Govind Swarup: Radio astronomer, innovator *par excellence* and a wonderfully inspiring leader

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They are ill discoverers that think there is no land, when they can see nothing but sea.

Francis Bacon

I must say at the outset that I have no special credentials to write an article about as famous a person as Govind Swarup. I am not one of his numerous students. Nor have I collaborated with him in research. Indeed, I am not even an astronomer, let alone a radio astronomer. But I have been one of his great admirers, and he has been a beacon of inspiration for me during the past four decades. I was therefore delighted – although surprised – when the Editor of *Current Science* invited me to write this article. The Editor reminded me that articles in this new series are primarily intended to inspire young people. I have, therefore, written this article in a manner that would highlight Swarup's remarkable characteristics as a scientist, an innovator and as a leader, rather than concentrate on his scientific achievements. After all, young people are inspired more by the 'personality' of a scientist rather than their 'CV'. I have also deliberately chosen to highlight some historical events related to the growth of modern astronomy in India, aspects that the young readers may find interesting.

I first heard about Govind Swarup in 1975 from Martin Rees in Cambridge (now Lord Rees, Astronomer Royal of England and till recently the Master of Trinity College in Cambridge and the President of the Royal Society of London). I was, at that time, working in the Cavendish Laboratory in Cambridge University. Although my research interest at that time was in the area of Physics of Condensed Matter, I was keenly following the revolutionary developments in General Relativity and Astrophysics, much of it happening in Cambridge itself. Naturally, this brought me into contact with Martin Rees, Roger Penrose, Stephen Hawking and many others. In one of the conversations with Martin Rees, he told me about this 'remarkable man, Govind Swarup' who had built a novel radio telescope in Ooty, and about the important contributions to cosmology being made using this telescope. He mentioned in very flattering terms the Ph D thesis of one of Swarup's students (Vijay Kapahi) which had come to him for evaluation. That is how I came to know of Swarup.

As it turned out, I moved from Cambridge to the Raman Research Institute (RRI), Bangalore in the beginning of 1976. Within weeks after my coming, I received an invitation from Govind Swarup to attend a small meeting he had convened at RRI to discuss a Summer School in Astronomy he was organizing in Bangalore in June 1976. I was rather surprised because I was still working in Condensed Matter Physics. There were only four persons present at this meeting: Govind Swarup, V. Radhakrishnan (Director of RRI), my young colleague Rajaram Nityananda and me. I vividly recall that meeting. While waiting for coffee to be served before getting down to the business of giving shape to the summer school, Rajaram was challenging us – as he was fond of doing – with clever problems, this time from *The Cavendish Problems in Physics* compiled by Sir Brian Pippard; these were tough problems from the Cambridge Tripos exams. I was amazed how effortlessly Swarup handled them, without ever getting up from his chair and going to the board; his tremendous intuitive powers were quite evident (by then, I was already aware of Radhakrishnan's very remarkable intellect). That was my first meeting with Swarup. Since then we have been close friends. Over the next few years, my own interests shifted gradually towards astrophysics and my world line became entangled with that of his group.

Early years

Swarup was born in Thakurdwara (Uttar Pradesh) in 1929. After matriculation, he went to Allahabad University for his college education. He completed his B Sc degree in 1948, and then went on to do his M Sc. During that period, Allahabad had a very good faculty which included

K. S. Krishnan, B. N. Srivatsava, Deodhar, Gorak Prasad, N. R. Dhar *et al.*; many of whom had authored well-known text books. Swarup was greatly impressed and inspired by K. S. Krishnan who taught him Electricity and Magnetism in his second year.

After completing M Sc in 1950, Swarup joined the National Physical Laboratory in New Delhi.

National Physical Laboratory (NPL)

The foundation stone for NPL was laid by Jawaharlal Nehru in January 1947. K. S. Krishnan was the founding Director. For the benefit of young readers, may I add a brief note? K. S. Krishnan was one of the many students who were working with C. V. Raman in Calcutta when he made the famous discovery in 1928. Krishnan was perhaps the most brilliant of them; he played an essential role in the discovery. In fact, the 'discovery paper' was jointly authored by C. V. Raman and K. S. Krishnan. At Nehru's invitation, Sir K.S.K. (as he was referred to) moved from Allahabad to assume the Directorship of the new laboratory.

By this time, K.S.K.'s interest had shifted to quantum theory of magnetism – a hot topic in physics at that time. The phenomenon of 'magnetic resonance' had been discovered just a few years earlier; electron spin resonance in 1944, and nuclear spin resonance in 1946; Nobel Prize was awarded for both these discoveries. K.S.K. asked young Swarup to build the necessary electronics to operate at a wavelength of 3 cm (frequency of 10 GHz) in order to study electron spin resonance – a tall order for someone just out of college! Such high frequency electronics was very novel at that time. Fortunately, NPL had acquired some surplus radar sets built during the Second World War. Swarup 'cannibalized' them for parts. But the know-how to build high frequency electronics had still to be obtained. The series of priceless volumes compiled by the Radiation Laboratory in MIT in Boston came to his rescue.

A few words about the 'Rad Lab' (as it used to be referred to) may be in order for the benefit of young readers. The development of microwave electronics, and the radar, was of paramount importance during the Second World War. The leading physicists in Britain and America were recruited for war efforts. The 'Rad Lab' was set up in this context in the autumn of 1940 by President Franklin Roosevelt. Some of the best brains in America were gathered there. The *magnetron* – the first microwave generator – which, incidentally, is today used in domestic microwave ovens! – was developed in Birmingham in England just around that time. Soon, one of them was secretly smuggled into the United States. This triggered a burst of intense research in microwave engineering. The 'Rad Lab' made stunning discoveries in the next five years. The research carried out there was documented in a series of volumes. After the World War ended, a few select places were able to discretely acquire copies of these volumes. NPL was one such place!

To return to our story, Swarup successfully set up the spin resonance experiment within 18 months – a remarkable achievement.

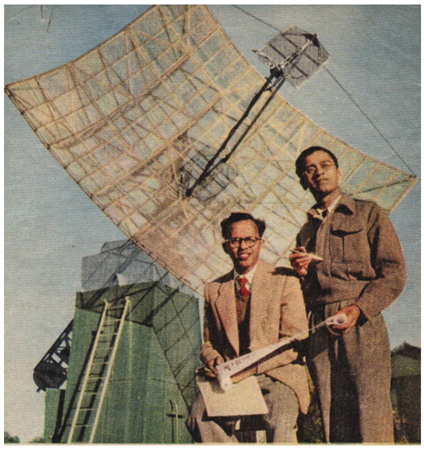
The URSI General Assembly of 1952

Although K.S.K.'s main interest at that time was quantum theory of magnetism, being a man of very broad interests – which transcended the boundaries of science, and included poetry and literature – his 'broad band antenna' picked up some interesting signals. After the Second World War ended, physicists around the world returned to the pursuit of research. But money was very hard to come by. Several of the physicists who worked on the development of radar used their expertise to design and build ingenious antennas to study radio waves from the Sun, stars and galaxies. The subject of Radio Astronomy was born. Within a span of five or six years several breathtaking discoveries were made, notably by Joseph Pawsey and his group in Sydney in Australia and by Martin Ryle and his group in Cambridge in England. Since all these persons came from a 'radio engineering' background, they usually presented their results in meetings of the International Radio Science Union (URSI). The General Assembly of URSI was to take place in Sydney in August 1952. Interestingly, Krishnan went to this meeting to learn about these developments. There, among other things, he learnt about the discoveries being made by Joseph Pawsey and his group in the Radio Physics Division of CSIRO (the Australian equivalent of CSIR in India). This group comprised of some of the most clever and original persons, such as Paul Wild, Wilbur Christiansen, John Bolton and Bernard Mills. Upon his return, K.S.K. gave a colloquium at NPL in which he described these momentous discoveries. That is how Swarup got interested in radio astronomy! He was also greatly enthused by K.S.K.'s announcement that he wanted to start some radio astronomy activities at NPL, despite meagre resources.

Off to Australia

In March 1953, Swarup set off to Sydney on a two-year Colombo Plan Fellowship to work with Pawsey and his group in the Radio Physics Division of CSIRO. K.S.K. had suggested that he apply for this; the idea was that Swarup should acquire some first-hand exposure to radio astronomy, before initiating some activities at NPL. When he reached Sydney, he found another young Indian there, R. Parthasarathy from Kodaikanal Observatory.

Pawsey suggested that Swarup should work for three months each with the groups led by Paul Wild, Wilbur Christiansen, John Bolton and Bernard Mills. Swarup did that, and thus had a ring side seat from which to watch epoch-making discoveries being made. What a way to get introduced to a new subject! During the second year of his Fellowship, Swarup and Parthasarathy converted an array of 32 antennae, each roughly 2 m in diameter, so that the operating wavelength would be 60 cm (500 MHz); they had originally been designed to operate at a wavelength of 21 cm. This was part of a sophisticated telescope designed and built by Christiansen for studying the Sun. To quote Swarup '*This was a great experience: building dipoles, a transmission line network and a receiver system; making the observations; and, finally, carrying out the data reduction – not to mention saving my dear friend Parthasarathy from drowning in the Potts Hill reservoir!*'



Govind Swarup (left) and R. Parthasarathy in Potts Hill field station. At the back is a radar antenna (salvaged after the War) which was being used for astronomical studies.

And then it was time to return to NPL. Just around that time, Christiansen had decided to build a new telescope. As a consequence, the 32 antenna array (mentioned above) was going to be scrapped. During a chance meeting, Swarup asked Pawsey if he would be willing to gift this telescope to India – the 32 antennae and the associated electronics. Pawsey, and his colleagues, readily agreed. Swarup wrote to K.S.K. in January 1955 asking if NPL would be willing to accept this generous gift. Krishnan replied promptly by saying 'I agree with you that we should be able to do some radio astronomy work even with the meagre resources available'.

Back at NPL in Delhi

Swarup returned to NPL, all ready to initiate radio astronomy activities there.

Christiansen's *Grating Telescope* was to be the nucleus around which he planned other activities. Unfortunately, a problem arose. While the authorities at CSIRO in Australia were more than willing to gift the telescope array, they wanted NPL to bear the cost of shipping it. Even though the cost was only around 1400 Australian Dollars (in today's exchange rate, about 80,000 rupees!), Krishnan could not get the consent of the government due to severe foreign exchange restrictions those days. [This may seem incredible to young people. When I went to the US for my Ph D, some ten years later, the maximum foreign exchange that was permissible was the equivalent of 250 rupees (just US$ 50 at that time). And I had to give a bank guarantee of 10,000 rupees that I would repatriate it back within twelve months; otherwise my passport would be revoked!.]

Since there seemed to be no way out, and the prospect of any radio astronomy activities appeared to be bleak, Swarup decided to go to the U.S. for a few years.

Roughly during that period, several other persons joined NPL, and K.S.K. did manage to start a radio astronomy group. The group consisted of Parthasarathy (who moved over from Kodaikanal Observatory upon his return from Australia), T. Krishnan (who did his Tripos in Cambridge, and then worked for a year with Sir Martin Ryle in the Cavendish Lab), N. V. G. Sarma, M. N. Joshi (soon after finishing their M Sc) and (for a while) M. R. Kundu. Meanwhile, CSIRO found the funds to bear the cost of shipping also, and Christiansen's grating array telescope was all set to find a new home in India. Motivated by this, Sarma and Joshi built the 500 MHz receiver for the grating array.

Thus, to adapt a phrase from Swarup, K.S.K., co-discoverer of the Raman Effect, and a world leader in the quantum theory of magnetism, was the *foster father for radio astronomy in India*. As we shall see, the persons mentioned above went on to make India a world leader in radio astronomy.

On to the United States of America

In August 1956, Swarup set off for the U.S. to work at the Fort Davis Radio Astronomy Station (in Texas) of the Harvard Observatory. He was seen off at Delhi airport by K.S.K. and D. S. Kothari! Within a few months, he had made an interesting discovery – a new type of radio burst from the Sun. Subsequently, he interpreted this radiation as due to cyclotron radiation (radiation emitted by electrons spiralling in a magnetic field).

The following year he decided to enrol for a Ph D in one of the American universities. He got offers of admission from Harvard, Caltech and Stanford. His mentor in Sydney, Joseph Pawsey, gave him the following advice. '*Stanford is famous for radio engineering, Caltech for its physics, and, of course, its astronomy research, and Harvard for its training in astronomy. If you are returning to India, I should recommend to you to place great emphasis in electronics. It is the key to open many doors.*' So Govind decided to go to Stanford and work under the guidance of R. N. Bracewell, a well-known radio astronomer. After obtaining his Ph D, he joined the faculty of Stanford in January 1961. There was also an attractive long term offer from the National Radio Astronomy Observatory which was planning a giant radio telescope.

A tryst with destiny

But there was an inner calling to return to India, build world class observing facilities and promote astronomical research in India. This was not a sudden urge. The spirit of nationalism was first kindled in him nearly twenty years earlier when Mahatma Gandhi launched the *Quit India* movement in 1942; Swarup was in school at that time. He was a B Sc student when India attained its independence. Like countless other Indians, he listened to the great speech by Jawaharlal Nehru at midnight on 14 August 1947. And he was deeply inspired by that speech. He was also deeply sensitive of the efforts being made by C. V. Raman and M. N. Saha to promote science in India.

Twenty years later, he was ready to return to India and do something significant, something that would make a difference to the astronomical community. The grandiose efforts of Homi Bhabha must have spurred his imagination. In August 1961, the General Assembly of the International Astronomical Union (IAU) met in Berkeley, California. [Despite the name 'Union', these General Assemblies of the IAU, and URSI, were scientific meetings, attended by a large number of astronomers from all over the world.] Four Indian radio astronomers (Swarup, T. Krishnan, T. K. Menon and M. R. Kundu) met on the sidelines of the meeting and discussed the idea of returning to India *together* and forming the nucleus of a large radio astronomy group. Having arrived at a consensus, they wrote a joint proposal. In brief, they proposed to start observations with the 32 antennae that had already reached NPL from Australia, and then plan something big and ambitious. They realized that low frequency telescopes – which are technically less challenging than high frequency telescopes but very labour-intensive – would be cheaper to build in India. They sent this joint proposal to several organizations in India. The idea of a 'joint letter' was seeded in Swarup's mind by Christiansen who told Swarup '*...you should get together for a joint attack on the monolith of Indian bureaucracy...*'. Confidential reference letters were also arranged from five most distinguished astronomers. One of them, Bart Bok, wrote as follows '*....it seems to me that their offer of returning to India as a group is a unique one and that should by all means be accepted and acted upon promptly. An offer like the present one comes only rarely in the history of a nation, which scientifically, is obviously coming of age.*'

The most positive response came from Homi Bhabha, the Director of the Tata Institute of Fundamental Research (TIFR) in Mumbai. Homi Bhabha was in the process of building the grand edifice of modern science in India, which included the Atomic Energy Establishment. On 20 January 1962, Bhabha sent a telegram to Swarup which read '*We have decided to form a radio astronomy group stop letter follows with offer stop*'. Two months later, in the letter he wrote to Swarup, Bhabha said '*If your group fulfils the expectation we have of it, this could lead to some very much bigger equipment and work in radio astronomy in India than we can foresee at present.*' (Prophetic words, as we shall see).

From Stanford to Bombay

Swarup decided to accept this invitation from Bhabha and resigned from Stanford

University. He also started thinking fresh about what he would attempt to do upon his return to India; he was not convinced that the kind of telescope mentioned in the 'proposal' that he and his friends had sent was versatile enough to work on contemporary problems at the frontiers of astronomy.

During his travels in Europe, on the way back to India from the U.S., he visited the Leiden Observatory and the famous Huygen's Laboratory. Jan Oort, a celebrated astronomer and the Head of the observatory, personally took him around. One of the things he showed him was a model of a 25 m diameter parabolic dish antenna that they were in the process of building. The great Jan Oort suggested to Swarup that he might build one such dish and use it to study the distribution of neutral hydrogen gas in the southern part of the sky, which is not accessible from Europe but would be easily accessible from the southern latitudes. Such a study would complement the survey they had done of the northern sky. Since Oort knew Bhabha, he was willing to provide TIFR with all the engineering drawings. The 21 cm line radiation from hydrogen atoms had been discovered only a few years earlier – one of the most momentous discoveries in the entire history of astronomy – and mapping the distribution of hydrogen was the hottest problem in astronomy.

But Swarup was not convinced. He remembered Pawsey's advice '*keep off the fashionable stuff as far as possible. Be original. Try, if possible, to develop ideas which one or more of you have originated.*'

Swarup joined TIFR in April 1963. Just around that time, two papers appeared in *Nature* announcing one of the most remarkable discoveries in the history of astronomy – the discovery of QUASARS. One of these papers reported a *lunar occultation observation of the first quasar to be discovered*. Soon it became clear that quasars had to be *super massive Black Holes*. A great revolution in astronomy had begun. This triggered an idea in Swarup's mind. The lunar occultation technique was an excellent way to measure the angular sizes of a large number of radio sources that had been discovered by Martin Ryle's group at the Cavendish Lab. It was clear that these sources were at very great distances from us; the discovery of quasars confirmed this. Thus a large sample of such sources would be useful to study the behaviour of the Universe at large. One of the raging controversies of that time was whether the Universe had a beginning or not – the confrontation between the *Big Bang* and *Steady State* theories of the Universe. The distant radio galaxies could be taken as the 'standard rods', and hence the importance of measuring the angular diameters. But there was a catch. The distant radio sources are very faint. Therefore one will need a very large telescope to detect them (in technical jargon, a telescope with a very large 'collecting area'; the 'bucket' collecting the electromagnetic waves had to be very large); and it had to be 'steerable', namely one should be able to point it in any direction. The largest antenna in the world at that time (the Jodrell Bank telescope operated by the University of Manchester) had a diameter of 76 m. Swarup estimated that he will need something four times larger than that – a collecting area of about 10,000 sq. m! Clearly, that was not feasible. This is the sort of situation Swarup revels in. He came up with a clever solution.

Since a large collecting area was a prerequisite for what he wanted to do, Swarup sought inspiration from a large telescope that was just being built by Bologna University in Italy. It was a 'cross', with an East–West section and a North–South section. The E–W section was a single huge parabolic cylinder, 564 m long and 35 m wide. The N–S section consisted of 64 'baby cylinders', 23 m long and 8 m wide, placed 10 m apart. The signals were to be detected by an array of dipoles located along the focal line of the cylinder. But this would not meet Swarup's requirements since it was a '*transit telescope*'. While the cylinder could be made to 'point' in the north–south direction by electronically phasing it, the cylinder could not be 'rotated' to continually track a source as it moved in the sky from east to west; it could only detect signals from sources as they crossed the local celestial meridian.

One day, while sitting in the West Canteen of the brand new TIFR building – which commands a magnificent view of the beautifully landscaped garden laid by Homi Bhabha, and the Arabian Sea beyond it – he got a brilliant idea! He thought of building a long parabolic cylindrical telescope *which could be rotated about its axis and installing it on a slope equal to the latitude of the location*. The axis of the cylinder would then be parallel to the rotation axis of the earth. This meant that sources could be 'tracked' (or observed for a long time) by simply rotating the cylinder about its axis at the same rate as the rotation of the earth, in other words, by using a simple clock. Exceedingly clever! Why was he making his life difficult by putting the cylinder on a sloping hill? It would be far easier to build it on a flat horizontal surface. If the rotation axis of the telescope was not parallel to the rotation axis of the Earth, then the telescope cannot be simply rotated at the rate the earth itself is rotating. It is for this reason that optical telescopes – till quite recently – were mounted in such a way that one of its axis is parallel to the axis of the earth; such mounts are called Equatorial mounts. Modern day telescope – radio and optical – are not mounted this way. But that is because we now have sophisticated computers to control their rotation. Back in the 1960s, sophisticated computers were extremely expensive and not easy to buy.

He first discussed this idea with M. G. K. Menon, the Dean of TIFR, who responded very enthusiastically. The next step was to discuss it with Bhabha. Swarup was thrilled that Bhabha was not only enthusiastic but (to quote Swarup) '*Bhabha grilled me for a couple of hours, probing in great detail the scientific objectives as well as the structural and mechanical intricacies of the telescope, which he could foresee straightaway*'. Bhabha also remarked '*Young man, do not waste your time writing a project report. Your main problem would be to collect a team. When you have managed that you can submit a project report and proceed with the design and fabrication.*'

The genesis of radio astronomy at TIFR

Swarup realized that a team can be gathered only around some activity. The 32 dish antennas gifted to India by CSIRO, Australia, finally arrived in India after the CSIRO decided to pay for the transportation also. At Bhabha's request, NPL agreed to transfer the telescope to TIFR. Setting up this radio interferometer was to be the first project of the newly formed group at TIFR. Two fresh graduates of the Atomic Energy Training

Photo on the left shows the East–West array of the 32 element radio telescope near Kalyan. This telescope, built by Christiansen for the study of the Sun, was gifted to India by CSIRO Australia. The photo on the right shows V. K. Kapahi (left) and Govind Swarup.

School, V. K. Kapahi and J. D. Isloor, were the first to join in August 1963. This small team went to work to set up the interferometer in Kalyan at the outskirts of Bombay. And they succeeded in a remarkably short time of just over a year. The Kalyan interferometer, operating at a frequency of 610 MHz, was used to study the Sun from 1965 to 1968.

While Swarup and his two young students were busy setting up the Kalyan array, there were further additions to the radio astronomy group at TIFR. N. V. G. Sarma and M. N. Joshi resigned from NPL and joined TIFR. Around the same time, R. P. Sinha and B. S. Bagri also joined Swarup's team as research students.

The Ooty Radio Telescope

Even while solar observations were being done with the Kalyan Telescope, Swarup and his student R. P. Sinha embarked on an extensive survey of the hills in the vicinity of Ooty. To recall, their objective was to find a hill with a north-south slope of roughly 11 degrees (equal to the latitude of Ooty). By early 1965, they had identified a suitable hill. Homi Bhabha visited the site and personally dealt with the formalities of acquiring that hill slope. [A fascinating account of this can be found in an article by Govind Swarup and Ramesh Sinha in *Current Science*, 1991, **60**(2), 75–78.] Bhabha formally approved the project towards the end of 1965. Tragically, Bhabha did not live to see this magnificent telescope; he died on 24 January 1966 in a plane crash in the French Alps.

The Ooty Radio Telescope (ORT) was completed towards the end of 1969. Forty five years later, it is still operational and producing wonderful science. I would like to urge the young readers to visit the telescope, for it is an inspiring sight. It is a parabolic cylinder 530 m long and 30 m wide, set on a sloping hillside. The slope was chosen such that the axis of the cylinder is parallel to the rotation axis of the earth. The typical radio antenna will have a curved solid reflecting surface which focuses the incident radiation to a detector at the 'focus'. In an optical telescope, the camera would be placed at the focus. In the case of a radio telescope, a 'receiver' operating at the appropriate frequency would be at the focus. The ORT was intended to operate in a frequency band centred at 326.5 MHz (corresponding to a wavelength of 92 cm). Since the wavelength is very large, the 'reflecting surface' need not be solid. In this case, the reflecting surface is made of 1100 stainless steel wires 0.38 mm in diameter and 530 m long. The reflecting surface is supported by 24 parabolic frames placed 23 m apart. Since this is a cylindrical telescope, there is a 'focal line', instead of a 'focal point'. Placed along the 500 m long focal line are 1024 'dipoles' operating in the band of 322 to 328.6 MHz. This telescope can be made to 'point' to a chosen source in the sky. The 'steering' of the telescope in the east–west direction is done by simply rotating the 530 m long cylinder about its axis! The 'steering' in the north-south direction is done by 'electronically phasing' the dipoles located in the focal line. Once a source is located, it can be tracked, practically from its rise in the east to setting in the west, by simply rotating the cylinder at the same rate as the rotation of the earth about its axis. Ingenious! The effective 'collecting area' of the ORT is very large – about 8000 sq. m. A dish antenna with the same collecting area would be about 140 m in diameter. A fully steerable antenna of that size was, at that time, beyond the technological capability anywhere in the world.

A telescope like that was not easy to build in the late 1960s. The technological capabilities were still primitive in India. While the Tata Consulting Engineers (known then as Tata Ebasco) did the structural and mechanical design, and the Calcutta Firm Bridge and Roof were identified to do the mechanical construction, the group itself lacked experienced engineers. Since foreign exchange was virtually impossible those days, the entire electronics had to be fabricated in India. The indigenous manufacture of critical components like coaxial cables, ultra-high frequency connectors, etc. was just starting. So it was a challenge to build a large telescope like that. The remote location of the site was an added complication.

Swarup's team was relatively young, consisting mostly of young research students; the median age of the team was just 26! The only relatively senior persons, besides Swarup, were N. V. G. Sarma, M. N. Joshi and S. S. Bhave, a mechanical engineer from TIFR. Since there were no experienced electrical or electronic engineers (they were to join the group a few years later), the students had to manage largely on their own. The entire electronics had to be built in-house by the handful of students, guided by Sarma and Joshi. This included the phase shifters, the 1024 dipoles along the focal line, the control system and the back end electronics. The students who were actively involved in the construction of the telescope were S. Ananthakrishnan, D. S. Bagri, V. Balasubramanian, S. Damle, J. D. Isloor, V. K. Kapahi, D. K. Mohanty and R. P. Sinha. They were assisted by a handful of technical persons. Rashid Ahmed was the Project Engineer in the beginning. The team worked incredibly hard, often 18 hours a day. Contrast this with the present-day trend where students refuse to dirty their hands. Expensive turnkey instruments are just bought off the shelf. Most students of astronomy do not even go to a telescope to observe; they submit proposals, and the data is sent to them by courier. Or, they use data archived by leading observatories and available in the public domain. Much of the charm of experimental science has disappeared. The 'publish or perish'

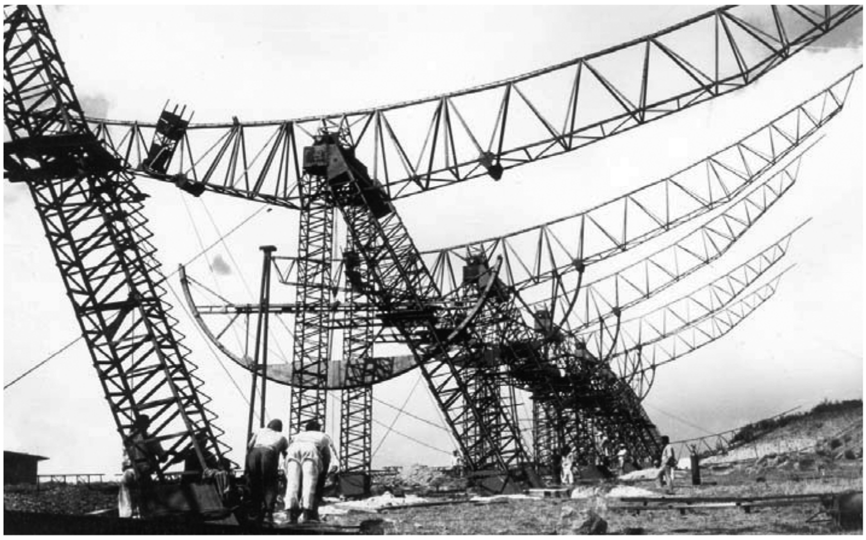


Photo taken during the erection of the parabolic cylinder.

A view of the northern section of the 530 m long cylinder. The vertical frames (24 of them in all) are of parabolic shape. These support the reflecting surface, made of 1100 stainless steel wires. The horizontal structures seen on the left are supports for the 1024 dipoles and phase shifters placed along the focal line.

syndrome has overtaken science. One can only be nostalgic about the days when students had a pioneering spirit; they were not obsessed with getting a 'quick Ph D'. Of course, they needed to be motivated and inspired by an inspired leader. Govind Swarup was certainly one of them!

Remarkably, the telescope was completed by December 1969! The fact that it was completed in an incredibly short span of four years bears testimony to both the commitment and dedication of the students, as well as the leadership quality of Govind Swarup.

The first astronomical observations were done on 18 February 1970. Then disaster struck in December 1971. Due to a coupling breaking loose, the entire southern portion of the telescope got free and rotated with respect to the northern half. The focal line with 1024 dipoles became a twisted mass of steel and crashed into the ground. The sad thing is that they knew such a thing could happen and had devised a safety mechanism. Ironically, the accident occurred just a week before the safety mechanism was to have been installed. The repair of the telescope took more than a year, and it was fully functional again only in mid-1973. By then some really talented engineers had joined the group [As we shall see, they went on to build the world's largest telescope]. But the loss of a year and half was most unfortunate. In 1968 Jocelyn Bell and Anthony Hewish in Cambridge discovered rapidly spinning, strongly magnetized neutron stars; they were detected as pulsating radio sources [Hewish was awarded the Nobel Prize in 1974 for this discovery]. Along with the discovery of quasars, the discovery of pulsars was truly momentous. The era of relativistic astrophysics, the era of neutron stars and black holes, had begun. The Ooty frequency of 327 MHz was the ideal frequency to study pulsars. Indeed, in 1968 D. K. Mohanty had embarked on building receivers for the study of pulsars. Although pulsar studies were undertaken at Ooty, the cream had been taken out during the period 1969–1973.

By 1975, the Ooty group had established itself as a world leader in observational cosmology. In subsequent years, the ORT was used for a variety of observations. To list a few of them, radio galaxies and quasars, the abundance of deuterium, supernova remnants, interstellar medium of the Milky Way Galaxy, the interplanetary medium, etc. This is not the occasion to highlight the scientific achievements of Swarup's group. I shall, however, make a couple of remarks in order to bring out the singular characteristics of Govind Swarup.

A young person visiting the telescope today may not be overawed by it as an engineering achievement. Naturally their calibration would be influenced by what has been achieved in India in recent years. To appreciate the technical achievement in building something like the Ooty telescope in the 1960s, one has to view it from a different perspective. The design and construction of a large structure with great precision posed a challenge to the engineering community in India; they had never undertaken a project like that before. S. Ananthakrishnan recalls a senior engineer from the Calcutta firm Bridge and Roof telling him 'We don't know anything about radio telescopes! You are asking for millimetre accuracy. When we design blast furnaces, we aim for an accuracy of a foot.' What made the engineers rise to the occasion was Swarup's inspirational leadership. Through his constant interaction with the engineers, he was able to infuse enthusiasm and motivate them. Recognizing this, Tata Consulting Engineers assigned some of their brilliant young engineers to this project. Swarup never takes any statement for granted, even if it is expounded by an established person. He would insist on a back of the envelope calculation to convince himself. He had the ability and self-confidence to do this at a coffee table, in the presence of others. This ability was a source of inspiration, as well as admiration, for the engineers working in the project. Although an occasional senior engineer from an outside agency might have been irritated by this style, this was Swarup's way of grooming his in-house engineers, and also exposing his research students to the intricacies of engineering design. As we shall see, this was to pay very rich dividends.

The other characteristic of Swarup that is worth highlighting is his originality. He could have chosen to build a good size conventional radio telescope, and used it for investigations that were currently fashionable. You will recall that the legendary Jan Oort had suggested to Swarup that he build a 25 m antenna to study the 21 cm line radiation from neutral hydrogen. The recent discovery of this line had triggered a major revolution in astronomy. The pursuit of this line of research would have been highly profitable. But Swarup did not do this. In this context I would like to recall what Lawrence Bragg said while justifying why he had chosen not to pursue in a big way nuclear physics and elementary particle physics at the Cavendish Laboratory, when he succeeded Rutherford as the Head of the Lab; after all, the Cavendish Lab had not only been the world leader in these fields, they created these fields! Bragg said '*Do not try to relive moments of past glory. Do not jump on a bandwagon simply because it is fashionable*.' Well, Swarup did not make those mistakes.

Cosmology was a very young science. There was a raging debate over the history of the Universe; was there a Big Bang beginning, or was the Steady State theory correct? Swarup had built a novel telescope which had a large collecting area, which was steerable, and which could track a source for several hours. He decided to use the telescope to answer some interesting questions in cosmology. But this required not only very high sensitivity but also very high *angular resolution* – far greater than what even this giant telescope was capable of. He decided to achieve the required ultra high angular resolution by observing the sources of interest when it was just being occulted (or eclipsed) by the Moon, in other words during ingress and egress. This technique is known as Lunar Occultation. The lunar limb acts as a straight edge that *diffracts* the radiation from the background star. *The high angular resolution is embedded in the diffraction pattern, which is scanned by the telescope as the source is eclipsed by the Moon*.

Cosmology, although a young science, was highly competitive. His competitors would include Martin Ryle's group at the Cavendish Laboratory. Swarup's confidence to take on the high priests was infectious; his young students – notably Vijay Kapahi, Gopal Krishna and C. R. Subrahmanya – decided to take on Cambridge, and the rest of the world. The lunar occultation survey of the faint radio sources that had originally been discovered by Martin Ryle's group turned out to be highly successful, yielding accurate positions and brightness profiles of about thousand radio sources. The positional accuracy was sufficient to make optical identification of the sources. This, in turn, enabled one to estimate the distances to these sources. This data base was also used to establish, for the first time, a correlation between their angular sizes and their flux densities. Based on this statistics, they concluded that the Big Bang theory was more tenable than the steady state theory. This created a major controversy within TIFR itself! On a different front, there was disagreement between the Cambridge and Ooty groups over the conclusions drawn from the Ooty observations. Finally, the ORT group led by Swarup prevailed! There could have been no greater tonic for boosting the self-confidence of the young

A partial view of the northern half of the cylindrical telescope after its completion. The focal line – running horizontally in the photo – with the dipoles and phase shifters can be clearly seen. The reflection of the Sun by the reflecting 'surface' can be seen as a vertical line of bright light. It is an awesome sight to see this parabolic cylinder, 530 m long, rotating about its axis as a single unit.

N. V. G. Sarma (left) and D. S. Bagri in the front row. V. K. Kapahi (left) and V. Balasubramanian in the row behind.

members of the group. Each one of them went on to make distinguished contributions in later years.

The 'balance sheet' after the exercise to build the Ooty radio telescope read something like this.

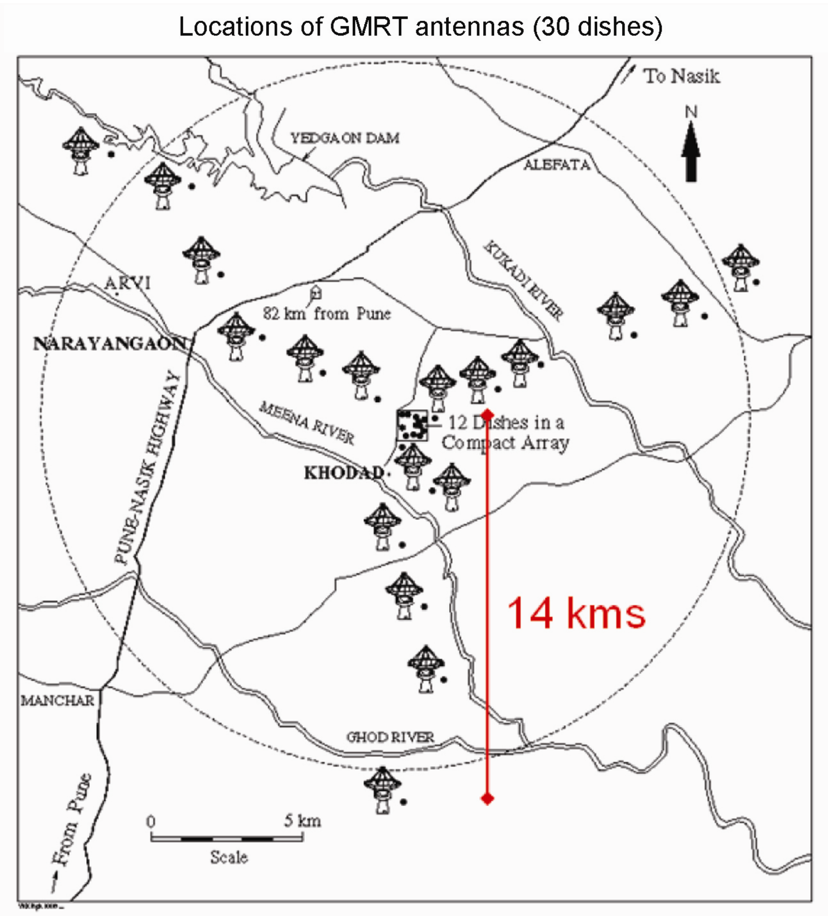
- A large number of talented young people were attracted to Swarup's 'crazy idea' (to quote one of his illustrious students) to build a novel world class telescope in the middle of nowhere. This included both students of science as well as engineering. The cream of the TIFR/Atomic Energy Training School wanted to work with Swarup.
- The project helped several engineering firms – such as Tata Consulting Engineers – to reach the next plateau in their capability and sophistication.
- The successful indigenous design and construction of the Ooty Radio Telescope led to the development of a large microwave antenna industry in India, starting with the construction of the ARVI satellite earth station north of Pune in 1971.
- The Ooty telescope produced not only good science; it produced a number of outstanding astronomers and engineers, endowed with leadership qualities.
- There was tremendous cohesion and camaraderie within the group.
- This group was to stay together and design and build the GMRT – the world's largest low frequency telescope.

The Giant Metre-wave Radio Telescope (GMRT)

Govind Swarup had earned the right to bask in glory after the spectacular success of the Ooty radio telescope. But by 1982 he was already dreaming of even bigger telescopes. By 1987, he and his former students (who, by then, had become distinguished scientists in their own right) had finalized the plan for the world's largest 'aperture synthesis telescope'.

A few words about 'aperture synthesis telescope' are in order. In aperture synthesis, a number of antennas, arranged in a particular pattern, or 'array', receive radiation from an astronomical source simultaneously and the signals are combined pair-wise. The method of combining the signal in most modern interferometers is a cross-correlation, but the signals can also be added. The response of each pair of antennas contains an amplitude and a phase which, customarily, are represented as a complex number. The expression 'aperture synthesis' derives from the concept that each pair of antennas acts like one piece of a single large telescope, and by combining the responses of pairs on all baselines, the aperture of a telescope as large as the longest baseline is, in principle, synthesized. This idea was first enunciated and exploited by Martin Ryle in the Cavendish Laboratory in the 1950s. He was awarded the Nobel Prize in 1974 for this discovery. The beauty of this idea is that the 'angular resolution' of such a telescope would be the same as that of an imaginary monolithic telescope filling the whole area. [The mirror in an optical telescope can be considered as such a 'filled aperture' since it contains the responses on all baseline separations up to the diameter of the mirror.] Further, the rotation of the earth changes the orientation of the line joining any two telescopes with respect to the celestial sphere. A straight line on the ground, viewed from some fixed direction in space, appears to change in length and orientation, as the Earth rotates. An East–West interferometer appears to move so that its spacing vector, viewed from the North celestial pole, describes a circular track in a plane perpendicular to the Earth's axis. A variable spacing interferometer can accomplish a set of such tracks in the plane perpendicular to the Earth's axis in a series of 12-h observations.

By 1970s, Martin Ryle had constructed an interferometer with several telescopes along a track of length equal to 5 km, and whose positions are mutually



GMRT consists of 30 dishes of 45 m diameter each. They are located in a Y-shaped array of about 25 km in extent, with twelve of them forming a compact array at the centre of the Y. As the Earth rotates, the orientation of the Y rotates with respect to the stars. Thus in ten hours of observation, one can get a map of a celestial source as though it were made with a dish 25 km in diameter!

adjustable. In the 1980s, the Very Large Array (VLA) was commissioned in New Mexico, USA. This observatory consists of 27 independent antennae, each of which has a dish diameter of 25 m. The antennae are distributed along the three arms of a track, shaped in a Y-configuration. Using the rail tracks that follow each of these arms the antennas can be physically relocated to a number of prepared positions, allowing aperture synthesis interferometry with a maximum baseline of 36 km: in essence, the array acts as a single antenna with that diameter.

A close-up view of one of the 45 m diameter GMRT dish antennas. The most remarkable thing about this design is the use of Stretched Mesh Attached to Rope Trusses, nicknamed SMART. The reflecting surface – a stainless steel mesh – is attached to these rope trusses. This is what gives the 'see-through-look' to the dish. This ingenious invention by Swarup greatly reduced the cost of the dish, by reducing the wind load, and has been acclaimed internationally. The receivers for operation at different frequencies are placed in a rotatable turret at the focus of the dish.

The truly gigantic size of these dishes can only be appreciated when one stands underneath them.

The telescope conceived by Swarup and his colleagues was along similar lines – but bigger! The GMRT would have 30 fully steerable parabolic dishes, each 45 m in diameter, and installed over a region of about 25 km. Its collecting area and sensitivity would be much better than that of the VLA. Further, it would have very impressive frequency coverage, ranging from 150 MHz to 1420 MHz. When completed, this was to be an international observing facility.

Lawrence Bragg once said 'No worthwhile scientific equipment is built for posterity. Invariably, some specific scientific objective is what leads to a successful instrument.' Although Swarup wanted GMRT to be used by astronomers from around the world, for a variety of purposes, what motivated him was a specific scientific goal. As mentioned before, cosmology was fast maturing as a discipline. According to the majority view, the discovery of the Cosmic Microwave Background Radiation provided clinching evidence in favour of the Big Bang theory. Theorists then turned their attention to how galaxies and clusters of galaxies formed from the primordial soup. There were conjectures, notably by the legendary Ya. B. Zeldovich in Moscow, regarding the cosmical epoch when giant clouds of hydrogen gas condensed to form large structures in the Universe. If those conjectures were true, then one should be able to detect those primordial hydrogen clouds, as they were before they condensed. Since the Universe is expanding, the 21 cm radiation emitted by them would be stretched (red shifted) to a wavelength of about one metre. Hence a metre-wave telescope was needed. Since the signals would be very weak, one needed very high sensitivity and angular resolution. This called for a giant telescope. This is why Swarup wanted to build GMRT. To make the telescope versatile for other observations, he wanted it to have broad frequency coverage.

Conventional parabolic dish antennas, built for operation at centimetre wavelengths, are extremely expensive. This is mainly because their high accuracy reflecting surface is bonded to a solid, suitably shaped structure. Such a solid structure has a huge 'wind load'. Therefore, a massive backup structure is needed to support them against large wind forces. Such massive antennas are naturally very expensive. Even though a 'mesh' reflecting surface would be adequate for metre wavelength radiation, a conventional 'solid' backup structure for the mesh for a 45 m antenna would be massive and very expensive. As a result, it would be impossible to have 30 antennas (with a total collecting area of 50,000 sq. m) within the allotted budget – unless some way was found to reduce the cost per dish. Sure enough, Swarup came up with an ingenious design, which is now internationally acclaimed. For a while he called it '*The Great Indian Rope Trick*'! Later he nicknamed it SMART, for Stretched Mesh Attached to Rope Trusses. In this concept, the conventional backup structure is replaced by a series of rope trusses (made of thin stainless steel wire ropes) stretched between radial parabolic frames and suitably tensioned to form a parabolic surface. A very low-solidity wire mesh (made of thin stainless steel wire) stretched over the rope trusses forms the reflecting surface.

The antennas are only one aspect of the telescope. The electronics for such a synthesis telescope is extremely complex. Everything had to be made indigenously; there was simply no question of importing anything. While the antennas were to be made by the industry, the entire electronics had to be designed and fabricated in-house. Even though this was twenty years after the Ooty telescope, it was a very different ball game, much larger in scale and complexity.

A view of some of the 12 antennas located at the centre of the Y-configuration.

Govind Swarup in conversation with Subrahmanyan Chandrasekhar (left) and Stephen Hawking (right).

Once again, it had to be a team effort, with Swarup leading them from the front. Fortunately, most of the ORT Team was still intact. Sadly, M. N. Joshi was no more. Although N. V. G. Sarma had moved to RRI, he played a very vital role in GMRT. [Sarma spearheaded the effort at RRI to make the horns and the receivers at 1420 MHz for the study of 21 cm line radiation from neutral hydrogen gas. A sophisticated receiver to study rotating neutron stars and a receiver to coherently add the signals from all the thirty antennas were also built at RRI.] Many of the engineers from the original Ooty team were still there, only more experienced now; and there were some new ones. As for the 'young kids', they had grown up, and were ready to join Swarup in building the world's largest telescope. This confidence was not mere cockiness; their confidence derived from building and operating the ORT successfully. The entire group shifted to Pune, where a new autonomous institute – National Centre for Radio Astrophysics (NCRA) – was created under the auspices of TIFR.

Swarup and his team did it again! The GMRT was successfully completed and started functioning in 2000. It was formally dedicated to the international astronomical community on 5 October 2001 by Ratan Tata.

I urge the young, and not so young, readers to visit GMRT. It will make your heart swell with pride. It is an awe-inspiring sight. The Nobel Laureate Subrahmanyan Chandrasekhar was so moved that he wrote in the Visitor's Book '*Shouldn't have thought that such things can be done*'. The first time I went there, and saw one of the antennas rise above the horizon as I was nearing the site, my feelings were similar to seeing the Great Pyramids for the first time!

The GMRT should become the benchmark for many things in Indian science. It demonstrates that self-reliance in instrumentation is possible. It is true that far more complicated things, such as Fast Breeder Reactors, advanced satellites, giant rockets like the PSLV and GSLV, have been made. But they were made by large organizations with large budgets. GMRT was made with a shoestring budget, at a fraction of what it would have cost elsewhere in the world. And it was made by a small team of scientists and engineers working in unison. Besides Swarup, the astronomers who worked intensely for many years on various aspects of the telescope were S. Ananthakrishnan, V. K. Kapahi, A. Pramesh Rao, C. R. Subrahmanya, V. K. Kulkarni, and their younger colleagues. It is appropriate that I also mention some of the extraordinary engineers who made this telescope possible: S. C. Tapde, N. V. Nagarathinam, M. K. Bhaskaran, M. R. Sankararaman, T. L. Venkatasubramoney, A. Praveen Kumar, R. Balasubramanian, and some others whom I did not know personally. The GMRT is an extraordinary achievement – by any standards.

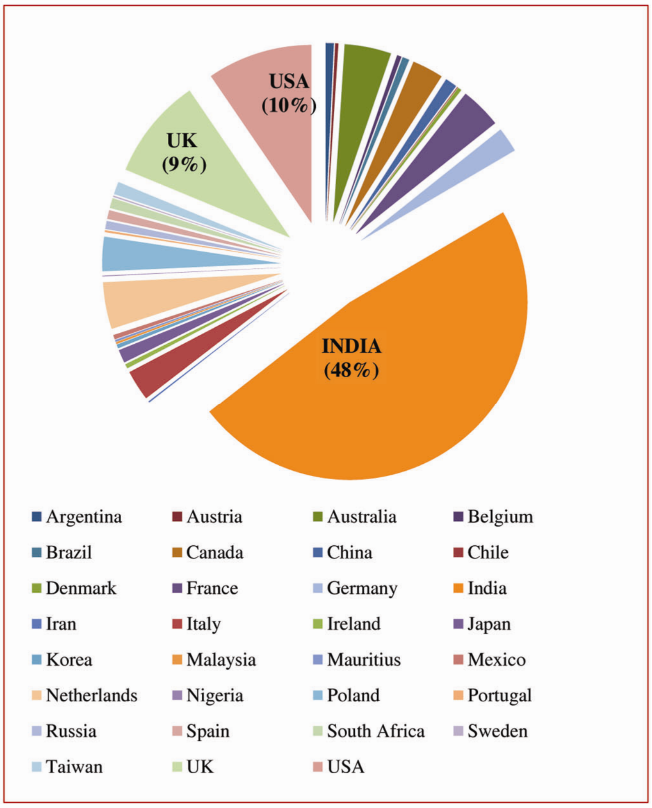
True to promise, *it has been an international facility from day one*. There is no reserved time even for NCRA astronomers. Observing proposals are invited from astronomers through periodic ‘announcement of opportunity’. The proposals are then subject to peer review, just like leading journals referee research papers. Observing time is then allotted, based on referee’s reports. Even Swarup had to submit proposals to observe with the telescope he conceived and built! A great tradition in astronomy has been maintained. *A new tradition had been started in India*.

GMRT is regarded as one of the major astronomical facilities in the world. Fifteen years after commissioning, GMRT continues to be used by astronomers from all the leading countries. Interestingly, roughly 50% of the time is used by astronomers from abroad, as can been seen in the accompanying pie-diagram and the histogram. This has been so since GMRT was thrown open for observations. This should be a source of inspiration for our young scientists, who often despair if research in the frontiers of science can ever be done in India, particularly in experimental science. Not only is there a truly world class radio telescope in India, it is being used extensively by the international community. This is the only instance I know of a scientific facility in India which is much sought after by leading scientists from various countries. The GMRT is a jewel in the international astronomical landscape.

While inaugurating the General Assembly of the International Astronomical Union in New Delhi in 1985, Prime Minister Rajiv Gandhi asked this of the Ooty telescope ‘It is certainly a great achievement. But will people come to see it 300 years from now, as they come to see the *Jantar Mantar* built by Raja Jaisingh?’ Structures like the Ooty telescope and the GMRT will crumble in a few decades due to corrosion; they will not last for centuries like masonry structures such as the *Jantar Mantar*. But while it is there, GMRT will continue to be used by the whole world, just as it is being done now. Therefore, in that sense, it is a far

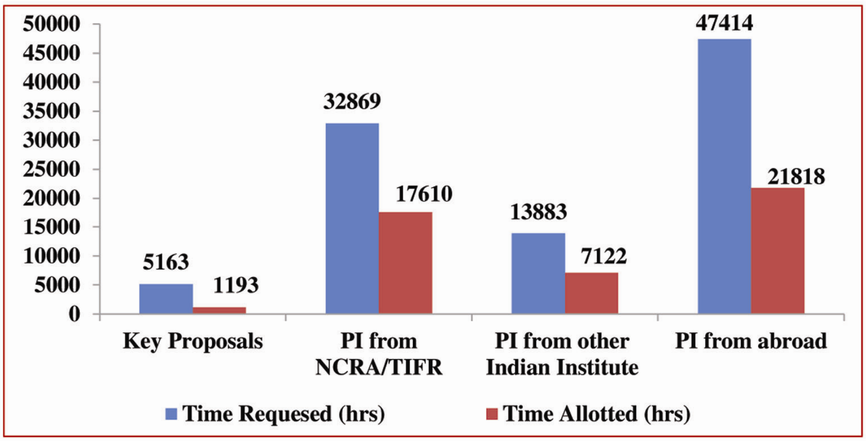
Countrywise distribution of proposals for Cycle 1 to 28
(January 2002–September 2015)

Country	Nos
Argentina	13
Austria	5
Australia	75
Belgium	7
Brazil	11
Canada	50
China	19
Chile	1
Denmark	6
France	66
Germany	40
India	847
Iran	2
Italy	49
Ireland	7
Japan	21
Korea	6
Malaysia	3
Mauritius	3
Mexico	7
Netherlands	75
Nigeria	1
Poland	55
Portugal	3
Russia	13
Spain	14
South Africa	16
Sweden	2
Taiwan	20
UK	163
USA	169
Total	1769



The GMRT is unique among the scientific facilities in India in that it is used by astronomers from all over the world. This diagram summarizes the statistics of proposals for which observing time was allotted during the first 28 cycles of operation; there are two cycles in every calendar year. As may be seen, a total of 1769 proposals have been allotted time on the GMRT during the first 28 cycles. Averaged over more than twelve years, 52% of the proposals for which time was allotted came from abroad.

GMRT proposal time allotment statistics (Cycle 1 to Cycle 28)



This histogram shows the statistics of time requested and time actually allotted. The great demand for observing time by astronomers from abroad is evident.

greater achievement than the *Jantar Mantar* ever was.

Still dreaming of things to do

Characteristically, Govind Swarup is not resting on his laurels. Like Jawaharlal Nehru, he must be inspired by Robert Frost:

The woods are lovely, dark and deep,
But I have promises to keep,
And miles to go before I sleep,
And miles to go before I sleep.

Two things are uppermost in Swarup's mind, at all times: Innovation and education. He never rests, and has no time for trivialities or gossip. And he won't let others while away their time either! Every time he has an idea, he will call some people, and put them to work. And I have been on his list for forty years. Typically, he will call and say 'Srini, I have a wonderful idea for an antenna that can be deployed on the Moon…' Or, 'Srini, the other day I went to a college and interacted with young students. This is what I want you to do…'

Yes, education has been one of his passions. He is always bubbling with ideas regarding how to attract brilliant young people to science. If many of his ideas have not fructified, it is because others who were supposed to pursue them, did not do so energetically enough. But some ideas he pursued relentlessly. He was one of the prime movers for a proposal made in 1997 for a 5-year integrated programme for intensive education in science for talented students after 10 + 2 schooling. After years of incubation, this idea has finally resulted in the government of India setting up the Indian Institutes of Science Education and Research (IISER) in Kolkata, Pune, Mohali, Bhopal and Thiruvananthapuram. Three more IISERs are to be set up in Tirupati, Odisha and Nagaland.

Awards and recognition

Not surprisingly, Swarup has received many coveted awards, both national and international. I would be doing an injustice to him if I were to dwell on these at any length, for he never aspired for any awards. Nevertheless, I would like to mention a few of them.

Govind Swarup is immensely proud of the fact that C. V. Raman elected him to the Fellowship of the Indian Academy of Sciences in 1967. Subsequently, he was elected to the Royal Society of London, and to the Pontifical Academy in the Vatican.

The astronomical community bestowed on him the Grote Reber Medal, the most coveted award for achievement in radio astronomy.

Pope Benedict XVI receiving Govind Swarup during the investiture ceremony when he was elected to the Pontifical Academy.

Lord Rees, President of the Royal Society and Astronomer Royal of England, presenting the Grote Reber Medal to Govind Swarup in 2007.

Some reflections

Govind Swarup is a quintessential scientist. Like most creative persons, he is totally engrossed in what he sets out to do; he lives in a cocoon. He is very unusual in the sense that he never trumpets his achievements – which are impressive by any standards. Perhaps as a result of this trait, he is not a 'celebrity' in his own country.

His remarkable success derives not only from his ingenuity but also from his leadership qualities – his ability to inspire not just talented young people, but also persons with more modest abilities. In that respect, he reminds one of the great Arnold Sommerfeld. As one of his illustrious students told me, Govind's boundless enthusiasm is tempered by pragmatism. While he always 'thought big', he restricted himself to what could possibly be achieved. But he always dabbled at the 'edge'.

Barring C. V. Raman and G. N. Ramachandran I can scarcely think of anyone else in India who has nurtured and groomed so many brilliant young scientists. In addition, Swarup's legacy includes a very large number of exceedingly talented engineers, identified, trained and nurtured by him, and who now are occupying prominent positions in prestigious institutions around the world. This is reminiscent of what Homi Bhabha and Satish Dhawan did, although on a much larger scale.

Fame has not changed him one bit. At the age of eighty five, he is still happiest when surrounded by young people, telling them about another of his 'crazy idea'. I used to see this in the Ooty Observatory cafeteria forty years ago, and

I see the same scene today. His interactions are always informal and anecdotal, and very long. But if one distils the conversation later on, one will find that he has challenged the young people with innumerable ideas.

Legends of science

How should one evaluate a scientist? Today, there is an excessive tendency to use various 'indices' to assess the impact of a scientist. One wonders if these 'indices' provide a 'necessary and sufficient criterion'. As Herman Bondi once remarked '*Name any topic "T". There will be several hundred persons working in that area. They will form a mutual admiration society, giving each other awards and inviting each other to conferences arranged by them.*' This may sound like a flippant remark, but this is the prevailing state of affairs. In this context, I may be permitted to quote Subrahmanyan Chandrasekhar:

'*On an occasion now more than 50 years ago, Milne reminded me that posterity, in time, will give us all our true measure and assign to each of us our due and humble place; and in the end it is the judgement of posterity that really matters. And Milne added: He really succeeds who perseveres according to his lights, unaffected by fortune, good or bad. And it is well to remember that there is in general no correlation between the judgement of posterity and the judgement of contemporaries.*'

There is no doubt in my mind that posterity will credit Govind Swarup with greatly influencing Indian astronomy. During the past five decades, he has always been highly original in his thinking, and has always 'thought big' – as Bhabha had advised him. Every one of his new initiatives was something that was out of the ordinary, novel and challenging. This invariably touched the chord of brilliant young students of science and engineering. That he has been able to inspire several generation of scientists and engineers – from 1963 till now! – is amazing. In this sense, his accomplishments transcend the conventional way to assess a scientist, namely their personal research contributions.

Someone once asked Rutherford the following 'You are always riding a wave in science, aren't you?' Rutherford boomed back 'I am creating the wave, am I not!' So it has been with Swarup. He started out as a pioneer. Fifty years later, he remains a pioneer.

Govind Swarup's career personifies the stuff legends are made of.

ACKNOWLEDGEMENTS. Today, India is recognized as a leader in radio astronomy. This is largely due to our demonstrated ability to design and build world class telescopes. In a sense, this article is a tribute not only to Swarup but to the entire *Swarup Team*, comprising of engineers and astronomers, now spanning three generations. They were pioneers then and are leaders now. It has been my pleasure and privilege to know and interact with them. This is an appropriate occasion for me to salute them. This is also an appropriate occasion for me to acknowledge and thank S. Ananthakrishnan for his friendship and sagacity over the years.

The astronomical scene has changed dramatically during the last couple of decades. Like in elementary particle research, in astronomy also, future facilities are necessarily going to be an *international effort*; no country can afford the cost. The Large Hadron Collider is an example from physics. In astronomy, the Thirty Metre Optical Telescope and the Square Kilometre Radio Telescope are presently being pursued by international consortia; and India is very much involved in both these efforts. This is the legacy of Govind Swarup. It is now up to the young scientists and engineers in India to follow in the footsteps of Swarup; there is no excuse for saying that 'there is no challenge'!

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