a dense medium would not be electrically neutral since the resulting positrons could decay in flight; also the cascade would accumulate delta-rays and Compton scattered electrons [11]. Cherenkov radio emission could then occur at longer wavelengths where there would be coherent emission from the net negative charge. Askaryan was primarily concerned with the emission of radiation from the particle cascade that would result from the interaction of a cosmic particle in a dense medium like rock, e.g., on the moon. Since this dielectric material is essentially transparent to radio waves, it can provide a large target mass for such elusive particles as neutrinos. Askaryan also pointed out that geomagnetic effects might also contribute to separation of the charged components in the shower and this dipole might provide an additional emission mechanism. He estimated the negative excess, ϵ in rock to be about 10%. If N = the number of particles in the shower, then instead of incoherent emission from N particles, we must consider coherent radiation from $(\epsilon \cdot N)^2$. If $N=10^6$ and $\epsilon=0.1$, then the coherence factor is 10^4, a huge gain. The coherence condition would require that the dimensions of the shower-emitting region should be comparable with the wavelength. The Cherenkov emission is proportional to $\nu.d\nu$, so that the reduced Cherenkov emission at, say, 50 MHz compared with 5 GHz would be more than compensated for by the increased coherence factor.

The Askaryan paper appears to have gone unnoticed by experimentalists until a follow-up paper by Alikanyan [12], on the emission of radio emission by high energy particles, was noted by Neil Porter who was asked to write an abstract for its publication in English. The paper referenced the earlier Askaryan paper but it was not available in Ireland. Knowing that Jelley had been interested in such phenomena, Porter sent a copy of the Alikanyan paper to Jelley with a note to the effect that it did not seem a very feasible technique (Porter, private communication). Jelley acquired the English version of the Askaryan paper and realized that the negative excess offered new possibilities for the radio detection of air showers. After an exchange of letters Jelley and Porter agreed to attempt a simple experiment. Since neither of them had access to radio telescopes they decided to enlist the help of the extensive post-war British radio astronomy community. F. Graham Smith, then at the Cambridge Radio Observatory, offered to assist; as he was about to take up a position of Deputy Director at the Jodrell Bank Radio Observatory, it was agreed that the experiment should be done there.

II THE EXPERIMENT

The experiment was to consist of a large area, broad band, medium wavelength, wide angle radio telescope coupled to an adjacent air shower array which would trigger the recording of the predicted radio analog signal from high energy showers at a reasonable rate. A radio telescope with these parameters is best matched by a simple dipole array. It was proposed to use the frequency reserved for the new BBC video signal at 44 MHz where a relatively noise-free bandwidth of 2.75 MHz could be achieved when the BBC transmitter was turned off. This was approximately from 00.00 to 9.00 AM (no late night talk shows!) so this was to be a night experiment with limited running time. I do not recall whose idea it was to use this band but, in retrospect, it was key to the successful outcome of the experiment. With the increased use of the radio bands for communication it would not be possible to do this today.

As the junior graduate student in the Dublin group I was assigned the task of designing and building the EAS trigger that would be used to signal the arrival of a large EAS. The design was based on calculations using analytical models of shower particle distributions. I believe these simple calculations (on our state- of-the-art IBM 1620 computer) constituted the only involvement of a computer in the experiment; computers were not involved in data taking or data analysis.

The construction of the air shower array entailed a number of trips to AERE where the array would be built and tested. AERE, as a large British government research laboratory with seemingly limitless resources, was a wonderland to a young Irish student. It was possible to put together a somewhat primitive but functional array of Geiger counters in a matter of weeks. Geiger counters were chosen because they were cheap and easily available. The simple design called for three trays of Geiger counters at the corners of an equilateral triangle of side 50 m; a trigger required a signal from each tray within 0.5 microseconds. In each of the three trays we had counters of various sizes so we could get a rough determination of the particle density and hence the shower size and its proximity. Geiger counters are slow and noisy and precautions had to be taken to ensure that the radio system was not susceptible to pickup from the shower trigger. To achieve this we planned to run the complete shower array from one battery supply, the radio detectors from another. In June 1964 the array was operated for a week at AERE (beside the Tandem Generator Building) where the trigger rate was about 2.5 events per hour, roughly corresponding to an EAS threshold of 10^{16} eV.

In July, 1964, the array was moved to the pastoral setting of Jodrell Bank, some 20 miles from Manchester. There, under Graham Smith's direction, a dipole array was being assembled, primarily by Bob Porter, a University of Manchester graduate student.

With John Jelley and senior Harwell technician, John Fruin, I assembled the small air shower array adjacent to the dipole array and in the shadow of a 15 m radio telescope whose instrument shack we commandeered. As with any new experiment in the field it was an exciting time. Within a week we had the array up and running and the Harwell pair left me to operate it for a couple of months.

The putative shower radio signal was delayed by passing it through one kilometer of coaxial cable in a rack enclosed in a Faraday cage with amplifiers distributed along the line to compensate for cable attenuation. The output of the radio detector was to be displayed on the 20 microsecond time-base of one channel of a two channel oscilloscope; a time signal was displayed on the other. The scope was triggered by the air shower array with the radio pulse expected between 5.0 and 6.0 microseconds from the beginning of the trace (there was considerable jitter in the array trigger) (Figure 1). This long time-base gave a display of the radio background noise both before and after the shower and was important in establishing that any detected bandwidth-limited pulses were really associated with the shower. The oscilloscope display was recorded on 35 mm film by a Shackman camera; a small lens also brought into focus a clock and hodoscope indicating which of the smaller Geiger counters had been struck.

We quickly learned that radio pulse investigations operate in a quite different environment from that seen by conventional radio astronomy. The long integrations

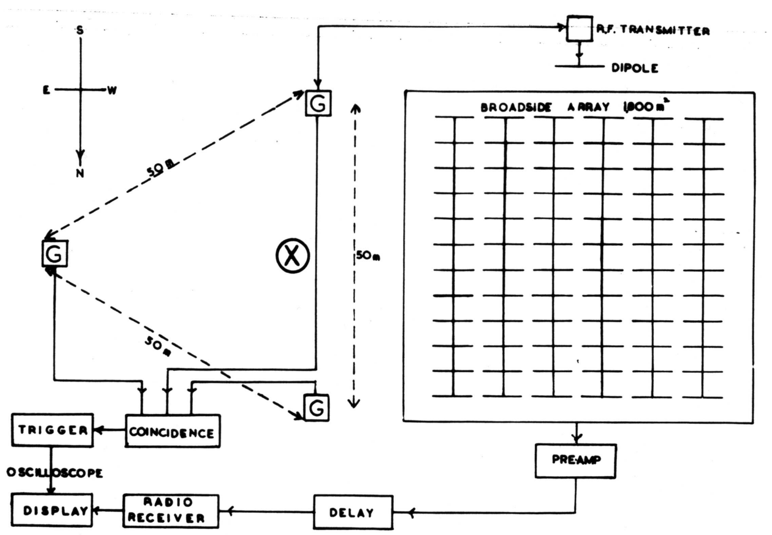

FIGURE 1. The Geiger counter array was set to one side of the dipole array which had a total area of 1,700 m^2. The rf transmitter was used in calibration experiments to measure the delay in the analog signal [1].

used by radio astronomers smoothed out the man-made pulsed radio background which we soon discovered to be dominated by such things as the nearby electric trains, the typewriters in the administration building and the erratic ignition systems of old cars driven by senior faculty. These problems were to be rediscovered by the radio astronomers who within a few years would discover the radio pulsars with very similar equipment.

Sadly I find I have no photographs of the dipole array which did not lend itself to photography (no more than the air shower array of Geiger counters did!). In contrast I have a detailed written log of those days; I was scheduled to get married in September and out of guilt at leaving all the marriage arrangements to my future wife, I wrote to her every day; romantic soul that I was, I filled my letters with day-to-day accounts of the progress of the experiment! The Geiger array ran pretty much without problems (apart from the inevitable eating of the high voltage cables by rabbits). The trays and cables were 0.5 m above ground level and kept air tight; even when the grassy area in which they were located was partially flooded they continued to operate!

The success of the experiment was in no small way due to the choice of frequency and bandwidth and relative radio quietness at that time. A chart recorder that recorded the integrated radio brightness demonstrated the nightly passage of the Milky Way and confirmed that we were indeed galactic noise-limited; the sky-brightness temperature varied from 6,000° to 20, 000°. The receiver noise temperature was 450°. No form of automatic gain control was used. By phasing the dipole array we were able to observe the transit of Cassiopeia A and thus determine our beamwidth (10° FWHM). This was my first experience of real astronomy using non-visible wavelengths!

III THE RESULTS

On August 19, 1964 all was ready for the first night of data taking. John Jelley was a meticulous experimentalist and had left a check list for the night operator to complete. Radio observatories are often lonely places at night and it was a little eerie setting up an experiment in a remote location to begin operation after midnight. All was now ready to test the hypothesis that air showers produced detectable radio emission. I confess to some anticipation and excitement as I set the system to operate that first night. These emotions were balanced by my discovery the next morning that after the first event the camera had jammed and no data was taken! The next night I was more careful: I double checked the Jelley list and waited for an hour to be certain that data was being recorded.

It was Sunday morning when I unloaded the camera, checked that the various housekeeping chart recorders showed nothing unusual and developed the long roll of film in the observatory dark room. In the dark room lights I made a quick check on the film and was delighted to see on the fifth image recorded exactly what we had been looking for, evidence for a very large radio pulse at precisely the right point on the time-base. Later that day I examined the full roll of film and noted no other evidence for emission but no background events either.

This was my first experience of a scientific discovery and young that I was, I assumed this was the norm of scientific research and that I should expect such happenings on a regular basis! Little did I realize that (a) I would wait another twenty years for a comparable happening (b) that this was the largest pulse we would record and (c) there would be no other evidence for emission in the remainder of the eight days of the run. Wisely I decided I should celebrate immediately; I did not have access to a telephone on site, there was no e-mail or other way to communicate with my supervisors, so I mounted my trusty government-issue bicycle and repaired to the nearest village some miles away where I downed some good English bitter.

The next week was a disappointment. All systems seemed to run perfectly but no radio pulses were evident. We were running with just one quarter of the dipole array completed. At the end of the week we were faced with the big decision; did our preliminary run justify the effort and expense of completing the array? I opted for completing the array which was an easy decision on my part since I was leaving for a few months and the cost, which was minimal, would be borne by Jodrell Bank.

In a month the array was completed and the experiment was run on almost every night until March 1965 (I did another stint of operation in December, 1964). To my immense relief more pulses appeared but only one off-scale pulse. In some 4,500 air shower triggered events, there were eleven with clearly discernible pulses in the right delay window. There were no comparable pulses anywhere else on the event times-bases or on time-bases triggered by a clock every half-hour. Some of these

FIGURE 2. Some of the oscilloscope traces showing the "large" radio pulses. The first (offscale) pulse was recorded on a different timebase than the others. The arrival time of the calibration transmitter pulse must be corrected for the time delay in the Geiger circuitry [1].

events are reproduced in Figure 2.

We also performed an analysis on the traces that did not show an obvious large pulse. This analysis was done in Dublin and consisted of recording the position of the maximum "noise" fluctuation on each oscilloscope trace. A clear peak was seen in the distribution in the anticipated interval (and none in the clock triggered events) providing independent evidence for the detection of radio emission. This data was folded with the distribution of measured pulse sizes in the large events to give the size spectrum shown in Figure 3.

IV INTERPRETATION

The observed rate of detected radio pulses was consistent with emission from cosmic ray air showers initiated by primaries of energy 5x10^{16} eV. The energy in the received radio pulse was about 1 eV. The air shower array did not give any information about the shower arrival direction and the small counter triggers did not allow a precise definition of either the size of the shower or the position of its axis. A series of follow-up experiments involved (a) use of an optical air shower to trigger on smaller showers with known arrival directions (b) operation in

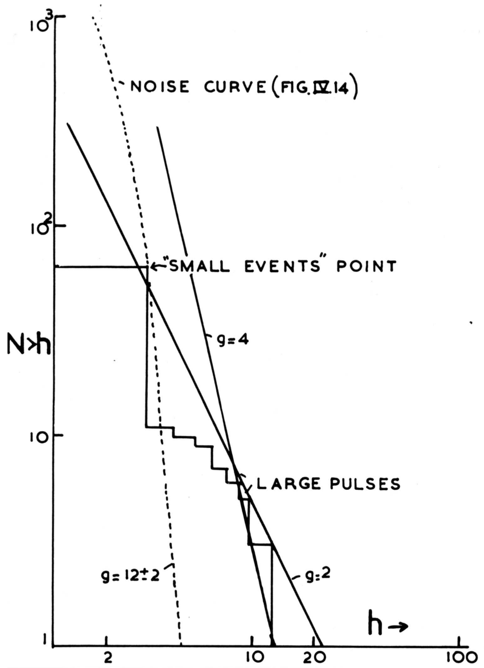

FIGURE 3. The distribution of pulse sizes measured in the delay window where radio air shower pulses are expected is plotted with a single point for the observed small events. The normal receiver noise spectrum pulse height distribution is also shown [1].

coincidence with the 15 m radio telescope fitted with a radio receiver at 150 MHz (c) a short run with one section of the dipole array rotated in orientation to favor North-South polarization. After 1966 (when I left UCD) the Dublin group extended the observed radio pulse frequencies into the UHF band and detected radio pulses that were probably radiated incoherently [13]. None of these experiments gave conclusive results on the nature of the emission but all were consistent with the hypothesis that the radio emission originated in large air showers.

Alternative radiation hypotheses were also considered including: (a) nuclear field bremsstrahlung; (b) transition radiation; (c) induction effects; (d) cosmic rays striking receivers; (e) reflection of TV signal; (f) molecular emission. Preliminary estimates eliminated all these as possible explanations of the observed radio emission [14] [1].

In the original Askaryan paper the possibility that radio emission might also result from geomagnetic effects on the shower particles were mentioned. This concept was developed by Porter in Dublin as we built the experiment. Two mechanisms were recognized in addition to the Cherenkov radiation from the negative excess: i) the separation of the positive and negative charges as they traversed the earth's magnetic field would create a dipole and give rise to radio emission; ii) as shower develops in the atmosphere, electrons are being moved to one side, positrons to the other by the magnetic field; the result is that the shower constitutes a current element which will also radiate radio waves. The full treatment of these processes was done eventually by Kahn and Lerche at Manchester University [15] and Colgate [16] at Los Alamos. A good summary of all aspects of these early experiments can be found in a review article by Allen [17]. Remarkably all three processes seemed to give signals of comparable magnitude (but with the detection of polarization and the measured distribution of radio signal with frequency, the consensus now seems to be that the current element is the dominant emission mechanism).

V CONCLUSIONS

The results from the initial experiment were published in a Letter to Nature [14] and in a Nuovo Cimento paper [18]. They were also reported at the 9th International Conference on Cosmic Rays (ICRC) in London in 1965 [19]. By that time the phenomenon had been independently confirmed by an experiment performed by the UCD group in the Dublin mountains, using a helical antenna with a receiver at 70 MHz with bandwidth 20 MHz and a plastic Cherenkov detector shower trigger [20]. These early results were given some prominence in the report of the ICRC EAS Highlight speaker, K. Greisen [21], from whose paper the following is quoted: "The technique is barely in its infancy, and too little is known about it to justify elaborate predictions. However, we feel confident that this achievement is a significant breakthrough, and that further study will reveal ways of obtaining types of information about the showers that were not available by other means. The signal will not, of course, be sensitive to fine details like the structure of the shower core; nor does the method seem adaptable to surveying at the same time all directions in which showers may arrive. However, it appears that the method may offer new orders of angular resolution; and it may complement particle detectors by being sensitive to the conditions of showers far above ground level. Also it will be able to detect showers in steeply inclined directions, in which the particles are absorbed before reaching the ground. Time will probably reveal other possibilities that are not apparent at this early stage." Sir Bernard Lovell was to note that this experiment fulfilled the original purpose of the first telescope constructed at Jodrell Bank in 1941 [22].

This optimistic assessment led to a spate of experimental activity which was mostly aimed at an exploration of the radiation mechanisms. Interest in the field can be assessed in the numbers of papers presented on the technique in subsequent ICRCs (Figure 4). Early interest in the potential of the technique seems to have waned as it was recognized that the emission was directed and thus not suited to distant shower detection and that the man-made pulse radio background was noisy and becoming more so. Thus the early hope that radio detectors might be used in stand alone systems to detect distant very large air showers was not realized. The recent interest in the detection of showers of energy $> 10^{20}$ eV has renewed interest in the radio detection technique.

I am grateful to Peter Gorham and David Salzberg for allowing me to indulge in this reminiscence of the early work and to Neil Porter and David Fegan for jogging

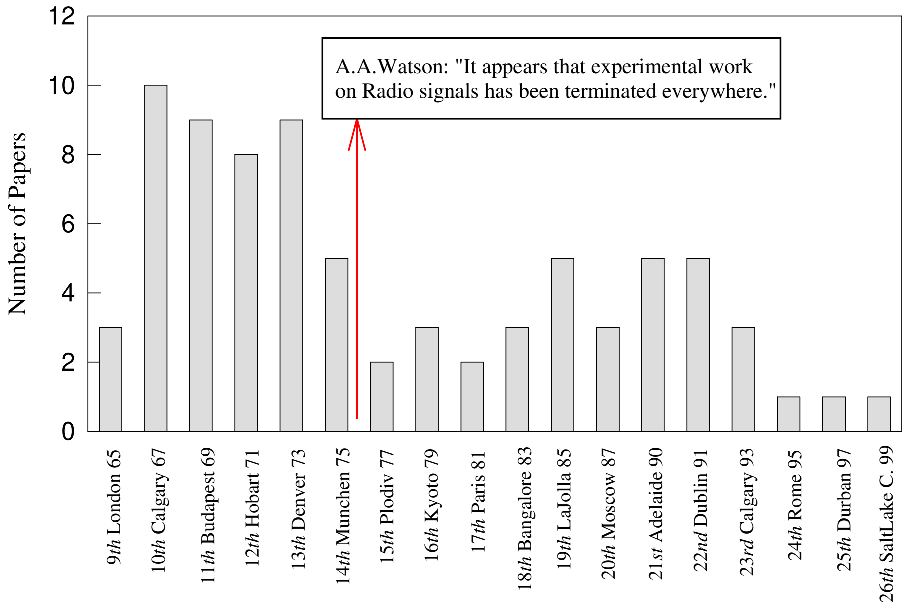

FIGURE 4. The number of papers on the radio emission of air showers presented at International Cosmic Ray Conferences from 1965 to the present day (compilation by H. Badran).

my memory on important details.

REFERENCES

1. Weekes, T.C.. Ph.D. Thesis, National University of Ireland, "Radio and Optical Methods of Detecting Cosmic Rays" unpublished (1966)
2. Auger, P.R. et al., Acad. des Sciences, Paris **206**, 410 (1938)
3. Blackett, P.M.S., Lovell, A.C.B., Proc. Roy. Soc. **177**, 183 (1941)
4. Galbraith, W., Jelley, J.V., Nature, **171**, 349 (1953)
5. Blackett, P.M.S., Phys. Abst., **52**, 4347
6. Weekes, T.C., Proc. Symposium on GeV-TeV Gamma Ray Astronomy (Heidelberg, June 2000), AIP (in press) (2000)
7. Jelley, J.V. "Cherenkov Radiation and its Applications", Pergamon Press (1958)
8. Jelley, J.V., Suppl. Nuovo Cimento **8**, 578 (1958)
9. Greisen, K., Ann. Rev. Nucl. Sci. **10**, 63 (1960)
10. Baltrusaitas,R.M et al. Nucl. Inst. Meth. **A240**, 410 (1985)
11. Askaryan, G.A., Soviet Physics, J.E.T.P., **14**, (2) 441 (1962)
12. Alikanyan, A.I., Laziev, E.U., Tumanyan, W.A., N.I.M., **20**, 276 (1963)
13. Fegan, D.J, Slevin, P.J., Nature, **217**, 440 (1968)
14. Jelley, J.V., Fruin, J.H., Porter, N.A. et al., Nature, **205**, 327 (1965)
15. Kahn, F.D., Lerche, I., Proc. Roy. Soc. A, **289**, 206 (1966)

16. Colgate, S.A. J. Geophys. Res., **72**, 4869 (1967)
17. Allen, H., Prog. in Elem. Part. and Cos. Ray Phys. (N.Holland Publ. Co.) **10**, 171 (1971)
18. Jelley, J.V., Fruin, J.H., Charman, W.N. et al., Nuovo Cimento, **46**, 649 (1966)
19. Smith, F.G., Porter, N.A., Jelley, J.V., Proc. 9th I.C.R.C. (London), **2**, 701 (1965)
20. Porter, N.A., Long, C.D., McBreen, B et al., Phys. Lett., **19**, (5), 415 (1965)
21. Greisen, K., Proc. 9th I.C.R.C. (London), **2**, 609 (1965)
22. Lovell, A.C.B., "The Story of Jodrell Bank", Oxford University Press (1968)