Bose statistics and the stars

R. Hanbury Brown

White Cottage, Penton Mewsey, Andover, Hants, SP11 0RQ, England

A brief account is given of the early development of a new technique, intensity interferometry, to measure the angular size of radio sources. Following the chance discovery that it was unaffected by scintillation it was proposed to apply the same principle to measuring visible stars. This proposal met with vigorous opposition from physicists when it was realized that it implied that the time of arrival of photons in two mutually coherent beams of light must be correlated. Two laboratory experiments were done to demonstrate that this correlation does in fact take place. Then, after a pilot model had measured the angular size of Sirius, a full scale stellar intensity interferometer was built and installed at Narrabri in Australia. In a programme lasting 12 years it measured the angular diameters of 32 single stars in the spectral range O to F and established the first wholly empirical temperature scale for stars in that range. For the last 10 years the work has been continued by the construction of the larger and more sensitive Sydney University Stellar Interferometer called SUSI.

Most of the work which I am going to talk about was done rather a long time ago; indeed it was started in 1949 at the Jodrell Bank Experimental Station of the University of Manchester. At that time the most exciting problem in radio-astronomy was the nature of the so-called radio stars – the bright points of radio emission which had been discovered in the sky. What were they – galaxies, stars, or nebulae? We didn't know. Most of us thought they were some sort of invisible stars and, as it turned out later, most of us were wrong.

I decided to measure their angular size – at least that would tell us if they were stars or galaxies. An obvious way of doing this was to make a radio analogue of Michelson's stellar interferometer using spaced radio antennas instead of spaced mirrors; but if it should turn out that these 'radio stars' were really stars, as we suspected, then to measure angles of the order of 1/100th of a second of arc or less, the two antennas would have to be thousands of kilometres apart. In 1949 I could see no way of doing this; the principal technical difficulties were to provide independent local oscillators with sufficient stability, and to equalize the very large and variable delay in the two channels. Nowadays all this can be done.

I worried over this problem for weeks until late one night I saw a possible way of making an interferometer which might work with a baseline of thousands of kilometres. In my mind I saw two people with identical radio receivers sitting in a field looking at cathode-ray tubes on which were displayed the noise from the same radio star; would they, I wondered, both see the same picture? If so, maybe I could find the angular size of the star by comparing their two pictures? To cut a long story short the answer was 'yes', and with the help of a friendly mathematician Richard Twiss, I developed the theory[1] of a radically new type of instrument which we were certain could be made to work with very long baselines, the intensity interferometer.

In due course an intensity interferometer working on a wavelength of 2 metres was built by R. C. Jennison and M. K. Das Gupta[2]; with it they measured the angular size of the two principal radio sources in the sky (Cygnus A and Cassiopeia A). Neither of these sources proved to be a star – one was a galaxy, the other a supernova remnant – to my disappointment there was no need for a very long baseline – it would have been much easier to use a radio version of Michelson's interferometer!

But all was not lost. One day while Richard Twiss and I were watching this radio interferometer actually working we realized, to our complete surprise, that we had overlooked one of the most valuable properties of an intensity interferometer – its measurements are totally unaffected by twinkling. It dawned on us that the same principle might, perhaps, be used to crack the ancient and difficult problem of measuring the angular size of the visible stars.

Michelson's stellar interferometer was limited by its size (20 ft) to measuring only six stars. Efforts to

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Talk given at the Raman Research Institute, Bangalore on 13 January 1994

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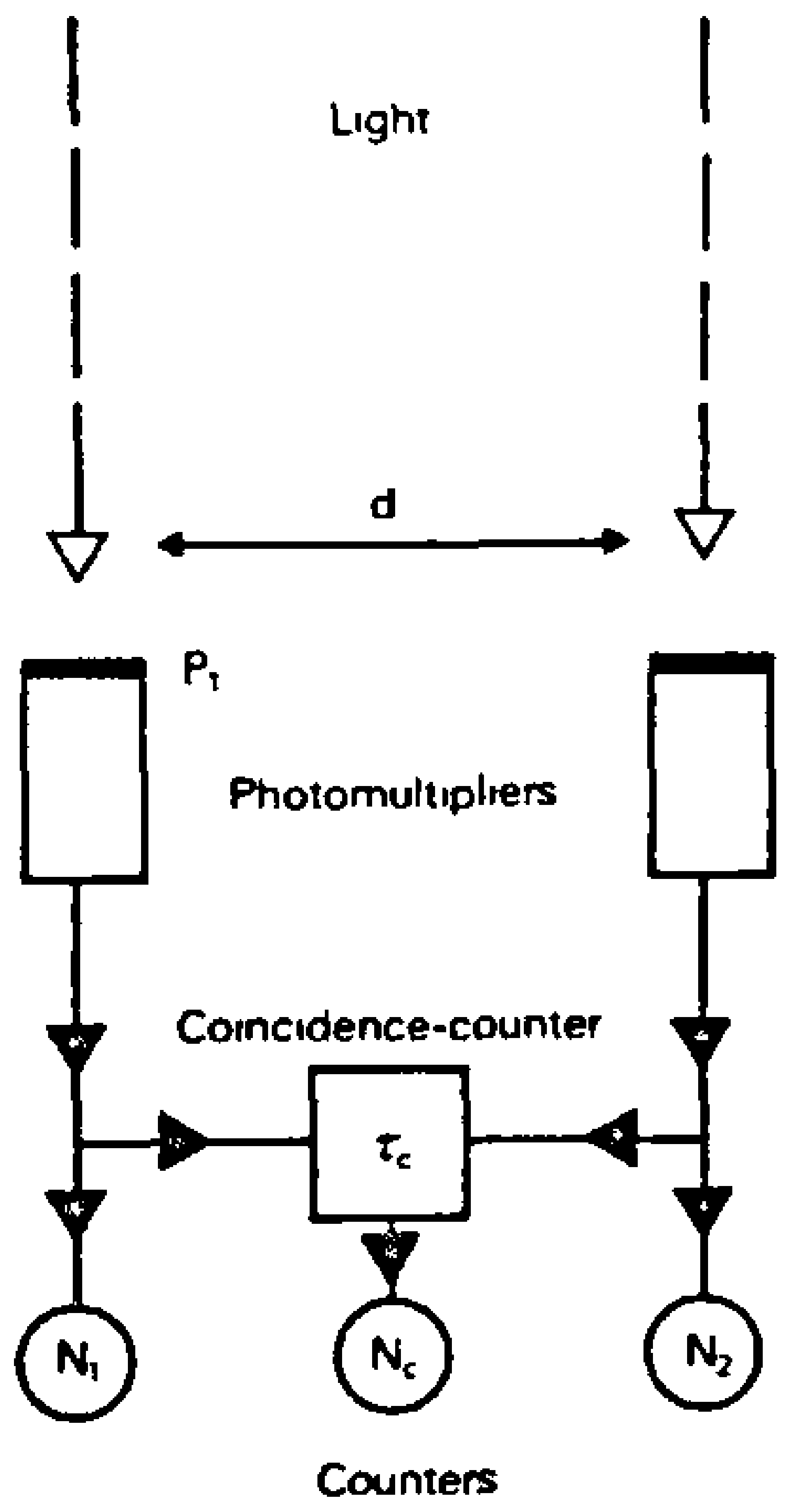

Figure 1. A coincidence-counting intensity interferometer.

enlarge it to 50 ft were made by Hale and others, but they failed and the work was discontinued in 1930. The major difficulties were, firstly, that the two paths of the light inside the instrument had to be held equal to a few microns and that proved too difficult mechanically; secondly, the effects of twinkling in the atmosphere were disastrous. What we now realized was that an intensity interferometer working with visible light would overcome both these difficulties; we decided to carry on where Michelson had left off.

It was at this point that we ran into trouble. We had worked out the mathematics of the intensity interferometer for radio waves and now we had to do it for light, and that meant that we must think about photons. So far the principle of our new instrument had been accepted without question, in those days radio engineers didn't worry about photons; but when we decided to apply it to light, physicists became interested and did worry about photons. Indeed they were very unhappy about what we proposed to do.

The trouble was that, when seen in terms of photons, our scheme looked like Figure 1. Individual photons from the star produce a pulse of current in the output of two separated phototubes and these pulses are fed to a coincidence counter. We showed theoretically that when the spacing between the two phototubes is large and the light on them is mutually incoherent then the coincidence rate is – obviously – that for two random streams of pulses. However, when the spacing is small and the light is mutually coherent, we showed that the times at which photons arrive at the two phototubes must be correlated; photons tend to arrive simultaneously at the two phototubes and the output of the coincidence counter is therefore increased. Furthermore we showed that this 'excess' coincidence rate is a measure of the mutual coherence of the light at the two phototubes and so, by measuring it at different spacings, it is possible to find the angular diameter of the star.

To most physicists our ideas were laughable. Their simplest argument, among many more highbrow ones, was that because photons are generated at random times and travel with the velocity of light, they must therefore arrive at random times. There is no conceivable way, we were told, in which they can arrive in pairs; to arrive hand in hand they would have to hang about waiting for each other! Obviously our proposal would not work.

Furthermore on page 18 of one of the holy books of physics, *Quantum Mechanics*, Dirac had written 'interference between different photons can never occur' – and yet our theory involved the coordinated behaviour of different photons. Every time I stuck my nose inside Manchester University, I was waylaid by a physicist brandishing some sacred text, Heitler or Dirac, showing that the behaviour of photons could never be correlated. They told me this in person, in letters and in print. Even after the publication of our first experiment, which I shall describe in a minute, laboratory experiments were carried out in Hungary and Canada which claimed to show that there was no correlation between photons. We analysed both these experiments in detail and published a paper pointing out that, with their experimental set-up, it would have taken the Canadians at least 1000 years to demonstrate the phenomenon and with their equipment the Hungarians would have had to observe for a time considerably longer than the age of the Earth! Neither of them had managed to work out the theoretical signal to noise ratio of their experiments – I couldn't do it either, but my colleague Richard Twiss could!

The difficulty which many physicists had in accepting that the arrival of photons can be correlated was that most of them were particle physicists who thought of a photon as a real thing with its own properties, like a cricket ball, whereas it is better to think of it as an *event* not as a *thing* – something which happens when light is generated or detected. They hadn't grasped that 'photon' and 'wave' are both metaphors which describe the behaviour of light only in a limited context; outside that context these metaphors can be very misleading.

To build a stellar intensity interferometer to measure visible stars we needed lots of money and to convince the people who might give us that money, and to reassure ourselves that our ideas were sound, we did some experiments.

As a first experiment[3] we built an optical analogue of our radio interferometer (Figure 2) We made an artificial star by focusing the light from a high pressure

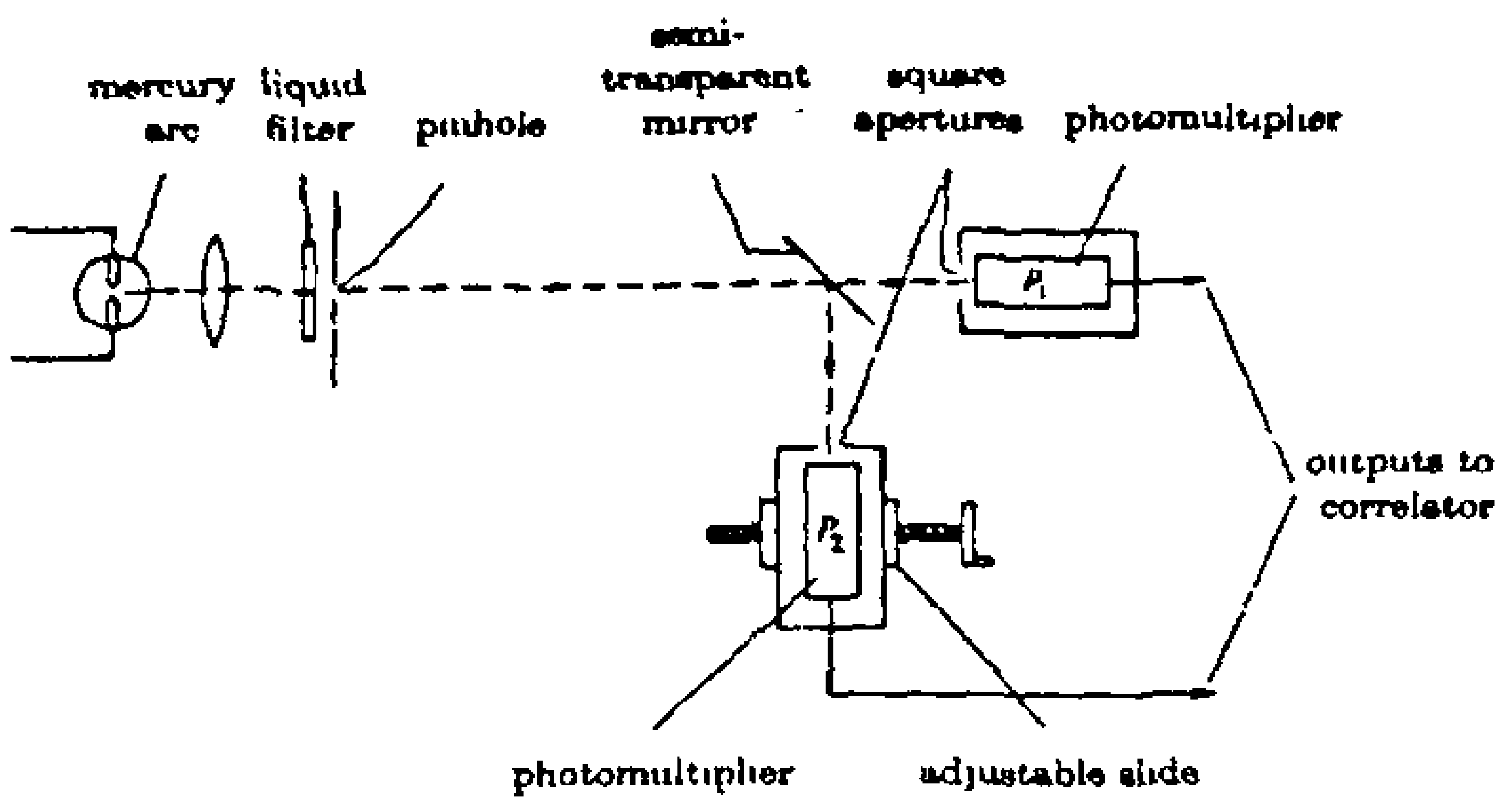

Figure 2. Optical system of first correlation experiment

mercury arc through a narrow band optical filter on to a pinhole. The light was then divided by a half-silvered mirror into two beams which were detected by identical phototubes. To vary the spacing between the detectors, as seen from the pinhole, one phototube could be translated sideways. In this experiment the number of photons was so great that the individual pulses in the output of a phototube were superimposed and formed a continuous waveform of noise which was fed to an electronic correlator with a bandwidth of about 50 MHz. The correlation between the two noise outputs was measured as a function of the spacing between the detectors. The total observing time was 9 hours; the results are shown by the points in Figure 3.

By assuming that the probability of emission of a photoelectron is proportional to the intensity of the light, we showed that there are two components of noise in the output current of a phototube, the classical 'particle' or 'shot' noise in a stream of electrons and the 'wave' noise due to the fluctuations in the intensity of the light itself. Obviously the particle noises from the two phototubes are uncorrelated; but if the light on their photocathodes is mutually coherent then the wave noises will be correlated. I will not go through the rather cumbersome expressions for the correlation which are given in the literature, but simply point to the solid line in Figure 3 which shows the theoretical correlation for this experiment.

As you can see the experimental results agreed well with theory and any residual doubts which we had about our proposal for an optical interferometer were laid to rest.

All the same, Twiss and I thought it would be interesting, and good for our public relations, to demonstrate more clearly that the arrival time of individual photons is actually correlated; we therefore set up the experiment shown by Figure 4. The optical layout was similar to the first experiment but to achieve a workable signal noise ratio with individual photons the light source must have a very high specific intensity; we used an electrodeless mercury isotope lamp excited by radio-frequency. The output of each phototube was taken through wide-band amplifiers to a coincidence counter with a resolving time of about 3.5 × 10^{-9} s.

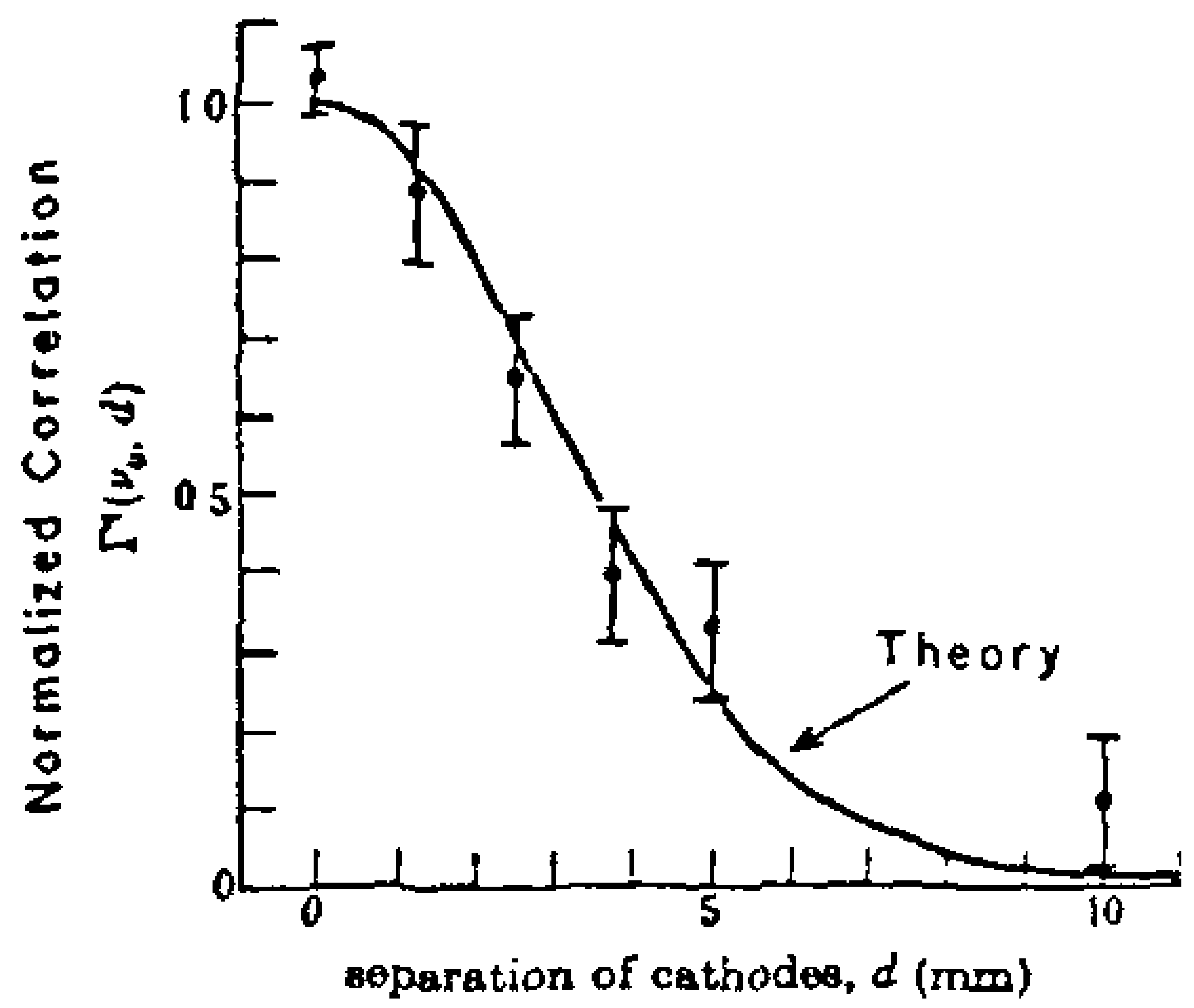

Figure 3. Results of first correlation experiment

The rate of arrival of photoelectrons in each channel (N_1, N_2) and the number of coincident pulses (N_c) was measured for two minutes, first with the two photocathodes superimposed, as seen from the pinhole, and then with them sufficiently far apart to resolve the pinhole. In a total exposure time of eight hours we measured the ratio of the 'excess' of correlated coincidences ($N_c - N_r$) to the random coincidences (N_r) to be,

$$(N_c - N_r)/N_r = 0.0193 \pm 0.0016 \text{ (p.e.). experimental}$$

Theory showed us that the coincidence rate should be,

$$N_c = N_1 N_2 2T_c [1 + \tfrac{1}{2} |\gamma_{12}|^2 T_0 / 2T_c] \qquad (1)$$

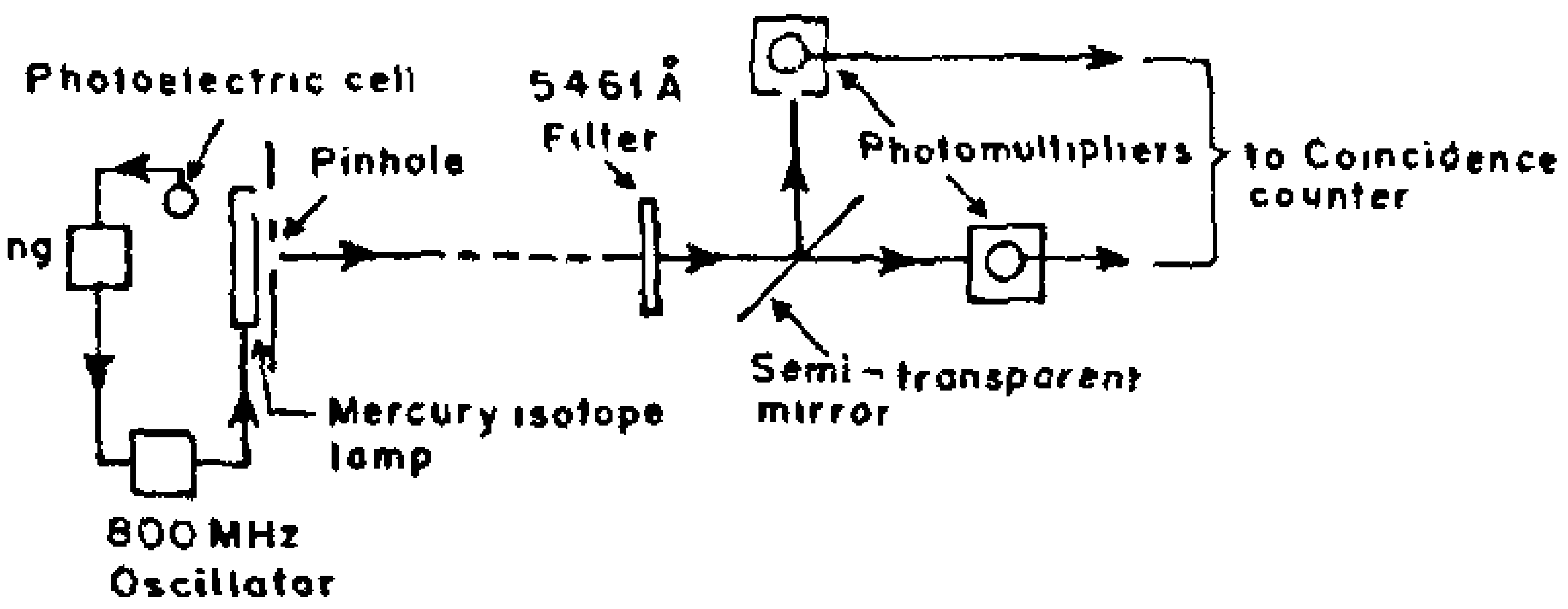

Figure 4. Optical system of second correlation experiment.

where $N_1 N_2$ are the counting rates in the two channels, T_c is the resolving time of the coincidence counter, T_0 is the coherence time of the light, $|\gamma_{12}|$ is the modulus of the mutual coherence of the light on the two photocathodes and it is assumed that in practice $T_c \gg T_0$.

The first term in equation (1) corresponds to the inevitable random coincidences between two streams of photoelectrons; the second term corresponds to the 'bunching' of particles which obey Bose statistics and it increases the coincidence rate when the light is mutually coherent on the two photocathodes.

The expected value of $(N_c - N_r)/N_r$, calculated from equation (1) after allowing for the partial resolution of the pinhole by the photocathodes and a small loss of correlation due to polarization in the half-silvered mirror, was

$$(N_c - N_r)/N_r = 0.020$$

(with an uncertainty of about 0.002).

Within the rather wide limits of error, the observed correlation agreed with theory.

Thus, although this second experiment was not as precise as the first, it was a clear demonstration that the time of arrival of individual photons in mutually coherent beams of light is actually correlated.

So far so good, but to raise money for a new interferometer we still had to show that we could actually measure a star. To do this I borrowed two very large searchlights from the Army, removed their arc lamps and put phototubes at the focus of their mirrors. With this equipment I measured the angular diameter of Sirius in 1956, the first time the angular size of a main sequence star had ever been measured. The whole thing worked perfectly; there was no need for high mechanical precision; furthermore Sirius twinkled violently most of the time but that didn't affect the measurements.

The stage was now set to build a full-scale instrument which we did in partnership with the University of Sydney. In 1962 it was installed in the Australian bush at Narrabri some 350 miles north west of Sydney.

It was a very striking instrument – the light from the star was received by two 260 inch mosaic glass mirrors which ran on a circular railway track 200 metres in diameter. At the focus of each mirror there was a photomultiplier whose output current was carried by a catenary cable to a laboratory in the centre of the track. The correlation between the electrical 'noise' in the two currents was measured by an electronic correlator with an electrical bandwidth of 100 MHz. The angular size of the star was measured by recording this correlation as a function of the spacing between the two mirrors.

It worked perfectly for 12 years during which time we measured the angular sizes of 32 of the brightest single stars in the southern sky in the spectral range O to F. Those measurements were the first ever to be made of main sequence stars. In fact they established the first wholly empirical temperature scale for stars; all previous scales had been based on theory. We did lots of other experiments, on double stars, spinning and emission-line stars and the Cerenkov radiation from gamma rays, but I won't bother you with all that.

The Stellar Intensity Interferometer was designed to measure stars brighter than magnitude + 2.5 and when that was done I shut it down and sold it for scrap, leaving the foundations of its great circular track for future archaeologists to interpret.

The work I started at Narrabri goes on. To measure fainter stars we decided to go back to square one and find out if the original difficulties of enlarging Michelson's stellar interferometer could be overcome using all the latest gadgets which weren't around in his day – lasers, narrow-band filters, phototubes, computers, active optics and all that sort of thing. We believe that this will yield a cheaper and more sensitive instrument than a larger intensity interferometer.

Let me show you how far we've got. The new instrument at Culgoora near Narrabri is called SUSI (Sydney University Stellar Interferometer) and is run by Professor John Davis. SUSI has 12 small mirrors – coelostats – in a line 640 metres long; they reflect the light from a star into an evacuated pipe which carries it to a central laboratory where there is a very impressive optical system. By selecting different pairs of mirrors it is possible to work with baselines in the range 5 to 640 metres.

The faintest star which SUSI can reach is expected to have a magnitude of + 8 or + 9, over 100 times fainter than the original instrument at Narrabri could reach, and the angular size range will be from 0.02 to 0.00005 seconds of arc. It has already worked with baselines of up to 80 m and in the near future I think we can look forward to great things.

1. Brown Hanbury, R. and Twiss, R. Q., *Phil Mag*, 1954, 45, 663–682
2. Jennison, R. C. and Das Gupta, M K., *Phil Mag Ser. (8)*, 1956, 1, 55.
3. Brown Hanbury, R., *The Intensity Interferometer*, London, Taylor and Francis, 1974.

Bose statistics – Before and after*

N. Mukunda

Centre for Theoretical Studies and Department of Physics, and Jawaharlal Nehru Centre for Advanced Scientific Research, Indian Institute of Science, Bangalore 560 012, India

Quantum theory was born in October 1900 with Max Planck's discovery of the law of spectral distribution of the energy density of black-body radiation. Around June–July 1924, Satyendra Nath Bose from the Department of Physics at Dacca University sent to Albert Einstein a short four-page paper containing the first logically complete derivation of Planck's Law. Einstein had a great deal to do with recognizing the importance of Bose's work, having it published, and applying the idea elsewhere.

The story of what happened in the quarter century between Planck and Bose has been recounted on many occasions[1], and as the saying goes, to do so again might be 'as tedious as a twice-told tale, to vex the dull ear of a drowsy man'[2]. But the occasion of Bose's birth centenary is very special, making it well worth telling the tale again for a new generation of readers. In this spirit, I will try to describe the background to Bose's work, as a crowning achievement in a great chapter of physics, and convey its significance and impact. With no pretense to completeness, some of the personalities in the history of this subject will be recalled, and the principal events selectively and briefly recapitulated in chronological order.

Universal temperature radiation

1859–60. The story begins with Gustav Kirchoff of the University of Heidelberg, sometimes called the grandfather of the quantum theory. Kirchoff studied the properties of radiation in equilibrium with matter at a given common temperature, and on thermodynamic arguments proved the following basic result[3]:

$U(\nu, T)$ = energy density of radiation at temperature T per unit frequency interval at frequency ν
= a universal function of ν and T, independent of the nature of the matter emitting and absorbing radiation. (1)

Such radiation has come to be called 'black-body radiation', or sometimes also 'temperature radiation'. This *universality* concept due to Kirchoff is clearly a very fundamental one; it naturally directed both experimental and theoretical attention to the measurement and explanation of the function $U(\nu, T)$.

1879. Some two decades later, Josef Stefan experimentally measured the total energy density of radiation at temperature T, 'summing' over all frequencies, and found that it was proportional to the fourth power of the temperature[4]:

$$\int_0^\infty d\nu \, U(\nu, T) = \sigma T^4. \tag{2}$$

1884. A few years later, Ludwig Boltzmann was able to give a theoretical explanation of Stefan's findings[5]. He treated temperature radiation as a thermodynamic system on its own, and made use of the fact that the pressure exerted by radiation is one-third its energy density. This directly led to the result, equation (2), which is known as the Stefan–Boltzmann Law – and the constant σ is named after both of them too.

1893. Next we come to the ingenious theoretical analysis of Wilhelm Wien, who proposed what would today be called a thought experiment[6]. He considered temperature radiation contained in a spherical cavity with perfectly reflecting walls, and analysed the effect of slowly – adiabatically – reducing the radius of the cavity. In the process the temperature of the radiation

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* Based on talk given on 13 January 1994, at the Raman Research Institute, Bangalore 560 012, India