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Professor Govind Swarup was a distinguished radio astronomer who drove the development of the field in India. Over a long career he built the Ooty Radio Telescope (ORT) and the Giant Metrewave Radio Telescope (GMRT), which are world-class facilities. Swarup was born in North India, had his undergraduate and post-graduate education at the University of Allahabad and then joined the National Physical Laboratory at New Delhi. He then travelled on a fellowship to Australia, to work on radio astronomy under J. L. Pawsey (FRS 1954). Later, in the USA, he completed his PhD with Ronald N. Bracewell at Stanford. Govind then accepted an offer made by Homi Bhabha FRS to begin radio astronomy work at the Tata Institute of Fundamental Research (TFIR). At TIFR, Govind conceived and built a novel, low cost, equatorially mounted cylindrical radio telescope, the ORT. The ORT was a versatile instrument and fuelled the growth of radio astronomy in India. In the late 1980s he conceived and led the construction of the GMRT, which again was based on a pioneering design. The GMRT is a remarkably successful instrument used by radio astronomers across the world. Govind Swarup has left behind a large group of radio astronomers who have continued his work and are finding new directions.

EARLY LIFE

Govind Swarup was born in 1929 in the small town of Thakurdwara in Moradabad district in the state of Uttar Pradesh in India, about 200 km to the northeast of Delhi. The town is

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in the plains adjoining the Himalayan foothills, and is located about 50 km from the famous Jim Corbett National Park, which is known for its tigers. Govind's father was Ram Raghuvir Saran and mother was Gunwati Saran. Govind's family had lived in the Moradabad region for generations. His great grandfather established a mill for cotton spinning in Moradabad in 1907, which was later managed by his grandfather. Govind's father built a cinema theatre in Delhi, and had a large farm in Moradabad district at which Govind spent his vacations.

Govind studied up to the seventh grade in the Sanathan Dharam School in Thakurdwara and then up to the tenth grade in the Hindu High School in Moradabad. In an autobiographical article in the *Annual Review of Astronomy and Astrophysics* (12)*, Govind recalled joining all the students in his school in a procession in August 1942 to shout 'Quit India', exhorting the British to leave the country. This was in support of the Quit India movement launched by Mahatma Gandhi. Govind also recalled reading articles by the Mahatma and his autobiography, which inspired him greatly. He read about the Milky Way galaxy (*Akash Ganga* in Hindi) in an article by the great Hindi poet Mahadevi Verma, which for him was the first lesson in astronomy. After his tenth grade, Govind's mother wanted him to become an engineer (engineering and medicine rank very high as professions for their children in most Indian mothers' minds to this day), but his father, being aware of his interests, sent him to the city of Allahabad to study science.

Starting off in science

Allahabad (now Prayagraj) is an ancient Indian city, located at the confluence of two great rivers, Ganga and Yamuna. During the freedom movement, many nationalist leaders visited Allahabad, with their meetings often taking place in Anand Bhavan (Abode of Happiness), a mansion built by Motilal Nehru, father of Jawaharlal Nehru, the first prime minister of India. Allahabad University, which is one of the oldest contemporary universities in the country, is a great seat of learning and research. Its most famous alumni include the astrophysicists Meghnad Saha FRS and Daulat Singh Kothari, and mathematician–physicist Harish-Chandra (FRS 1973). The alumni of Allahabad University also include three former prime ministers and two former presidents of India, and a former prime minister of Nepal. The young Govind was therefore in a very fertile and inspiring environment. Govind studied mathematics, physics and chemistry for two years at the Ewing Christian College, and then joined Allahabad University for his BSc.

Right in the first year of Govind's course, one of his teachers was Professor Sir K. S. Krishnan FRS, who had been a research student of Professor C. V. Raman FRS and was a co-author with him on the discovery paper of the effect for which Raman got the Nobel Prize. Krishnan mentored Govind for many years and set him on the path to radio astronomy. At midnight on 14–15 August 1947 Govind listened at Anand Bhavan to the radio relay of a stirring speech on India's 'Tryst with Destiny' being made by Jawaharlal Nehru in New Delhi as India attained independence.

In 1948 there was a session of the Indian Science Congress at Allahabad, where Govind and his fellow students were able to interact closely with two of the eminent people who came

* Numbers in this form refer to the bibliography at the end of the text.

to the Congress, C. V. Raman and the British mathematician and physicist Sydney Chapman FRS.

Govind obtained his MSc in 1948 from Allahabad University. Following his MSc, he joined the National Physical Laboratory (NPL) in New Delhi, which is a premier institution of the Council for Scientific and Industrial Research (CSIR). It was set up in January 1947 to strengthen and advance physics-based research and development in the country; one of its functions is to act as a measurement standards laboratory. Govind's former teacher, K. S. Krishnan, was appointed as the first director of NPL. Krishnan had then become interested in electron spin resonance (ESR), also known as paramagnetic resonance, which was discovered by Yevgeny Zavoisky in the erstwhile Soviet Union in 1945. Krishnan provided Govind with some papers that described observations of ESR in solids at microwave wavelengths, and asked him to build an apparatus for observing ESR at 3 cm wavelength, which corresponds to a frequency of 10 GHz. Govind was to use available war surplus radar equipment from which to get the components, and he had access to volumes of the *MIT Radiation* laboratory series devoted to radar and microwave technology developed at MIT during the war. With these limited resources, the then 22-year-old Govind got the apparatus ready in 18 months. This first experience was clearly very influential for Govind. Everything that he subsequently built in India involved innovation, improvization, stretching available resources to their limits through unique designs and doing whatever was needed to be done in the local circumstances to create world-class observing facilities.

Two years after joining NPL, Govind was introduced to his true calling because of a journey that K. S. Krishnan undertook to Australia. Krishnan attended an important radio sciences meeting, the General Assembly of the International Union of Radio Science (URSI) in Sydney in August 1952. At the meeting he heard much about the new discoveries made in the then emerging field of radio astronomy by scientists and engineers of the Division of Radio Physics of the Commonwealth Scientific and Research Organisation (CSIRO), led by J. L. Pawsey (FRS 1954). They had built several radio telescopes, and had published their results in a series of papers that constituted about one-half of all the papers in radio astronomy published worldwide until then. After his return to NPL, Krishnan described these exciting developments in a colloquium that greatly interested Govind. After reading some papers in the field, Govind decided that he should be working in radio astronomy, and he was able to make a beginning in the best possible way very soon. Krishnan recommended him for a Colombo Plan fellowship, which he obtained to work with the Radio Physics group at CSIRO.

In Australia on the Colombo Plan

The Colombo Plan for Cooperative Economic and Social Development in Asia and the Pacific, a Commonwealth initiative, was intended to assist the sharing and transfer of technology among member countries. It had a strong component of skills development. Krishnan arranged for funding via the Colombo Plan for Govind to travel to Australia and work with the CSIRO Radio Physics group. Govind was in Australia for two years, from 1953 to 1955. Joe Pawsey, the head of the Radio Physics group, suggested to Govind that he spend the first year working with four different experimental groups and the second year working on an independent project. Accordingly, Govind spent three months each working in the groups led by W. N. Christiansen, B. Y. Mills, J. P. Wild (FRS 1970) and J. G. Bolton (FRS 1973), who were all leading radio astronomers. Christiansen set Govind the task of making a two-dimensional (2D) image of the Sun, based on data from 1D strip scans at various position angles that had been obtained using two 1420 MHz grating interferometers at Potts Hill (figure 1). This was an extremely laborious process, involving multiple computations of Fourier transforms using an electrical calculator and graph paper. The map, when finally made (Christiansen & Warburton 1955) showed limb brightening, confirming earlier theoretical predictions. As Govind recounted (12), based on this painstaking early experience, several years later he came up with a simpler way of converting 1D strip scans into a 2D image. This was at Stanford, at a time when he was just about to leave for India. Consequently, he could not develop the idea further. However, Bracewell & Riddle (1967), with suitable modifications, used the technique to make a 2D image of the Moon using strip scan data from the Stanford interferometer. The method is now widely used in computerized tomography for medical imaging.

For his remaining projects in Australia, Govind developed various instruments, ranging from a high voltage DC power supply to a receiver working at 45 MHz to study solar bursts, and a phase shifter for a new ‘cross’-type antenna that was being built by Mills.

As per Pawsey’s advice, Govind was to spend the second year working on an independent project. The Sun at that time was one of the most widely studied radio sources. The richness of the solar emission phenomena, including the ‘quiet Sun’ emission, as well as the time and frequency characteristics of the different kinds of radio bursts, was being gradually uncovered. There was also considerable theoretical activity aimed at trying to understand these phenomena. For his project, Govind decided to work together with R. Parthasarathy (another Indian astronomer, also visiting Australia under the Colombo Plan) to observe the Sun at 500 MHz. Earlier observations by Stanier (1950) had indicated that there was no limb brightening at 500 MHz, which was contrary to theoretical predictions. Govind and Parthasarathy worked at converting the 1420 MHz 32-element interferometer built by Christiansen to work at 500 MHz in order to cross check this result. Phasing up the interferometer was a laborious process, involving pairwise measurement of the phases of the signal from each antenna and then equalizing the phases by introduction of a suitable length of transmission line. However, it was all finally done, and their measurements showed the expected limb brightening (1, 2). The same set-up was also used to observe radio emission associated with sunspots (3).

The Radio Physics group had no further plans for the 32-element interferometer modified by Govind and Parthasarathy, so when it was time to return to India, Govind asked if the antennas could be donated to NPL for use in India. Joe Pawsey readily agreed to this, and NPL was also happy to accept the antennas. CSIR (the parent organization of NPL), however, also requested CSIRO to bear the transportation costs. This unfortunately led to a significant amount of correspondence and delay, and by the time the dishes finally arrived in India, Govind had moved to Fort Davis, Texas. The dishes did eventually find a use, however, being made into the Kalyan Radio Telescope, described below.

USA

At NPL Govind waited for the paperwork for the transfer of the Mills cross antennas to get done, but eventually, seeing little sign of convergence, he decided to apply to a few places in the United States to continue his work in radio astronomy. Donald Menzel of Harvard University offered him a research associate position at the newly established Fort Davis

Figure 1. Govind Swarup (seated) and R. Parthasarathy at Potts Hill field station. A radar antenna salvaged from the Second World War equipment being used as a radio telescope is seen in the background. From *Illustrated Weekly Times, of India*, 1954 (copyright unknown).

Observatory. In 1956 Govind, along with his new bride, Bina, flew to the USA. After a brief stop at Harvard, where he was shown around by Bart Bok, Govind took up the position at Fort Davis to work with Alan Maxwell. The primary instrument at Fort Davis was a 28-foot paraboloid, used for observations of the Sun at a range of frequencies from 100 to 500 MHz. The system was significantly more sensitive than any other existing solar radio telescope. Govind took daily observations of the Sun, with the broad aim of correlating solar radio bursts with other known solar phenomena such as flares.

One of the important discoveries he made during this period was of solar 'U'-type flares, where the frequency of the emission decreases and then increases with time, making a U shape in a plot of the dynamic (time vs frequency) spectrum. This suggested that the emitting material was being guided along magnetic field lines of opposite polarity, for example bipolar Sun spots (4).

Following his research at Fort Davis, Govind decided to complete his formal education by getting a PhD degree. He had offers from a number of leading universities, and wrote to Joe Pawsey for advice on which one to accept. Pawsey wrote back (12): 'I also agree with you in trying to get a combination of astronomy, electronics and physics. If you are returning to India, I should recommend to you to place great emphasis on electronics. It is a key to open many doors. Stanford is famous for radio engineering, Caltech for its physics and, of course, its astronomy research, and Harvard for its training in astronomy.' Following this advice, Govind moved to Stanford to work with Ron Bracewell for his PhD (figure 2). Stanford offered him financial support, which was tied to half-time work on the Stanford Cross. One of the tasks that Govind had to do was to adjust the phases of all 32 antennas in the cross, tedious work involving pair by pair comparisons, as he had done earlier for the array at Potts Hill with Parthasarathy. After one round of phase adjustments, it was found that the array output was still erroneous, which was traced to an error in the spacing of the antennas. This was corrected, after which the array had to be phased again. Daunted at having to start over from scratch, and having to handle this work along with his course work, Govind began to think of better ways of phasing the antennas. The scheme he came up with (5) was to broadcast a signal from a central location to all the antennas, where part of it was modulated and sent back. This allowed one to measure the 'round trip phase' rapidly, and a task that earlier took several weeks could now be accomplished in a few minutes. Over the years, this scheme has been routinely used at all radio interferometers, as well as for measuring the round trip phase of transmitters in space.

Following his PhD, which was titled 'Studies of solar microwave emission using a highly directional antenna', Govind was offered positions at various other institutions in the USA. However, since he was already planning to return to India, he did not accept any of them. Instead he took up a three-year appointment as an assistant professor at Stanford University.

Ambitious plans to set up a radio astronomy group in India

During his stay at Stanford, Govind had been thinking about returning to India and setting up a radio astronomy group there. He discussed these ideas on several occasions with two other young Indian radio astronomers then working in the USA, M. R. Kundu and T. K. Menon, and, finding them in agreement, wrote about the matter to Pawsey, Christiansen and Frank Kerr in Australia. He got a positive response, along with the suggestion that a fourth Indian astronomer, T. Krishnan, who was then with the Radio Physics group in Sydney, should also be included in the group returning together to India. Pawsey advised the group that they should work unitedly on a large project, to keep off fashionable stuff and develop their own ideas, and to keep in mind the importance of good experimental technique.

The four Indian radio astronomers, Swarup, Kundu, Krishan and Menon met at the International Astronomical Union General Assembly in Berkeley in 1961, following which they developed a joint proposal to set up a programme of radio astronomical observations with the 32 antennas that had been sent from Australia to the NPL in New Delhi. That was to be the first step of a more ambitious programme for radio astronomy in India, including the setting up of a radio telescope of novel design that would provide high resolution at lower radio frequencies, since such a telescope would be cheaper to build in India. The proposal was sent to five research organizations in India, including the Tata Institute of Fundamental Research

Figure 2. Govind Swarup with Ron Bracewell, his PhD supervisor, at Stanford University (copyright unknown).

in Bombay (now Mumbai). Copies of the proposal were also sent to five leading astronomers, Bart Bok, J.-F. Denisse, Jan Oort FRS, J. L. Pawsey and Harlow Shapley, with the request that they provide confidential assessment to the organizations to which the proposal had been sent. Some of the supporting letters sent are on record, and reproduced in figure 3 is an extract of a letter from Bart Bok to Homi Bhabha FRS.

Dr Homi Bhabha FRS set up the Tata Institute of Fundamental Research (TIFR) in 1945, and later the Department of Atomic Energy. He obtained his PhD on cosmic radiation and the creation of positrons and electrons as a student of R. H. Fowler FRS at the University of Cambridge. He was a visionary with great talent for identifying areas of research that could be productively undertaken in India. He had set up a very good cosmic ray research group and

> Here is the case of four young, but renowned, Indian Radio Astronomers, all thoroughly trained and with good research records, and with a background for doing effective radio astronomical research hardly equalled by any group that one might assemble anywhere in the world. Any one of the four can readily obtain offers of positions in the field of radio astronomy, and all four are doing good work in the organizations with which they are associated. It seems to me that their offer to return to India as a group is a unique one, and one that should by all means be accepted and acted upon promptly. An offer like the present one comes only rarely in the history of the scientific development of a nation which, scientifically is obviously coming of age.

Figure 3. Extract of a letter from Bart Bok to Homi Bhabha. Used with permission of TIFR.

it was clear to him that the plan for radio astronomy proposed by the four young researchers had the same kind of promise. Bhabha met T. K. Menon, as the representative of the group of four, in Washington DC in November 1961. The meeting went very well, and Menon wrote to his colleagues about the impressively large financial outlay that Bhabha had in mind for developing major facilities for the group.

After lengthy discussions—described in Goss (2014)—with Homi Bhabha and M. G. K. Menon (FRS 1970), who was then the dean of the physics faculty at TIFR, Govind was appointed as reader and arrived at TIFR with his family in April 1963 to take up the position. He remained with the institute until he passed away in September 2020. Interestingly, the time spent by the other three members of the group in TIFR was very different. Kundu arrived at TIFR in 1965 and returned to the USA in 1968 to join the University of Maryland, where he remained until his passing away in 2010. Menon joined TIFR only in 1970 and left in 1974 for the University of British Columbia, where he is now an emeritus professor. T. Krishnan never joined TIFR.

Cygnus A

Cygnus A (Cyg A) is one of the best-studied radio galaxies. It is extremely powerful at radio wavelengths and is located relatively close to us, so that the radio flux from it is very high. In general, the more powerful or luminous a source is, the rarer it will be, and therefore such sources would be at great distances from us. At a distance of ‘only’ 760 million light years, Cyg A is anomalously close to us, so that it appears very bright at radio wavelengths and could be detected by the earliest telescopes. It was first detected as a discrete radio source in the constellation Cygnus in the late 1940s. It was then observed by early versions of radio interferometers, which provided ground-breaking results. Jennison & Dasgupta (1953), who were both research students at the Jodrell Bank observatory, found from their interferometric observations that Cyg A was actually made up of two well separated radio sources or lobes. Soon after that, Baade & Minkowski (1954) used the precise position of Cyg A, determined from interferometric observations, to identify it with an elliptical galaxy, making Cyg A one of the first radio galaxies to be identified. The two lobes were situated symmetrically on two sides of the galaxy. It was later established that double radio structures are common to radio galaxies, and that they are powered by energetic jets that emerge from a central engine. The discovery of the double structures was key to the development of the theoretical models of the radio sources.

While Govind was at Stanford, he was mostly concerned with radio observations of the Sun. But he did interesting work on Cyg A, using an interferometer at Stanford, which J. S. Pickens and he had designed. Observations of Cyg A revealed a bridge of radio emission between the two radio lobes. There had been some indication of such a structure in observations by Lequeux (1962), but the interferometric observations (6) had for the first time sufficient resolution to clearly reveal the structure. This pioneering observation was later followed by the discovery of such structures in many radio galaxies. They occur through the interaction of the energetic jets that arise from the central nucleus with the ambient medium and the radio lobes. This work on the radio bridge in Cyg A was the last scientific project that Govind carried out at Stanford. We thank Professor Gopal-Krishna for having drawn our attention to this work, which is described in greater detail in Gopal-Krishna (2021).

At the Tata Institute of Fundamental Research

Arrival in Bombay

Govind, his wife Bina and their two young children arrived in Bombay (now Mumbai) by boat in 1963. After visiting their parents and relatives in the north, they settled in an apartment block of the Department of Atomic Energy, Kenilworth, located in one of the poshest areas of Mumbai called Malabar Hill. Bina remembers that as new arrivals they were helped greatly to settle down in the large city, with which they were not familiar, by colleagues from the TIFR, particularly M. G. K. Menon. While Govind embarked on his work in radio astronomy, Bina obtained a BEd degree and became a teacher in a very well known school; she remained involved with teaching for many years.

The Kalyan Radio Telescope

Soon after joining TIFR in 1963, Govind started a radio astronomy group there with fresh students such as Vijay Kapahi (who would later become the second Centre Director of the National Centre for Radio Astronomy) from the Bhabha Atomic Research Centre (BARC) training school, as well as colleagues with experience in radio astronomy who moved from NPL to TIFR. By this time the 32 antennas donated by CSIRO had also arrived at TIFR. The nascent radio astronomy group used these antennas to set up a 610 MHz array near Kalyan, a town about 40 km away from TIFR (figure 4). The system used a novel transmission line arrangement to connect the antennas (8) and was soon being used for making observations of the Sun. The early work on limb brightening of solar emission appeared in *Nature* (7). The Kalyan Radio Telescope was also an invaluable training ground for the newly joined students.

The Ooty Radio Telescope

While the Kalyan Radio Telescope was being set up, Govind was already planning for a much bigger telescope. The first quasar, 3C273, was discovered (Hazard *et al.* 1963) just around the time that Govind joined TIFR. While compact radio sources had been observed for many years before this, their optical counterparts were in general difficult to determine, because the relatively poor angular resolution of the early radio telescopes prevented the accurate determination of radio source positions in the sky. The position of the radio source 3C273 was first accurately determined by observations by Hazard *et al.* (1963) with the Parkes 64 m radio telescope of the occultation of the radio source by the Moon. Once the position was accurately

Figure 4. Setting up the Kalyan Radio Telescope. Govind Swarup is on the right. Used with permission of TIFR.

known, it was relatively straightforward to identify the optical counterpart, and follow-up spectroscopy showed that it was at the then record-breaking redshift of 0.158 (Schmidt 1963).

This discovery set Govind thinking about the possibility of using lunar occultation to make high angular resolution measurements of a large number of radio sources. At that time, there were two competing cosmological models: the Big Bang model, where the Universe had an origin and evolved with time, and the Steady State model, where there was no origin in time and the observable properties of the Universe were the same at all locations in space and time. Observations with a radio interferometer at Cambridge of the variation of the number of radio sources as a function of the observed flux (‘the log(N) log(S)’ relation) had been interpreted as invalidating the Steady State model (Ryle & Clarke 1961). The argument, however, assumed that the fainter radio sources were further away. Fred Hoyle FRS, a proponent of the Steady State model, argued that the fainter sources need not be further away, and in the absence of measurements of the distances to the sources, the issue remained controversial. One way to cross-check this was to measure the angular sizes of radio sources. If fainter sources were further away, one would expect them statistically to have smaller angular sizes. Unfortunately, there were very few sources with measured angular sizes. Govind realized that one could use lunar occultation to measure the angular sizes of a large number of sources, which could help resolve this issue. The catch, though, was that the sensitivity required was very large, at least four times larger than the best existing radio telescope of that time (i.e. the Jodrell Bank 76 m and the Parkes 64 m telescopes). Obviously, building a bigger Jodrell Bank-type parabolic dish antenna in India was not a feasible solution.

Gnawing away at this problem, Govind came up with an ingenious solution. Parabolic cylinders are much cheaper to construct than parabolic dishes, but have the disadvantage of being able to rotate only about a single axis. Tracking a celestial source with a traditional two-axis (altitude–azimuth) mounted antenna requires one to be able to rotate the antenna about two axes. The only way to track a celestial source by rotation about a single axis is to make the rotation axis parallel to that of the Earth (i.e. an ‘equatorial’ mount). Govind realized that the low latitude range of South India made it possible to have an equatorially mounted cylinder, provided one could locate a hill whose north–south slope was matched to the latitude. A parabolic cylinder built along the hill slope would then be effectively equatorially mounted, and could track the sky by rotation about the cylinder axis. M. G. K. Menon and Homi Bhabha were both extremely supportive, and work began quickly.

After an extensive site survey, a suitable hill slope was found at Muthorai village, at the outskirts of Udhagamandalam (‘Ooty’) in the Nilgiri Mountains. The telescope that Govind had conceived (the Ooty Radio Telescope, ORT) was a 530 m long, 30 m wide offset parabolic cylinder, with a reflecting surface made up of 1100 stainless steel wires. The mechanical design was done by Tata Consulting Engineers, and the construction contract was given to M/s Bridge and Roof of Kolkata.

Building this large and sophisticated telescope in India in the 1960s presented a number of challenges. Even the most routine of components could be hard to source. For example, a widely used coaxial cable connector (‘Type N’ connector) was not available in India at that time and, because foreign exchange was scarce, it was difficult to import. Govind had to get it developed locally using conceptual designs available in the literature. A large number of electronics systems had to be developed in-house. The young team worked away, however, and the first lunar occultation observations with the telescope were made on 18 February 1970. Shortly after the telescope was commissioned, it suffered a serious accident: the main shaft broke. Undeterred, the team did the required major repair, and also added a number of additional safety features. Following that, the telescope has operated without incident continuously until today. It remains one of the largest steerable radio telescopes in the world.

The ORT carried out lunar occultation observations of a large number of sources, among other things clearly establishing that radio sources evolve (Kapahi 1975; see next section). It also carried out a number of other studies, including the discovery of a non-thermal halo around the galactic centre (10), and discovery of the gravitationally lensed source 1830-211 (Rao & Subrahmanyan 1988; Jauncey *et al.* 1991). The telescope was also used for carrying out extensive studies of ionized gas in the Galaxy using radio recombination lines (e.g. Anantharamaiah 1985; Roshi & Anantharamaiah 1997), observations of pulsars (Saripalli *et* *al.* 1999; Krishnakumar *et al.* 2015) and extensive studies of the heliosphere via interplanetary scintillation of extragalactic sources (Manoharan 2012)

Bhabha had conceived of the ORT as part of a much larger inter-university centre, and a large parcel of land had been acquired for this. The aim was to create a centre for the training of scientists and engineers for challenging projects like the ORT. Unfortunately, owing to the untimely death of Bhabha in 1966, this did not come to fruition. Govind, however, retained an abiding interest in creating facilities for the training of young engineers and scientists.

Cosmology with the Ooty Radio Telescope

As mentioned above, one of Govind's motivations in constructing the ORT was to measure the angular diameters of radio sources, so that cosmological issues could be addressed. Many cosmic radio sources have two large lobes emitting radio waves along with a central nucleus that is, the ultimate source of the radio energy. The separation of the luminous extremities of the radio lobes provides a measure of the linear size of a radio source. In the Euclidean space of our normal experience, the greater the distance to such a source, the smaller its angular size will appear to be, but over cosmological distances Albert Einstein's General Theory of Relativity has to be used, in which space-time is curved and the Universe expands with time. Then the angular size of a radio source of the same linear size decreases with distance up to a certain maximum distance, and thereafter it can remain constant or even start increasing again, depending on the details of the cosmological model. If the change in the angular size of a radio source of fixed size with changing distance can be determined, then it should be possible to deduce the correct cosmological model.

While it is difficult to measure the distance to radio sources, the flux of energy received from the source can act as a proxy for the distance. For a source of a given power, the further the source is from the Earth, the less the flux received from it. Since both the angular size and the flux depend on distance, the dependence of the angular size on the flux can be worked out for a given cosmological model. For the simple Euclidean Universe, for a source with given power and size, the angular size would be proportional to the square root of the flux. Departures from this simple relation would provide clues to the correct cosmological model. The correlation between angular size and distance/flux had been studied by radio astronomers, but the results were not conclusive because not many measurements were available, especially for radio sources at great distance, where the effect of General Relativity would be most discernible. Govind realized that the ORT could help mitigate this problem, since it would provide significantly smaller angular sizes and fluxes than were earlier available.

By the early 1970s, high resolution observations with the ORT using the lunar occultation technique had provided angular sizes of several hundred sources. The radio flux of all these sources was observed to be weak, indicating that potentially these sources were at great distances. Govind combined these data with previous measurements made using the One-Mile radio telescope of the Mullard Radio Astronomy Observatory located near Cambridge and data from other existing catalogues, to put together a large set of radio sources with a range of measured flux and angular size.

A plot of angular size against flux showed that there indeed was a trend in the data for sources with smaller angular size to have lower flux, which would be consistent with such sources being at great distances. But there was great scatter in the data, which should indeed be expected, because of the different source powers and sizes, as well as noise introduced owing to the complicated measurement processes. To get over these limitations, Govind decided to

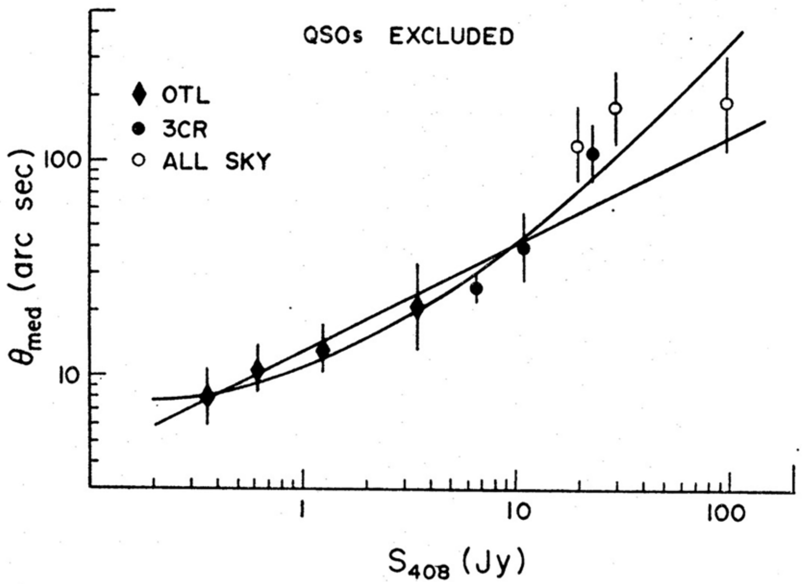

FIG. 4. *A plot of the median value of angular size θ_m against the median value of flux density S_{408}, excluding QSOs.*

Figure 5. From ‘Angular size–flux density relation for extragalactic radio sources’, by Govind Swarup (9). Reproduced with permission.

use the median values of the angular size and flux of sources in a number of bins of the flux. The result was dramatic, with a clear trend seen of the weaker sources being smaller and the brighter sources being larger, which was the anticipated result. A plot of the median values for radio galaxies is shown in figure 5 (9). The figure shows that, statistically, sources with lower flux, i.e. the fainter sources, have lower angular sizes, which is consistent with the fainter sources being further away, which is an important result. The distribution of the points in the figure is not statistically inconsistent with the expectation for a Euclidean Universe, but for the fainter sources, a hint of departure from the simple relation is seen. However, the data were not enough to provide further insight into the nature of the cosmological model. Govind’s work was carried forward by his student Vijay Kapahi (Kapahi 1975) and others to argue against the simple Steady State theory of the Universe.

The Ooty Synthesis Radio Telescope

The next project of the TIFR radio astronomy group was to build a number of outriggers to the ORT so that the entire system could operate as a synthesis instrument. The Ooty Synthesis Radio Telescope (OSRT) consisted of seven smaller cylinders situated up to 4 km away from the main ORT. Since the terrain was thickly forested, the only practical way to link the antennas together was via radio links. The signals received by the smaller dishes were correlated with that received by the ORT to make a synthesis instrument operating at 327 MHz.

The OSRT was used to study both galactic and extragalactic sources at low radio frequencies, and work done using the instrument included the discovery of a giant radio galaxy (Saripalli *et al.* 1986). The OSRT also served as a useful training ground for the students and engineers in building, operating and using a synthesis radio telescope.

The Giant Equatorial Radio Telescope

The key innovation of the ORT was to have the telescope effectively equatorially mounted, that is, the cylinder's axis is parallel to the Earth's rotation axis. The ORT was located at a latitude of about 11°, and constructing a half kilometre long cylinder along a 11° slope was a non-trivial technical challenge. In 1975, on the way back from the URSI General Assembly at Lima in Peru, Govind's plane made an unscheduled halt in the city of Belem in Brazil. Belem is almost at the Equator, and waiting there for his flight to get rescheduled, it struck Govind that a much larger equatorially mounted cylinder could be built at the Equator. Back in India he wrote to Brazilian astronomers that he knew, but got no response. Shortly afterwards he met Sam Okoye, a Nigerian radio astronomer, who was keen to follow up on this idea. At an International Astronomical Union summer school held in Nigeria the idea solidified into a proposal for an international institute of space sciences and electronics to be set up in Kenya, which would build and operate the telescope. The name chosen for the telescope was the Giant Equatorial Radio Telescope (GERT).

Seed funding for the design of GERT was obtained from UNESCO. The design work was carried out by the Tata Consulting Engineers. The final proposal envisaged a 2 km long and 50 m wide central cylinder with smaller 100 m long and 50 m wide cylinders located up to 14 km away, with the entire array operating as a synthesis instrument at 38, 327 and 610 MHz with a total collecting area of about 150 000 m^2. The Indian government agreed to provide half of the cost, provided the Kenyan government covered the remaining half. Unfortunately, because of political turmoil in Kenya following the death of President Jomo Kenyatta, funding commitment from Kenya could not be obtained. An alternative site for the telescope in Indonesia was then explored and, although the Indonesian government was supportive, the project did not get off the ground. However, Govind remained keen on the idea of a large radio telescope to be internationally funded and built.

The Giant Metrewave Radio Telescope (GMRT)

In the early 1980s, Professor B. V. Sreekantan, the then director of TIFR, urged Govind to initiate a truly innovative new radio astronomy project. The obvious candidate would be to build a large synthesis radio telescope working at metre wavelengths, the frequency range at which there was considerable expertise in the country. The facility also would be globally unique, since all the other large interferometers at that time operated at shorter wavelengths. In order to get reasonable angular resolution at these long wavelengths, the array would have to be a few tens of kilometres across. This presented a major technical challenge, *viz.* how to transport broadband signals from the distant antennas to the central digital correlator. The only other radio astronomy array of this size was the Very Large Array, which used waveguides to transport the signals. This would be a very expensive solution, and also not very practical in India, where large, flat and sparsely populated pieces of land are extremely rare.

A colleague from Australia (Alec Little) mentioned in a letter that they were exploring the possibility of using the then new technology of optical fibres for radio astronomy. Govind realized that this would be a practical solution for India, and shortly afterwards came up with a modified version of the GERT, where the central 2 km long cylinder was broken up into 34 smaller cylinders in a Y-shaped array 25 km across. This proposal was fleshed out as the GMRT.

The main science drivers were the study of neutral hydrogen in proto-clusters in the early Universe (i.e. emission from the so-called 'Zeldovich' pancakes, which are expected to form in the Hot Dark Matter model), pulsars and radio galaxies. Pulsars and radio galaxies have steep radio spectra and are good targets for low frequency radio telescopes, and the red-shifted emission from neutral hydrogen at a redshift *ca* 3 would also be observable at low radio frequencies, *viz. ca* 300 MHz.

As the idea was developed, however, it was increasingly felt that it would be better to have parabolic dishes rather than parabolic cylinders as the primary array element. Dishes provide better steerability than cylinders, and are more amenable to providing a broad frequency coverage. The Tata Consulting Engineers were charged with the task of coming up with an economic design for a parabolic dish where the reflecting surface was a mesh instead of solid panels. At low radio frequencies, wire meshes provide adequate reflectivity, and have the advantage of requiring significantly less backup structure for support. The Tata Consulting Engineers' design was, however, still far too costly compared with parabolic cylinders, so Govind set himself the task of trying to find a still cheaper concept. What he came up with was to use suitably tensed wire ropes to form the basic parabolic shape, and then stretch wire mesh between the ropes to form the reflective surface. This concept, which he dubbed SMART (for stretched mesh attached to rope trusses), resulted in a radical reduction in the required backup structure, and hence cost. This innovation made it possible to build a large antenna array at a very modest cost.

The site selected for the GMRT was near Narayangaon, which is about 80 km north of Pune, in Maharashtra state (figure 6). The array configuration was a 'hybrid' one, consisting of 14 antennas more or less randomly distributed in a 1 km $\times$ 1 km region (the 'central square'), and 16 antennas distributed along three approximately Y-shaped arms, each about 14 km long. The antennas in the central square would provide good sensitivity to diffuse extended emission (such as that expected from proto-clusters at $z \approx 3$), while the distant arm antennas would provide good angular resolution for studies of radio galaxies, etc.

An important consideration from the start was to enable pulsar observations. Consequently, two digital backends were developed, one the traditional correlator for imaging studies, and the other a digital array combiner that would allow real-time beam formation with very high time-resolution. The array combiner, along with the feed and receiver system at the highest frequency (the 21 cm band), were developed by the Raman Research Institute in Bangalore. The servo systems for the antennas were developed by the BARC. Most of the remaining electronic subsystems were developed in-house, including the system for transport of analogue radio frequency signals along optical fibres. At the time the fibres were procured for the GMRT, it was one of the largest orders for optical fibre in India.

The construction of the GMRT was a major technical as well as organizational challenge. Land acquisition in India is rarely straightforward, but thanks to Govind and his team's indefatigable efforts a large enough tract of land within commuting distance of Pune was acquired without getting entangled in procedural issues. Govind and the team made great

Figure 6. The 45 m diameter antennas of the GMRT were constructed at ground level and then raised onto their altitude–azimuth mounts by hand-operated winches. Here Govind (front row, light-blue hat) lends a hand to the winching operation. Others in the front row (from left to right) are S. C. Tapde (the GMRT project engineer), B. S. Mathikere (the engineer at the GMRT site) and Vijay Kapahi (who succeeded Govind as centre director, NCRA). Used with permission of TIFR.

effort to work with the nearby villagers to ensure that the land acquisition went smoothly; decades later, when Govind passed away, many of them spoke eloquently about his efforts, which put their village on the scientific map of not just India but the whole world.

The GMRT engineering team was small, and needed to be augmented. Govind travelled to the best engineering colleges in India, and attracted a team of bright young engineers to join in the effort of designing the telescope. Much of the instrumentation, particularly the fibre optic system and the digital hardware, was being designed in India for the first time. It took a while for the team to experiment and learn how to build a reliable, high dynamic range link; there was a lot of experimentation and learning in the field. The digital system was built in stages, starting with a smaller system, then growing to an eight-antenna correlator and gradually scaling up to the full 30-antenna dual polarized correlator. Construction of the antennas themselves was also a challenge. The construction teams experimented with a variety of approaches, before finally coming up with a practical solution. All the structural elements of the antenna were fabricated *in situ*, and the dish itself was assembled on the ground before being winched to the top of its concrete mounts. All these problems were successfully solved, and by early 2000 scientific observations were underway (figure 7).

As mentioned above, one of the original science drivers for the GMRT was the search for large primordial hydrogen clouds predicted in the Hot Dark Matter model. However, by the time the GMRT proposal was being formalized there was growing evidence for the Cold Dark Matter (CDM) model for structure formation in the Universe. In the CDM model, structure

Figure 7. Three of the 30 GMRT dishes. Each dish is 45 m in diameter, and the entire array is spread over a region about 25 km across. The signal from each antenna is brought to a central location via optical fibre for further digital processing. The GMRT is a national facility, but is operated under an ‘open sky’ policy. Astronomers from across the world can propose use of the GMRT; time is allocated purely on scientific merit as judged by an independent time allocation committee. The telescope is extremely versatile. Science done with the GMRT ranges from studies of the heliosphere to the very early stages of the Universe (the so-called Epoch of Reionization) and a whole host of phenomena at distances intermediate between these two. Photograph courtesy of National Centre for Radio Astrophysics, India.

formation was ‘bottom up’, meaning that small structures would form first and later coalesce to form bigger structures. The high redshift proto-clusters that had been one of the main proposed targets for GMRT observations seemed unlikely to exist. Large proto-clusters are expected in the Hot Dark Matter model, where structures form ‘top down’, i.e. large structures form first and then fragment to form smaller ones. The small structures expected at high redshifts in the CDM model would be too faint to detect with the GMRT. Interestingly, the GMRT science proposal did detail some ideas on how one could use the GMRT to statistically detect the emission from a collection of small sources, even if any one of them is too faint to be individually detected. Independent of this, the GMRT when completed was a highly flexible and versatile instrument, and it would be fair to say it led to a renaissance in the field of low frequency radio astronomy (11).

The Indian Institutes of Science Education and Research

As mentioned earlier, the ORT had originally been planned to be part of a larger inter-university centre, which would, among other things, generate trained scientific staff for the country's ambitious scientific programmes. Unfortunately, with the untimely death of Homi Bhabha, the inter-university centre never came to fruition. Govind, however, remained passionate about the importance of training new generations of scientists. Along with other senior astronomers, he was instrumental in starting the Joint Astronomy Programme. This programme, which was set up jointly by several research institutes located in the Bengaluru area, has now been successfully running for more than 50 years and includes some of the most distinguished Indian astronomers among its alumni. Training of PhD students was also a critical component of the National Centre for Radio Astrophysics (NCRA) in Pune, of which Govind was the founder director. After he retired from NCRA, Govind grew increasingly convinced that it was important to start targeting talented students at a younger age. To do this one would need high quality institutions that would attract students to science from the undergraduate level itself. Along with the former vice-chancellor of Pune University, Professor V. G. Bhide, he developed a proposal for setting up such institutions, and also worked both within the scientific community and with the government to generate support for this initiative. Although Govind was not fully able to get this off the ground, the task was later taken up by others, and culminated in the setting up of what are now known as the Indian Institutes of Science Education and Research, of which there are now nine in the country.

Some final words on Govind

Govind Swarup passed away on 7 September 2020 at the age of 91. He remained mentally sharp and active to the very end. Until just a few days before his final hospitalization he continued working on a biographical paper for the *Annual Reviews*, which was published posthumously (12). He also kept in touch with the latest developments in astronomy, emailing colleagues whenever he came across an article that he thought would be of interest.

As in all other things, Govind had made careful plans for what he wanted done after his death. In accordance with his wishes, his body was taken straight from the hospital to the crematorium. A couple of people, whom Govind had identified in his instructions, spoke briefly about Govind's life and contributions, before the body was transported into the fire. Govind's ashes are buried at the GMRT site, where a small memorial has been built. The internment was attended not just by GMRT staff, but also by the people from the nearby villages, who remembered him with fondness and gratitude.

In person, Govind was friendly, approachable and always bubbling over with enthusiasm. Bina says that, in spite of his extreme preoccupation with his work, Govind was always available for the family and was a loving husband and father. He took a keen interest in young students, inspiring generations of them to take up astronomy. Even in his eighties he could be found in the NCRA canteen, chatting with the graduate students, discussing their work or some topic that had caught his attention. He was equally at ease talking to junior lab technicians as to the most celebrated scientists of his day. Govind and Bina ran an open house, so the discussions often continued over snacks and meals in their home.

The memorial functions organized after Govind's passing away were remarkable for the wide cross-section of people who spoke about his influence on their lives. Lab technicians recalled him teaching them the importance of meticulousness when building and testing equipment, bank managers spoke about how he got them to appreciate the importance of doing fundamental science, and some of the most well-known scientists from India and abroad spoke about his lasting influence on radio astronomy and the Indian scientific community. One of the most moving tributes was from a young astronomer, Nitin Mohan, who had defended his thesis just two weeks after Govind passed away. Nitin worked on GMRT observations of Venus, in collaboration with Govind. He recalled Govind's passion and enthusiasm for the work, but most particularly he remembered Govind's help and advice when, as so often happens with PhD students, he was disheartened and ready to give up.

For those of us who were fortunate to meet and interact with Govind, this summarizes nicely our sense of loss. India and the world lost a pioneering scientist, but we also lost a friend, a well-wisher who took keen interest in our work and wellbeing, someone who was always ready with help and advice when we needed it.

Awards and honours

Over the years a large number of honours were bestowed upon Govind. A partial list is given below:

S. S. Bhatnagar Award, Padma Shri (the fourth highest civilian award in India)
P. C. Mahalnobis Medal
Dr Vainu Bappu Memorial Award
Tskolovosky Medal
Meghnad Saha Medal
TWAS Prize in Physics
John Howard Dellinger Gold Medal
R. D. Birla Award in Physics
C. V. Raman Medal
M. P. Birla Award
Khwarizmi International Award
H. K. Firodia Award
Herschel Medal
Grote Reber Medal
Homi Bhabha Award for Lifetime Achievement

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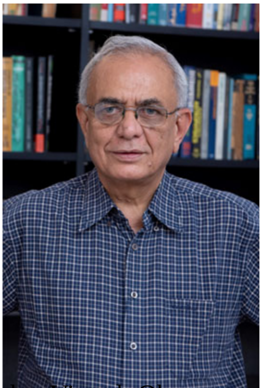
Author profiles

Ajit Kembhavi



Ajit Kembhavi is an astrophysicist. He is professor emeritus at the Inter-University Centre for Astronomy and Astrophysics (IUCAA), Pune, India. He was director there until August 2015. He is one of the founder members of IUCAA and a founder of the Pune Knowledge Cluster.

Kembhavi works on extragalactic and high energy astrophysics, the application of artificial intelligence to astronomy and biology. He has published a large number of research papers and several books in English and Marathi. He is involved in many national and international collaborations and is one of the key persons responsible for India joining the Thirty Metre Telescope project as a partner and taking up the LIGO-India project. He has led the Virtual Observatory-India project, which has made important contributions to data management, analysis, visualization and the development of tools for statistical analysis.

Kembhavi has been a member of the Space Commission of the Government of India and is presently a member of the ISRO's Apex Science Board. He was vice-president of the International Astronomical Union, president of the Astronomical Society of India and president of the Indian Association of General Relativity and Gravitation.

Jayaram Chengalur

Jayaram Chengalur has a BTech in electrical engineering from the Indian Institute of Technology, Kanpur. While an undergraduate, he did a summer project with Professor Govind Swarup, which inspired him to take up radio astronomy as a career. Following a PhD from Cornell University, and a post-doctoral fellowship in The Netherlands, he joined NCRA-TIFR. He continues to be at TIFR, where he is currently the director.

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