In Memoriam: Govind Swarup

Prof. Govind Swarup (Figure 1), the doyen of radio astronomy in India and also an internationally acclaimed radio astronomer, breathed his last on September 7, 2020, in Pune, India. He is survived by his wife, Mrs. Bina Swarup; their son, Vipin Swarup; and their daughter, Anju Basu. Prof. Swarup was a legendary figure who will be remembered in the times to come, not just for pioneering radio astronomy in India, but also as one who had big ideas and knew how to make them real.

Figure 1. Govind Swarup (1929–2020).

Govind Swarup was born on March 23, 1929, in Thakurdwara, a small town in the Moradabad district of Uttar Pradesh. His father, Ram Raghuvir Saran, established the first theater in Delhi, the capital of India. His mother, Gunavati Devi, was a housewife who encouraged Govind to read. In 1944, he matriculated with distinction, and then went to Ewing Christian College in Allahabad for his intermediate college studies. These were unforgettable years for him. He learnt to swim at the confluence of the Ganges and Jamuna Rivers, a talent that would come in handy later at Potts Hill reservoir in Sydney, Australia. Leadership qualities in him were evident at this early age, as he became Secretary of the College's Physics Club.

During 1946-1950, Govind completed his BSc and MSc in Physics. Govind was greatly inspired by his teacher, Prof. K. S. Krishnan, who was to later play an important role. During these years, Govind also subscribed to "Harijan," a weekly journal published by Mahatma Gandhi, whom he greatly admired, and he developed a great love for his motherland.

After obtaining his MSc, Govind joined the National Physical Laboratory (NPL), New Delhi. His teacher, K. S. Krishnan, had in the meanwhile become the founder Director of NPL, and Krishnan's research interest was primarily the quantum theory of magnetism: a hot topic in physics at that time. Krishnan asked young Govind to build the necessary electronics to operate at a wavelength of 3 cm ($f = 10$ GHz) in order to study electron-spin resonance. Such high-frequency electronics were very novel at that time. Using some surplus radar sets from WWII, Govind managed to successfully set up the spin-resonance experiment within 18 months: a remarkable achievement.

Krishnan was a person of broad interests. In his pursuit for initiating new and exciting activities at NPL, he attended the Tenth General Assembly of URSI, held at Sydney, Australia, in August 1952. Among other things, he there learnt about the dramatic and remarkable discoveries in the field of radio astronomy being made by Joseph Pawsey and his group at the Radio Physics Division of CSIRO (the Australian equivalent of CSIR in India). This group was comprised of some of the most outstanding experimentalists, such as J. Paul Wild, Wilbur N. Christiansen, John G. Bolton, and Bernard Y. Mills. Upon his return, Krishnan gave a colloquium at NPL in which he described these momentous discoveries. That is how Govind got interested in radio astronomy! Govind was also greatly enthused by Krishnan's announcement that he wanted to start radio astronomy activities at NPL, despite their meager resources. To provide the initial training and a first-hand exposure to radio astronomy, Krishnan put forward Govind's name for a two-year fellowship under the Colombo Plan to work at the Radio Physics Division of CSIRO in Sydney.

In March 1953, Govind and another Indian recipient of the Colombo Plan Fellowship, R. Parthasarathy from the Kodaikanal Observatory in Tamil Nadu, arrived at Sydney to work with J. L. Pawsey and his Radio Physics group. Govind had a remarkable career during his stay of two years and four months, working, in turn, with Christiansen, Wild, Mills, and Bolton. This training had a major lasting influence on Govind's career. He specifically cited the example of his learning the powerful technique of radio interferometry from Christiansen. Govind and Parthsarathy also spent time doing some experimental work themselves under the direction of Pawsey. They worked on a sophisticated telescope designed and built by Christiansen for studying the sun, converting the array of 32 antennas, each roughly 2 m in diameter, so that the operating wavelength would be 60 cm (500 MHz) instead of the 20 cm for which they had originally been designed. This experience was of great value to these young scientists, working independently on hardware construction, observations, data reduction, and the interpretation of the results. It was also during this time that his swimming ability came in handy, when he had an occasion to save Parthasarathy from drowning in the Potts Hill reservoir! As it turned out, Christiansen decided to build a new telescope and in the process, the present 32-element array was to be scrapped. On being requested by Govind, Pawsey agreed to donate those 32 elements of the 1.7 m dishes to NPL, India.

Govind returned to NPL in August 1955, ready to initiate radio-astronomy research, using Christiansen's array

Figure 2. A view of the Ooty Radio Telescope facing due west (courtesy NCRA, Pune).

from Potts Hill as the nucleus around which he planned the initial activities. Roughly during that period, several other persons – Parthasarathy, T. Krishnan, N. V. G. Sarma, M. N. Joshi, and M. R. Kundu – also joined NPL. Dr. Krishnan did thus manage to get a group together and start radio astronomy in NPL. To adapt a phrase from Govind, K. S. Krishnan, who also later became an URSI Vice President, was thus really the foster father for radio astronomy in India. Unfortunately, there was a major delay in getting the 32 dishes from Australia, and hence Govind decided to go to the US for a few years. Gradually, the other group members left too, causing this fledgling group to disperse within a short period.

Before leaving for the US, Govind got married in a conventional arranged Indian marriage. He left for the US with his wife, Bina, in August 1956, to join the Harvard College Observatory. He went to study the dynamic spectra of solar bursts using the 100 MHz to 600 MHz swept-frequency radio spectrograph that had just been installed there. Within a few months, he had made an interesting discovery: the new "Type U" solar radio bursts. In the following year, on the advice of his former mentor, Joseph Pawsey, he decided to join Stanford University and work under the guidance of Prof. R. N. Bracewell, a well-known radio astronomer, in September 1957. Stanford was famous for radio engineering, and Pawsey recommended that if Govind really wanted to return to India, he needed to focus on developing his skills in electronics.

Govind's PhD work mainly involved the setting up of the radio heliograph array on the outskirts of the Stanford University campus. The array was designed to produce daily maps of solar radio-emitting regions at 9.2 cm. During 1956-62, apart from "Type U" bursts, Govind developed a gyro-radiation model for explaining the microwave solar emission, and made studies of the radio emission from the quiet sun. In 1959, in collaboration with K. S. Yang, he developed a round-trip transmission technique for phase measurements. In 1962, he also found the first example of a steep spectrum "bridge" of radio emission between the two radio lobes of the powerful radio galaxy, Cyg-A, using the Stanford Compound Interferometer. Such bridges allow estimates of the age of a radio galaxy.

After obtaining his PhD, Govind joined the faculty of Stanford in January 1961. In the following year, the ex-pat group of young Indian researchers, comprised of Govind Swarup, T. K. Menon, M. R. Kundu, and T. Krishnan, all of whom became well known in their later careers, came together and decided to return to India to set up radio-astronomy experimental facilities. Although they applied to many places in India, it was Prof. Homi Bhabha, founder Director of the Tata Institute of Fundamental Research (TIFR) at Mumbai, who assured them that he was forming a radio-astronomy group and invited them to return. However, it was only Govind who immediately came back and joined TIFR on April 2, 1963. Profs. Kundu and Menon came back later, but did not stay for long.

During the initial period of 1963-1966, two of his former NPL colleagues, N. V. G. Sarma and M. N. Joshi from NPL, and a few other young recruits, such as Vijay Kapahi, J. D. Isloor, Ramesh Sinha, Suresh Damle, Durga Bagri, T. Velusamy V. Balasubramnian, and one of us (SA), joined Govind's group. Under the overall guidance of Govind, the group first set up the Kalyan Radio Telescope (in 1963-1965), using the 32 antennas of the Potts Hill array that had come from Australia. Later, with additional engineering and technical personnel (1965-1970), they went on to build the more ambitious 530 m long and 30 m wide steerable parabolic-cylindrical Ooty Radio Telescope (ORT), situated at Ootacamund (Ooty for short) in south India. The unique and innovative design of this was

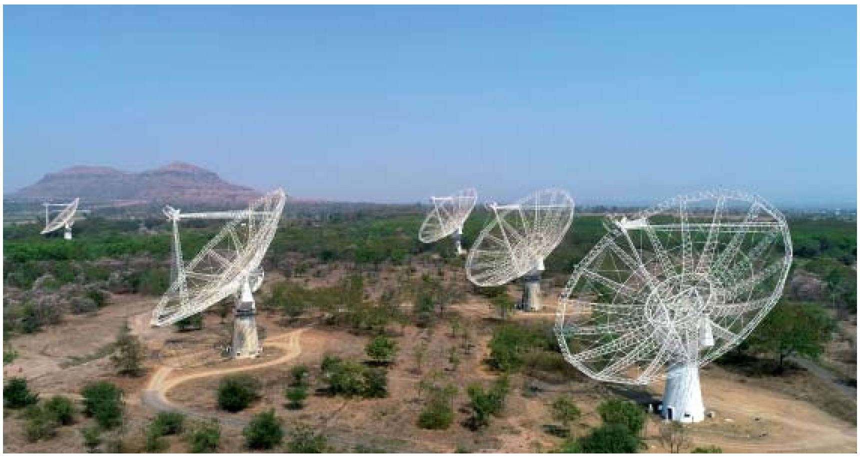

Figure 3. A panoramic view of a few of the antennas of the Giant Meterwave Radio Telescope array (courtesy NCRA, Pune).

conceived by Govind. The ORT (Figure 2) was placed on a North-South oriented and suitably inclined hill so as to make its long axis of rotation parallel to that of the Earth, enabling it to track celestial radio sources in hour angle for 9.5 hrs. Using the method of lunar occultation, it provided for the first time high-angular-resolution data (1 arcsec to 10 arcsec) for the linear sizes of more than 1,000 weak radio sources. The evolution of these with redshift (or distance) provided independent evidence for the Big Bang model of the Universe. Occultation observations made using the ORT of the galactic center source, Sgr-A, yielded the first two-dimensional separation of its thermal and non-thermal emissions. Over the years, the ORT has been used for a variety of studies including interplanetary scintillations and the solar wind, pulsars, radio recombination lines, etc., and remains an active and working facility to this date after fifty years: in fact, it is nearing completion of a major new upgrade.

The next project that Govind and his team realized was the Ooty Synthesis Radio Telescope (OSRT, completed in 1984), which extended the ORT into an aperture-synthesis interferometer by adding seven smaller cylindrical antennas at distances up to 4 km. Although relatively short-lived, the OSRT provided valuable experience in building and operating interferometers, which was to prove useful in giving confidence to take the next big step. During the late 1970s, Govind had also tried to build a very large instrument, called the Giant Equatorial Radio Telescope (GERT), in Kenya or Indonesia on the equator, but this could not materialize. As fallouts of his main radio-astronomy activities, Govind also helped in building India's first communication-satellite antenna at Arvi, north of Pune, and helped in building an antenna group in the Electronics Corporation of India Limited (ECIL), Hyderabad. This unit has since grown into a major enterprise for building antennas for many government of India projects. He also worked on solar thermal energy for societal benefit.

During 1984-1996, with several experienced colleagues, Govind conceived and directed the design and construction of the Giant Meterwave Radio Telescope (GMRT). That undoubtedly marked the pinnacle of his career of building iconic, front-line experimental facilities. Consisting of 30 fully steerable parabolic dishes of 45 m diameter that were located in an approximately Y-shaped array of about 25 km in extent in western India, about 80 km from the city of Pune, the GMRT (Figure 3) is a highly versatile and powerful instrument. It is the world's largest radio telescope operating in the frequency range of about 130 MHz to 1430 MHz. Novel concepts developed by Govind and his team made it possible to construct the large GMRT antennas very economically. GMRT also had some other innovations, such as being one of the first radio interferometers to use optical fibers to transport the antenna signals to the central processing station, and to simultaneously support both the interferometry and beam-former modes.

The making of the GMRT was not without its fair share of challenges, ranging from the complexity of the mechanical structure to the radio-frequency electronics and the complex digital-signal-processing systems: the correlator and beamformer electronics. It is to the credit of Govind's team that they were able to successfully tackle these challenges. The completed GMRT was opened to the global community from early 2002 onwards. In the process, Govind attracted a new generation of young members, including one of us (YG), who brought in fresh talent to supplement the experienced team that had grown since the days of the ORT. More recently, this younger generation has carried the torch forward with a significant upgrade of the GMRT that was completed in 2019, and was, most fittingly, inaugurated by Govind on the occasion of his 90th birthday.

Since its commissioning in the late 1990s, the GMRT has been used by astronomers from all over the world to produce many path-breaking discoveries and results. During this period, Govind himself worked with younger colleagues to make observations with the GMRT of the emission and absorption of atomic hydrogen from objects in the early Universe, and investigated deficiency of radio sources at 327 MHz towards the prominent cold spot of the cosmic microwave background radiation. In the last few years, he had also been working with students to detect and characterize the radio emissions from the planet Venus using GMRT observations.

To summarize, during the past five decades and more, working with different generations of colleagues, Govind made pioneering contributions in the building of front-line radio-astronomy facilities in India. He carried out important research in areas such as solar radio emission, radio galaxies, quasars and cosmology, and interplanetary scintillations and pulsars.

Govind was elected Fellow of the Royal Society, London, and also of all the three major Science Academies of India: Indian National Science Academy, Indian Academy of Sciences, National Academy of Sciences India. He was also elected to the Fellowship of the Third World Academy of Sciences; the Royal Astronomical Society, London; the Astronomical Society of India (President 1975-77); and the International Astronomical Union (IAU) (President, Commission 40 on radio astronomy, 1979-82). He was a member of the Executive Committee of the Inter Union Commission for Frequency Allocation (IUCAF) during 1990-1995; the IAU Working Group for Future Large Scale Facilities (1994-2000); Chair of the Indian National Committee for URSI (1986-88 and 1995-97); URSI Standing Committee for Future General Assemblies (1999-2002); and the editorial boards of many journals.

The list of awards received by Govind is long, and we name here only the prominent awards: Padma Shri, one of the highest civilian awards for distinguished service of the Government of India (1973); S. S. Bhatnagar Award, Council of Scientific and Industrial Research, CSIR, India (1972); Tskolovosky Medal, Federation of Cosmonautics, USSR (1987); The Third World Academy of Sciences Award in Physics (1988); John Howard Dellinger Gold Medal, URSI (1990); 12th Khwarizmi International Award, Iran (1999); Herschel Medal of the Royal Astronomical Society (2006); Grote Reber Medal (2007); Pontifical Academy Award (2011).

There was a great deal of camaraderie in the ORT group headed by Govind, particularly in the first 20 years. Ooty was a small and remote town, perched on the Nilgiri Hills. The group members and their families found great joy in gathering together for all kinds of celebrations. It was in one of those memorable evenings on New Year's eve, when everyone was on a high, that the idea of GMRT took shape after many arguments on what the group should do going forward. The very next day, on the afternoon of January 1, 1984, Govind called some of his colleagues to lay out his dream of building a Y array of many parabolic cylinders, similar to the VLA array that had just become operational. This finally evolved into the concept that became the GMRT.

The site for GMRT was finalized after extensive site surveys by one of us (SA) and others, with the central core located in a quiet rural area of one square kilometer near a village called Khodad (north of the Pune district in western India) in 1985. The Y array did not turn out to be of three straight arms, as these, especially the Western arm, had to be somewhat zigzag. The joke went around saying that since the Western arm was close to a vineyard and their Champagne factory outlet, the people laying out this line had had a glass too many! In reality, of course, the deviations were due to many villages located near the antenna sites, and constraints on availability of land.

Govind was a very persistent and hardworking researcher. In the early days, the graduate students used to say that he gained energy from everyone at the table, while all others became exhausted! As years went by, we saw him motivating everyone he came across without any formalities, and challenging them to do their best. One of us (YG) remembers being challenged, in 1996 (at a fairly early stage in his career), to take up the task of completing the complex digital processing system for the GMRT: one of the critical elements that was holding up the successful completion of the GMRT. Govind was also highly motivated and focused on what he wanted to achieve in the time available. This resulted over the past five decades in the creation of a large school and facilities that are likely to remain strong for a long time.

After his formal retirement, Govind tried to set up an Indian Institute for Science and Technology Education (IISTE) with his friend, the former Vice Chancellor of Pune University, Prof. V. G. Bhide. They almost succeeded, but the government changed in the meanwhile, and the task was taken forward by others into what became the Indian Institute for Science Education Research (IISER) of today.

There was an interesting incident that took place during URSI GA 2005 in Delhi. The venue was Vigyan Bhavan (then the main science conference facility in New Delhi), which had been booked for all the eight days of the meeting. However, just 10 days before the URSI GA meeting, the government of India decided to hold another important meeting there on one of the days, to be addressed by the President of India, Dr. A. P. J. Abdul Kalam. On being persuaded by one of us (SA), Govind agreed to write a telegram directly to Dr. Kalam, requesting him earnestly to shift the venue of his other meeting. A few days later, it was learnt that the President had indeed shifted the venue! Later on, during a private conversation at his presidential residence, Dr. Kalam mentioned that he "of course had to shift the venue because the telegram came from Govind Swarup!"

Govind had thus become a legend in India, and elsewhere, even during his lifetime. In spite of all his achievements and accolades, he continued to be down to earth and extremely approachable throughout his life, to the very end. He leaves behind a tremendous legacy of

Figure 4. Felicitations to Prof. Govind Swarup on his 90th birthday at the URSI Asia Pacific Radio Science Conference 2019 (URSI AP-RASC 2019) (l-r) Amitava Sen Gupta, S. Ananthakrishnan, Makoto Ando, Govind Swarup, R. Paulraj, and Ondrej Santolik (from InRaSS archives).

Figure 5. From the ceremony marking the inauguration of the upgraded GMRT by Govind Swarup on March 21, 2019, in Pune, during a special event in the conference, "The Metrewavelength Sky – II" organized by NCRA (l-r) K. VijayRaghavan, Bina Swarup, Govind Swarup, Anil Kakodkar, Yashwant Gupta, and Sandip Trivedi (courtesy NCRA, Pune).

institutions and individuals who will carry forward his good work.

Last year, the URSI Asia Pacific Radio Science Conference (URSI AP-RASC 2019) was held in New Delhi during Match 12-16, 2019, organized by the Indian Radio Science Society (InRaSS). It was decided to felicitate Govind on his 90th birthday, falling around the same time (Figure 4). He graciously accepted our invitation and traveled to Delhi, despite his extremely frail health condition. He also gave an inspiring keynote address in a special Commission J session that was organized in his honor. The following week, he was felicitated on his 90th birthday by the NCRA, where he most fittingly inaugurated the upgraded GMRT (Figure 5), which will carry on his legacy for many more years to come.

By a fortuitous turn of events, it was just announced that GMRT has been selected for an IEEE Milestone award. It is only the third such award in India, after the discoveries of Sir J. C. Bose and Sir C. V. Raman, the former being one of the first radio scientists and the latter a Nobel Prize winning physicist. Govind Swarup would have been truly proud.

We pay our homage to a great son of India and our heart-felt condolences to his family. May his soul rest in peace.

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