AMAL KUMAR RAYCHAUDHURI

(14 September 1923 – 18 June 2005)

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(1923-2005)

Elected Fellow 1987

EARLY DAYS

AMAL KUMAR RAYCHAUDHURI a doyen of Indian general relativists, popularly referred to as AKR by his friends and admirers, was born in Barisal, now in Bangladesh, on 14 September, 1923. His father was a school teacher in mathematics in Kolkata and AKR might have imbibed his love for mathematics from him. In an interview[1] AKR has described how he loved to solve problems from his school textbook well before the portion was taught in class. On one occasion he wrote a solution of a math problem in the examination, which he believed to be more elegant than the solution given by the teacher. The Headmaster was much impressed by this solution and published it in the school magazine giving due credit to AKR for its authorship.

However, the Raychaudhuri clan was greatly inspired by his father's cousin Professor Hemchandra Raychaudhuri, a renowned historian and Carmichael Professor of History at the University of Calcutta[2]. It is very likely that it was from the scholarly Hemchandra that AKR and others of his family of the same generation derived inspiration to achieve academic excellence. On his mother's side, her two brothers had brilliant careers with one opting for law and the other for medicine.

The reason for mentioning these family examples is that very often early influences from high achievers in close proximity can serve as motivators for intellectual and creative brilliance. Although the Raychaudhuri family was amongst the local aristocrats, the Barisal region did not have much to offer by way of scholastic ambience. It was, moreover a hotbed for nationalistic activities which, though well motivated, did not permit the nurture of academic talent. Not surprisingly, the young AKR was brought up in Kolkata where he graduated from the Presidency College and later went on to do his M.Sc. in physics at the University of Calcutta.

After his Masters, AKR joined the Indian Association for the Cultivation of Science (IACS) in Kolkata where he spent four years in the research scientist cadre in the field of X-ray crystallography. However, those four years came to nothing as AKR realized that his liking lay not in that experimental field but in theoretical physics, a subject demanding mathematical abilities of a high order, which he excelled in. In 1950 he joined the Ashutosh College, Kolkata, in a teaching position.

The leading personality in applied mathematics in those days was Professor NR Sen, who had built up a school of general relativity around him. AKR joined his group and developed a liking for astrophysics and relativity, although his interest was more from a mathematical angle. However, he soon discovered that Professor Sen did not much encourage his line of investigations in general relativity. Indeed, AKR found the attitude of Sen's group too conservative for his liking and after some time stopped going to the group meetings[1].

In 1958 AKR married Nomita Sen. They had four children, sons Amlanava and Asimava and daughters Madhukshara and Parongama.

RESEARCH

AKR, really began his research career as a loner. His ideas were highly original and he felt the need to have opinion of some distinguished scientist in the field and preferred to approach the legendary Satyendra Nath Bose. Bose's response appears to have been negative as he refused to discuss the work or offer advice[2]. The area in general relativity and cosmology that AKR chose to work on, related to the formation of large scale structure in the universe. This field had been explored by Eddington and Lemaitre in the 1930s but had not been much discussed by contemporary cosmologists of the 1950s. Today it holds centre stage in cosmology and several groups all over the world are active in it, using high speed computers as a necessary aid. The purpose of the exercise is to demonstrate how in a largely homogeneous and isotropic universe, matter conglomerations could be built up. More than five decades ago, there was very little of direct observation to help the model builder. However, against that background AKR's 1952 paper[3] stands out as a perceptive attempt to come to grips with this problem.

AKR's early work also included clarifying the physical nature of the classical Schwarzschild solution. What is the status of the Schwarzschild radius $2GM/c^2$ at which the metric apparently becomes singular? Raychaudhuri worked out a collapsing solution that showed how this radial distance from the centre could be attained and that there was no singularity there[4].

AKR's main impact, however, was in the field of cosmological models. The attempt to understand the large scale properties of the universe with the help of mathematical models really took off in 1917 with Einstein's attempts to describe the universe (believed to be static) as a 'solution' of his field equations:

$$R_{ik} - 1/2\, g_{ik}R + \lambda\, g_{ik}R = - [8\pi G/\, c^4]\, T_{ik}.$$

The first two terms on the left hand side denote tensor quantities specifying the curvature of spacetime while the right hand side introduces the physical content of the universe through the energy momentum tensor. The term on the left hand side containing the constant λ is the so-called cosmological term representing in

Newtonian terms, a force of repulsion between any two particles, proportional to their distance apart.

These equations are a set of ten nonlinear partial differential equations in four spacetime variables and to solve them in full generality is an impossible task. So, Einstein assumed simplifying properties for the universe which made the problem simpler and more tractable. In his attempts to get a static solution Einstein was forced to modify his original equations by adding the cosmological term.

The cosmological models used by later theoreticians were also obtained from Einstein's general theory of relativity. Alexander Friedmann[5] and Abbe Georges Lemaitre[6] in the 1920s, assumed the universe to satisfy the cosmological principle as well as Weyl's postulate. The latter assumed that the motion of large scale matter (e.g. galaxies) in the universe is highly regular, permitting the use of special coordinates to describe space and time. Thus it is assumed that the world lines of galaxies form a bundle of non-intersecting time-like geodesics which have a system of space-like hypersurfaces orthogonal to them. These hypersurfaces allow us to define a 'cosmic' time t, with a global property that at t = constant, the space in the universe (as defined by the typical Weyl hypersurface) is homogeneous and isotropic. The typical galaxy likewise can be given constant comoving spatial coordinates (r, θ, ϕ). The homogeneity and isotropy of the universe is what the cosmological principle assumes. Given these assumptions the line element describing the spacetime geometry of the large scale universe is the well-known Robertson-Walker (R-W) line element:

$$ds^2 = c^2\, dt^2 - S^2(\,t\,)\,[\,dr^2/\,(1 - kr^2\,) + r^2(\,d\theta^2 + \sin^2\theta\,d\phi^2)].$$

Here S is a function that describes the expansion of the universe (if S increases with cosmic time) while the curvature parameter k takes values +1, 0 or, −1 depending on whether the hypersurfaces t = constant have positive curvature (closed space), zero curvature (flat space) or negative curvature (open space).

The function S(t) and the parameter k can in principle be determined by solving Einstein's field equations and relating the geometry of the model to observations of the real universe. All Friedmann-Lemaitre models describe an expanding universe, which was soon seen to be consistent with the astronomical observations of Edwin Hubble[7]. However, it was clear by 1950 that all models of the above class, i.e., using the R-W line element have an epoch when S was zero. This epoch, at which one may set t = 0, is commonly known as the 'big bang' epoch.

The big bang epoch has a peculiar status in cosmology. To some it represents a profound statement about the creation of the universe. Prior to this epoch, there was no universe; after the big bang, there was all of it – expanding away at extremely large, literally infinite speed. The density and temperature of the universe after the big bang were infinite too. Did this represent the primordial creation process, giving

a scientific version of what many religions have professed about the 'Creation'? To others this represented no more than what it was, namely a mathematical singularity. The notion of an infinite universe contained in a zero volume at infinite temperature indicated that the mathematical apparatus used to describe the universe, namely the R-W line element and the Einstein equations was defective. Can one find a better description that got rid of the singularity? A possible way was to abandon the highly symmetric R-W line element but still retain faith in the Einstein equations.

One way to try for this was to assume that the universe has a spin. As we know, in a spinning frame of reference pseudo (inertial) forces arise and these include the centrifugal force. The centrifugal force is outward directed from the axis of spin and so will try to prevent the collapse of matter towards the axis. This is why some cosmologists felt that spinning models would prevent singularity.

The first interesting spinning universe model had been constructed by Kurt Gödel[8] in 1949 and had been proposed as a demonstration that such a model violates Mach's principle. The Gödel universe, though mathematically interesting, did not have contact with reality so far as astronomical observations were concerned. It was stationary, had closed time-like lines and used the cosmological constant which in the 1950s was not much in favour. Could one have dynamical models that had an expanding spinning universe sans a singular phase?

While some specific models were being investigated, Raychaudhuri made an entry into the field with a general equation that now bears his name[9]. The Raychaudhuri equation may be simply stated thus:

$$d\Theta/ds + \Theta^2/3 = R_{ik} u^i u^k + 2\,\omega^2 - 2\sigma^2 + [du^k/ds];k,$$

where, the various terms of the equation may be briefly explained as follows. The u_i is the four-velocity vector of the particles in the universe, assumed to form a congruence of world lines. Θ is the function denoting the divergence of this flow vector and as such measures the expansion ($\Theta > 0$) or contraction ($\Theta < 0$) of the system of particles. The ω is a measure of its spin while σ measures its shear. The derivative d/ds measures the rate of change of a physical quantity along the path of a typical fluid element. Thus du^k/ds is the 4-acceleration measured along the fluid path. The Ricci tensor R_{ik} reminds us that we are working within the framework of Einstein's equations. The singularity arises when the expansion function Θ goes to plus or minus infinity.

The significance of the Raychaudhuri equation is as follows. The first term on the right hand side denotes the effect of gravity of the contents of the universe. It has generally a negative sign and in this case tells us that its tendency is to help formation of singularity. The second term arising from spin has positive sign and it does go towards avoiding a singularity. However, there is also the term with the

opposite sign, arising from shear that helps the system towards singularity. Thus the outcome is left tantalizingly indecisive. But more importantly, the equation clearly separates and identifies the dynamical effects from various sources that control the expansion or otherwise of the universe.

The Raychaudhuri equation paved the way for later research into the singularity problem. Thus the important results of the late 1960s by Roger Penrose, Stephen Hawking and Robert Geroch gave detailed conditions that decided the outcome in various cases[10]. The overall conclusion was that the singularity is unavoidable unless one has strange energy conditions, i.e., the presence of negative energy fields or negative stresses. The starting point of all these investigations was the Raychaudhuri equation. One can see this consequence from the fact that we can have universes with shear but no spin, but not vice versa. Thus although spin brings a tendency to avoid singularity, it is always accompanied by shear that overrides this tendency.

Apart from this fundamental work, AKR continued his work in gravity theories, especially the Brans-Dicke theory that allowed a variable gravitational constant. His interest in singularities continued and almost to the end of his life he was engrossed in problems of this nature. He was publishing in reputed journals long past his (notional) retirement. In his later work he returned to the singularity question and pursued his earlier quest of singularity-free models which violated the conditions of the singularity theorems of Penrose, *et al*. In a paper published in collaboration with Naresh Dadhich he showed (following an earlier work of Senovilla), how a singularity-free spherically symmetric model of the universe could be obtained.

His involvement as a resource person, with the activities of the Inter-University Centre for Astronomy and Astrophysics (IUCAA) since it was set up in 1988 considerably helped the research oriented activities of that centre.

TEACHING

Any account of AKR would be incomplete if it did not highlight his role as a teacher. In 1961 he joined the Presidency College, Kolkata as Professor of Physics. The Presidency College has a long reputation of attracting the cream of students from Bengal. Good students stand to gain considerably from inspiring teaching and this is what they got from AKR. His analogies to explain difficult concepts, his wit and sometimes bluntness made him a teacher to remember. Despite his successes as a researcher in gravity theory, one can say that his impact on the large body of students was even more valuable.

There are today scientists all over India and abroad, and other Presidency-alumni, who at some time came under AKR's teaching umbrella and have felt empowered for it. There is an account[1] given by one such distinguished past-student of Presidency College, stating that he and some of his colleagues were so impressed

by AKR's personality that they used to follow him from his home to College to see (and possibly emulate) whatever he did. They saw AKR ride a tramcar to the College and after getting down visit the 'chana-choorwallah' (vendor of roasted chick peas) for a mouthful of chanachoor. Following the Shakespearean adage[11]

> *Upon what meat doth this our Caesar feed,*
> *That he is grown so great?*

These students also started patronizing the chanachoorwallah!

Despite the awe in which his students held him, AKR was accessible to them and was available to answer their doubts and queries even outside the lecture hall. In fact in an interview[1] he once lamented that whereas in the USA he encountered a lot of questions from students, most of his students in India seemed to take everything he said uncritically.

AKR wrote a monograph on Theoretical Cosmology which is now a well known introduction to the subject for those who wish to enter it for research. There one gets an account of the Raychaudhuri equation 'straight from the horse's mouth'. He also wrote college texts on classical mechanics and electromagnetism which bring out his pedagogical skills. One of his books (on dynamics) is in Bengali.

A PERSONAL PERSPECTIVE

Unlike a large number of alumni of the Presidency College, I had the opportunity of learning from AKR only from a distance! In 1960, when I was a budding research scholar at Cambridge, my supervisor Fred Hoyle asked me to work on spinning universes, with the expectation that they might provide finitely oscillating cosmological models. Indeed Heckmann and Schucking[12] in Germany were claiming that they had a model which would do that. While digging through background matter for this work, I came across Raychaudhuri's equation which set out the entire issue in correct perspective. Eventually I was able to show that the Heckmann-Schucking model did not fulfill the expectations centred around it. However, it was then that Hoyle and I felt impressed by AKR's work and hoped to meet him one day.

That opportunity arose in 1963 at the Texas Symposium on Gravitational Collapse and Relativistic Astrophysics where we met AKR who was also an invitee. Hoyle's first reaction on meeting AKR was to remark that 'he was so young'. Probably he expected AKR , because of the profundity of his work to be a much older man!

I came in closer contact with AKR only after my return to India in 1972, by which time he had already established himself as a teaching icon. Both as a teacher and a research worker he had set a high standard for a university academic that will be hard to equal.

HONOURS AND RECOGNITION

Needless to say, AKR was well recognized by his peers internationally in the field of general relativity and gravitation. He was elected member of the International Committee on General Relativity and Gravitation for the period 1974-83. He did not travel abroad much, despite many invitations from various relativity groups; the exception being his one-year at the University of Maryland.

For one who did not wish to push himself in public eye, recognition at home came more slowly but surely. AKR was elected Fellow of the Indian Academy of Sciences in 1982 and of the Indian National Science Academy in 1987. He was INSA Senior Scientist from 1988 to 1991 and UGC Emeritus Fellow from 1986 to 1988. He was also Fellow of the National Academy of Sciences. During 1980-82, he was President of the Indian Association of General Relativity and Gravitation. Apart from getting his Doctor of Science degree at the University of Calcutta (with one of the examiners, Professor JA Wheeler recording special appreciation of the work done), AKR received doctorates *honoris causa* from Burdwan, Kalyani and Vidyasagar Universities. He was an Honorary Fellow of IUCAA.

Even after retirement, AKR was associated actively with the Centre for General Relativity and Cosmology at Jadavpur University where he was an Honorary Professor. He died from cardiac arrest on 18 June, 2005. He is survived by his wife Nomita, and their four children.

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