Udupi Ramachandra Rao

V. Jayaraman

Udupi Ramachandra Rao, known more as U. R. Rao, is an internationally acclaimed space scientist and rated by the coveted *Space News* magazine in 2004 as one of the top 10 international personalities, who made a difference in civil, commerce and military space in the world since 1989. Joan Johnson Freese, an analyst of the Asian space programmes and the then Chair of the Department of National Security decision-making at the Naval War College in New Port, USA said to the *Space News* that one of the testaments of Rao's skills was that he built a robust space programme in a democratic country, which is much more difficult than in countries with autocratic rulers. Considering that in a country where even a defeat in a cricket match is touted as a national catastrophe, it is truly remarkable that India could emerge as a strong global player in space technology applications on par with the top space agencies. None can deny the stellar role played by Rao in this unenviable task of building an endogenous space technology capability in India, weathering all the initial difficulties, obstacles and failures he faced and also his continued emphasis and passion for addressing unique applications of direct relevance to India using the advanced weather, remote sensing and communication satellites. I, as his last Ph D student, and as a colleague fortunate enough to be associated with him for more than 40 years since the *Aryabhata* days, consider this as a great privilege to pay this academic tribute to this passionate scientist and a great leader.

Rao is an exceptionally versatile scientist with a wide-ranging repertoire in many contemporary topics. Even today, the 82-years young Rao is regular to his office at Antariksh Bhavan, the ISRO Headquarters in Bangalore, and busy with the latest emerging topics around the world, be it in space science and technology, disaster management or in climate change; and is it not amazing that he is doing it for more than 50 years almost from the very dawn of space technology in the world?

Here, I recall vividly a comment made by a reader, Ron Cram, in a science blog (wattsupwiththat.com/2011/01/21/cosmic-rays-contribute-40-to-global-warming-study/), which vociferously discussed about the recent 'controversial' paper by Rao on 'Contribution of changing galactic cosmic ray flux to global warming'[1]. Ron wondered '*...is it by the same U. R. Rao who was publishing science papers back in 1963? Or is it his grandson? Long career, if it is the same man. Congrats to him!*'. Yes, it is really remarkable for a scientist, continuing to be so active in core science subject(s) for more than 50 years or so, even after taking up many other high pressure management responsibilities.

Let me add a couple of more recent events to bring the above aspects into focus. When I went to Rao recently for getting some inputs for this article, he was busy dictating a letter as a Commentary (this issue, p. 1474) on a recent paper which appeared in the *Journal of Geophysical Research*[2] attributing Earth's magnetic field as being responsible for making the Earth unique and habitable. Cram was probably not aware that Rao had published way back in 1980–81 two papers on the crucial role of the magnetic field on the evolution of life on Earth[3,4]. Hence, Rao was sending his Commentary on this article. He also narrated the background of his earlier papers, published essentially due to the encouragement from Sivaraj Ramaseshan and Satish Dhawan during their visit to a place near Hubli (in Karnataka) in February 1980 for conducting some field experiments on the famous Total Solar Eclipse of the day. Hearing Rao espousing Earth's magnetic field as the causal factor for life on Earth, it was Ramaseshan who asked him to write the paper for *Pramana* and later inspired him to send it to the *Journal of British Interplanetary Society*.

It is such a combination of passion, forthrightness and concern for scientific details and technological achievements that keeps Rao very active even now in all the contemporary space missions of India, like his continued involvement in India's Mars Orbiter Mission and the proposed *Aditya* mission to Sun. He is so much excited about *Aditya* mission that he ensured that it went through a thorough revamp of its mission objectives including its orbital parameters to make the mission more meaningful and contemporary. Now, thanks to Rao, *Aditya* may become the first mission from India to be placed in the Lagrangian Point, L1, one of the libration points in orbital configuration, 1.5 million km from the Earth, where a satellite when placed will have the same angular velocity as that of the Earth with respect to Sun and hence, maintain the same position in relation to Sun as seen from Earth. There are many scientific issues that are attracting his attention like studying the Sun's chromosphere, the transition region, the Corona and its heating problem. Rao wonders 'Even now, no one is able to satisfactorily give a reason as to how the temperature shoots up from thousands of degrees in chromosphere to millions of degrees in the coronal region through the transition zone within no time, and what sensors with what sensitivity are needed to capture that event.' With his sharp mind and intellect, Rao is busy finalizing the appropriate selection of sensors and their inclusion onboard *Aditya*.

Early days

Rao was born on 10 March 1932 to Lakshminarayana Acharya and Krishnaveni Amma in Adamaru village, Udupi, Karnataka. He had his early education in Christian High School, Udupi and inter-junior course in Veerashaiva College, Bellary. He studied his B Sc at the Government Arts & Science College, Ananthapur under Madras University; and got his M Sc in Physics from Banaras Hindu University, Varanasi in 1953.

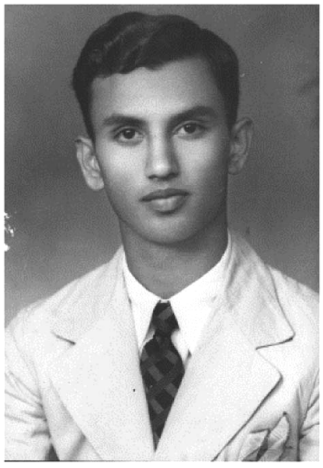
After a few months working as a lecturer in Ahmednagar and later in Mysore, he commenced the remarkable part of his long journey towards exploring space science and its advanced frontiers. He registered as a doctoral student at the Physical Research Laboratory (PRL), Ahmedabad in 1954 under Vikram Sarabhai and was awarded the Ph D from Gujarat University in 1960. His doctoral research studies using inclined telescopes

led to the unambiguous establishment of diurnal and semi-diurnal variations of galactic cosmic ray intensity. It is during this period that the world saw the launch of the first satellite *Sputnik* in 1957 by the then USSR, followed by USA's *Explorer 1* in 1960.

Exposure to frontier space sciences

Joining the Massachusetts Institute of Technology (MIT), USA in 1961 as a postdoc, Rao along with his colleague K. G. McCracken, carried out a path-breaking computation of cosmic ray particle trajectories in space using complex simulation of geomagnetic field. Here, Rao made use of the cosmic rays observed on the ground as tracers to study the electromagnetic state of the interplanetary space. Around this time, the launch of *Mariner 2* in 1962, the first-ever robotic space probe to Planet Venus with the solar plasma and charged particle sensors, provided an opportunity to detect the high-energy charged particles flowing outwards from the Sun, including several brief solar flares, as well as cosmic rays from outside the solar system itself. Making use of *Mariner 2* data, and working along with Conway Snyder and Marcia Neugabauer of the Jet Propulsion Laboratory (JPL), Rao made a path-breaking discovery of the continuous emission of the solar wind, their characteristics and correlation with the geomagnetic disturbance.

Further, working at South West Center for Advanced Studies at Dallas in 1963 (now known as University of Texas at Dallas), Rao became the Principal Investigator, along with McCracken, for *Pioneers-6, 7, 8, 9* deep space probes and the *Explorer 34, 41* satellites. This research led to Rao's much acclaimed work on solar cosmic ray anisotropies and their relationship with interplanetary magnetic field. They were the first anisotropy measurements, which conclusively proved that solar cosmic-ray protons exhibit strong field aligned anisotropies in the initial phase of the solar flare, which later get totally isotrophized in the decaying phase, unlike the solar flare electrons, which do not exhibit large anisotropies even in the initial phase due to small scale scattering in the interplanetary magnetic field. Rao's extensive work also led to the evolution of a single convection–diffusion model for explaining the long-lived solar proton anisotropies in both prompt and delayed solar flare events, in terms of the particle motion along the twisted interplanetary magnetic tubes of force, which are stretched in the form of an Archimedean spiral. These experiments also were the first to establish the acceleration of energetic particles in the shock fronts, and enhance the understanding of the nature of the co-rotating Furbush decreases of the galactic cosmic ray intensity, following a coronal mass ejection.



Young Rao in Massachusetts Institute of Technology.

Rao with McCracken (extreme left) and F. S. Johnson (extreme right).

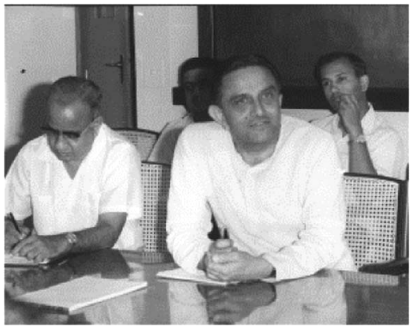
Returning to India

Rao returned to India in 1966 and joined PRL at the invitation of Vikram Sarabhai and carried out extensive work in high energy astronomy, particularly on the correlation between the time variation of optical and X-ray emission of X-ray sources in the energy range 2–20 keV using balloon, rocket and satellite-borne instrumentation. Rao and his group also made significant contribution to the understanding of the cosmic X-ray and gamma ray background and studied the effects of celestial X-ray sources on the ionization of nocturnal-D-region ionosphere.

While Rao was busy at PRL carrying out his space science activities, Sarabhai was in the process of identifying suitable leaders towards his vision of making India a self-reliant space power, being convinced of its immense potential to leapfrog in national developmental activities. During late-1968, Sarabhai requested Rao to prepare a blueprint for development of satellite technology and its applications. Once it was ready, he convinced a reluctant Rao, the only person at that time with direct working experience on spacecraft systems at NASA, to take charge and shape the Indian satellite programme.

Putting together a team of around 20 engineers from the then Space Science Technology Centre (SSTC), Thiruvananthapuram and a small team of around 20 from PRL under what was then known as

Rao at Physical Research Laboratory.



Rao with Vikram Sarabhai. H. G. S. Murthy on the left.

Satellite Systems Division (SSD), Rao started designing a 100 kg satellite for possible launch on an American Scout Launch vehicle. But things changed irreversibly when prompted by a letter from D. P. Dhar, Indian Ambassador to Russia, to the then Prime Minister Indira Gandhi. Sarabhai organized a meeting with Soviet Ambassador, Pegov, to explore the possibility of USSR providing the launch support for India. Later, a high-power team, with Rao as a member, had discussions in August 1971 at Moscow with USSR Academy of Sciences, when USSR agreed to provide a free launch for a totally Indian built satellite on a Soviet rocket carrier.

Building satellite technology – with grit and determination

Unfortunately, Sarabhai passed away in his sleep in December 1971 at a young age of 52. M. G. K. Menon became the interim Chairman of ISRO and during his period, a momentous decision was made to establish the satellite project at Bangalore, based on the assessment of the available supporting industries and infrastructure. The historic agreement for the launch of the first Indian satellite from a Soviet Cosmodrome was signed on 10 May 1972 by Academician M. Keldysh, President of USSR Academy of Sciences and Menon. Rao was made the Project Director of the Indian Scientific Satellite Project and was given less than 36 months to get the satellite ready for launch by a Soviet launcher. Satish Dhawan came back from his sabbatical at Caltech, USA and took over as ISRO Chairman.

Rao's determination to achieve the seemingly impossible task of building the satellite for the first time in the country, within the stipulated time and budget, without any basic infrastructure in place, was something phenomenal. The project management and system engineering abilities of Rao, came into the fore then. He moved quickly in getting some industrial sheds allotted by the Government of Karnataka in Peenya, Bangalore and got them re-modelled, suitably modified and appropriately equipped to establish a sophisticated electronic laboratory, a clean room for satellite assembly, a one-metre thermo-vacuum chamber, and control system infrastructure and mechanical facilities. He worked out arrangements for extensive use of the fabrication and test facilities in various industries at Bangalore and elsewhere. Parallelly, he went on to recruit around 150 young engineers and scientists in various disciplines from across the country. The realization of the first satellite, later named *Aryabhata*, with an enthusiastic dynamic young team with no practical experience on any spacecraft system was really a challenge. Rao accomplished this miracle with flying colours. It was amazing that five models of the spacecraft were made in the shortest time; a quarter size model, which was flown on a balloon at TIFR Balloon Facility, Hyderabad; an engineering model which was flight-tested using a helicopter over SHAR and the Bear's Lake station near Moscow; a prototype and two flight models. All within the stipulated time and budget!

The average age of *Aryabhata* team was just around 25 years in April 1975, when the 358 kg *Aryabhata* satellite was launched from Kapustin Yar Cosmodrome, about 150 km from Volgograd in USSR. Even now, whenever anyone wonders about how he could manage such a complex project staring from a scratch in Indian settings, Rao says: 'Yes, I had a young team, though inexperienced, was very committed. The unmatched enthusiasm, dedication, hard work, and the tremendous confidence, and the co-operative team spirit displayed by them to accomplish the goals and their "never say impossible" attitude were contagious, and became part of ISRO culture later.'

Some of us who were associated with *Aryabhata* will always remember Rao's abundant energy, dynamism and his sense of urgency and enthusiasm to get the things done on time with professional finesse. He proved conclusively that India had the ability to master the high technology and deliver world-class products, if there is a professional leadership that leads from the front, bestowing confidence and encouragement, and posing adequate scientific and technological challenges to the younger generation. It is no wonder then that the sheds at Peenya became a major centre of attraction for scientists, administrators as well as prominent politicians. Prime Minister, Indira Gandhi was prominent among them to witness the final integration of the flight model of *Aryabhata*.

Indira Gandhi arriving to witness *Aryabhata*.

Immediately after *Aryabhata*, Rao became the first Director of the ISRO Satellite Centre, Bangalore, formed as a full-fledged centre for the development of satellite technology in the country. He went on to conceive the experimental remote sensing satellites, *Bhaskara 1&2*, *Rohini D2* and technology satellites in the SROSS series, which provided the foundation for the operational Indian Remote Sensing Satellites (IRS) for natural resources and environmental applications; and the experimental communication satellite, *Apple*, as first step to boldly embark on ISRO's ambitious operational Indian National Satellites (INSAT) for communication applications.

Bhaskara 1&2 marked the pioneering baby steps taken in the experimental phase of the Indian remote sensing programme with a TV Vidicon camera and a SAMEER microwave payload on a spinning platform! Be sure, birth-pangs were not easy! I still remember the excruciating moments after launch, when a corona problem was encountered in orbit in the high voltage supply to the image intensifiers of the TV payload; the extensive ground simulation tests done, the detailed circuit analysis carried out to understand the problem and the close scrutiny and reviews by Rao, particularly of the final document we prepared on the analysis and the possible solutions. Rao's personal expertise in handling many HV supplies for X-ray and Gamma ray payloads and his knowledge of potting compounds came out quite handy during those reviews. Thus, it was a moment of great satisfaction when the solution provided by the simulation team did miracles and the TV payload was successfully switched on later after months of waiting.

The first experimental communication satellite, *Ariane Passenger Payload Experiment* (*APPLE*), was a free launch

opportunity provided by ESA in their developmental flight of *ARIANE-3* launch vehicle and grasped by ISRO through a request for proposal (RFP). *APPLE* spacecraft was supposed to carry one of three satellite payloads meant for *ARIANE-3* and sandwiched between a CAT module at the bottom, and the METEOSAT on the top. Apart from insisting on integrated stack vibration test, the agreement with ESA, even called for providing a structurally equivalent dummy satellite, if functional spacecraft is not ready on time. Such was the pressure and probably the (lack of) confidence ESA had in ISRO in those days to develop the satellite from a scratch! With Rao's constant drive and encouragement, ISRO resorted to many innovative means to develop and test the satellite to meet the stringent ARIANE schedule. The famous picture of *APPLE* being transported on a bullock cart with rubber tyres for EMC test became a symbol of our innovative approach and was even characterized as 'Collision of Centuries' by *Newsweek* magazine.

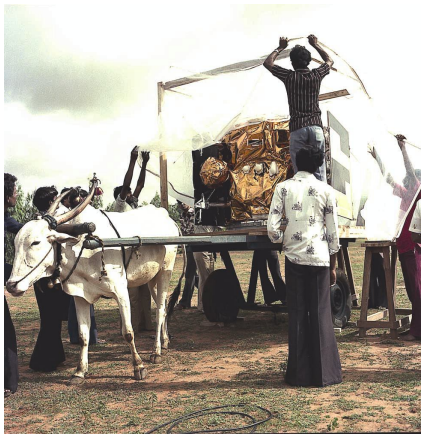
APPLE, the first 3-axis stabilized mission for ISRO, with all the associated technologies, and carrying 2 C-band transponders, was realized in record time meeting many challenges of new developments and qualification. *APPLE* went on to work for 2 years in spite of hitches in orbit like the non-deployment of one solar panel.

Anyone who has worked with Rao will vouch for the determination, confidence and the faith he had nurtured in his team of scientists and engineers. It was one such instance during 1983 that he wanted them to build an indigenous *INSAT-2* series of spacecraft. That it happened immediately after the difficult days of some of the bad experience with the multi-purpose *INSAT-1* satellites procured from USA, shows the intensity of the situation and the hard decision making ability of Rao as the leader. At that time, *INSAT-1A* had failed in the orbit and *INSAT-1B* just commissioned after some difficult in-orbit manoeuvres like heating the solar array hinges by exposing it to the Sun. Rao felt that ISRO should and could do better than the procured satellites. Remember, ISRO had only a very limited experience of *Aryabhata*, *Bhaskara* and *APPLE* at that time. Planning indigenously a complex *INSAT-2* satellite with multi-purpose applications with that experience, was really a courageous act. Rao had also a battle elsewhere in the Planning Commission to convince them that the unique multi-purpose communication concept adopted in *INSAT* was really technically viable and most cost-effective. True to his nature, he did not allow the external shocks to affect the internal morale of the engineers working on the cutting edge spacecraft technology. With his perseverance and constant support, he established unambiguously the technical prowess and capability of the communication satellite programme in ISRO and the *INSAT-2* system was realized in early-90s. The mantra given by Rao then was 'If somebody can do, we can do better'. It is this confidence and motivation provided by Rao in those days that led the ISRO team to take up much higher challenges of later days. Today, ISRO is in the process of making much bigger, high-power communication spacecraft of 4T–6T class that can accommodate 40 transponders and more in the frequencies from S, C, to Ku band from the just 2 C-band transponders flown in *APPLE*!

Similar is the achievement in Remote Sensing satellite arena too. Once again thanks to encouragement given by Rao, George Joseph and his team came up with a proposal of a charge coupled device (CCD)-based electronic scanning camera system in *Indian Remote Sensing satellite-1A* (*IRS-1A*) a new concept at that time, as the contemporary US LANDSAT system was still using mechanical scanning for their imaging system using photodiodes. Thus, the launching of *IRS-1A* in 1988 providing high quality images was a tribute to the technology foresight and prowess of ISRO and Rao's leadership. IRS became a well-known global brand, even capturing global leadership within the next 5–6 years for the highest spatial resolution remote sensing camera, when *IRS-1C* was launched in 1995. It is a remarkable feat for the country, as India's imaging capability made a quantum jump from around 1 km spatial resolution in *Bhaskara 1&2* to better than 1 m, in the *Technology Experimental Satellite* (*TES*) launched in 1999. All within 20 years!

Rao should also be credited for the way he brought in systemic changes in the complex project management structure for ISRO's satellite projects. Based on his own exposure and experience at NASA, and ably aided by K. Kasturirangan, who was the Project Director for *Bhaskara 1&2* and *IRS-1A* satellites, Rao introduced the matrix management structure for optimally utilizing the scarce human resources across the projects; ensuring decision-making at decentralized level where technological expertise lies; and at the same time, emphasizing on configuration management and systems engineering practices of enhanced coordination, interface control, quality assurance and professional documentation. Over the years, this basic organizational structure envisaged by Rao has largely remained the same in the management of ISRO's satellite projects. Abdus Salam was amongst the many who were impressed by the extraordinary pace of satellite activities under Rao and he visited the ISRO Satellite Centre, a couple of times. Being a champion of third-world countries, Abdus Salam wanted India's expertise propagated to other developing countries. It was due to his insistence that Rao conducted a 2-month-long course on 'Physics of communication' at Trieste, Italy in November 1983.

Rao became Chairman, ISRO on 1 October 1984, after the superannuation of



APPLE on a bullock cart.

Rao with Abdus Salam.

Satish Dhawan. Incidentally, that transition also marked the end of the experimental era and the beginning of the operational era in Indian Space programme. Rao was expected to carry on the job of consolidating from the experience gained from the experimental satellites like *Aryabhata*, *Bhaskara* and *APPLE*, as well as, from the launch vehicle SLV and take ISRO to the next level.

The task was not easy. Obviously, the prime requirement of any operationalization, is the timely execution of goal-oriented programmes to provide uninterrupted space services in a reliable and cost-effective manner. Continued R&D on the cutting-edge technologies to be on par with the best in the world, bringing awareness about the potentials of the space technology and promoting the applications to newer users, and encouraging them to adapt them at their end are part of this operationalization process. Building self-reliance in spacecraft and launch vehicle technology, bestowed with restrictions and embargos from the developed world, was a major challenge. International collaboration is yet another important element in space technology and applications. Rao as Chairman of ISRO for around 10 years addressed all these elements as well as the human resources development, professionally leading from the front, in meeting many challenges, failures, and hurdles and it would take many pages if one tries to list them all.

Launch vehicles – overcoming hurdles

Rao, as the Chairman of the Indian Space Programme, also accelerated the development of launch vehicle technology. India had, by then, successfully demonstrated the Satellite Launch Vehicle (SLV-3) in July 1980 with a 40 kg *Rohini* satellite (*RS-1*), followed by launches in May 1981 carrying *RS-D1*, and in April 1983 carrying *RS-D2* satellite. While SLV-3 established a number of technologies relevant to launch vehicle and had provided necessary confidence to ISRO team for taking up more challenging tasks, it was well realized that operational launch vehicles capable of placing remote sensing and communication satellites had to be developed to establish self reliance in launch vehicle technology. Hence, in order to quickly develop and qualify many newer technologies like closed-loop guidance system, strap-on technology, bulbous heat shields and highly accurate inertial platforms, it was decided to go in for the Augmented Satellite Launch Vehicle (ASLV), upgrading the first stage of SLV-3 with two strap-on boosters, with motors identical to that of the first stage. ASLV was expected to be capable of launching 130–150 kg class of satellites into a low earth orbit. Many massive facilities were created within and outside ISRO and initiatives put in place for industry participation in a big way, to support the development of operational launch vehicles. Unfortunately, the first two developmental flights of ASLV carried out in March 1987 and July 1988 did not succeed. These failures seemed to threaten the confidence of ISRO launch community. But, the encouragement provided by Rao as the Chairman during this critical period, is an astounding testimony to his leadership style. The failure analysis of ASLV turned out to be the most rewarding exercise ever done by ISRO. Based on the inputs and the improvements made, the third and fourth flights of ASLV, carried out in May 1992 and May 1994, were fully successful, validating the very useful lessons learnt from the earlier failures. ASLV programme was terminated then, after having provided valuable lessons and the technologies needed for taking up boldly the more challenging PSLV and GSLV.

PSLV was not just bigger than ASLV, but was much different in configuration as well, with its unique configuration of alternate solid and liquid stages, calling for new technologies, materials, gigantic facilities including modification of launch complex itself as well as large industrial back-up. Added to this, there were also other issues of sanctions and embargos imposed by USA. With all these, the PSLV developmental activities were accomplished successfully and the first PSLV was launched in September 1993. But, unfortunately the flight failed to complete the mission due to an inadvertent error in digital autopilot software in the guidance and control processor. Every other system worked to the fullest expectations. With the correction incorporated, the second PSLV flight launched in October 1994, was totally successful. Rao had by then superannuated in April 1994, and Kasturirangan had taken over as Chairman, ISRO. Since then, PSLV has made 25 successive successful flights. Today, PSLV is ISRO's reliable workhorse and has been regularly used for launching the operational *IRS* satellites, besides even satellites like *EDUSAT* and *Chandrayaan*, as also the recent *Mars Orbiter Mission* (*MOM*). PSLV has also enabled ISRO to become a significant player in the international launch vehicle market.

During this period, Rao also initiated the development of cryo-technology and the development of Geosynchronous Launch Vehicle (GSLV) capable of launching 2–2.5 tonnes class of satellites into geostationary orbit. This story of cryogenic engines has been told many times and is well known to the general public by now. Just to summarize, based on the project approval for GSLV in October 1990, ISRO signed an agreement with Glavkosmos (GK), USSR for three GSLV launches with two 12-tonne cryo engines (C12) fabricated in USSR with the participation of ISRO engineers and the third built in India with the technology transferred from USSR. However, the agreement could not be executed due to the total embargo by USA on both GK and ISRO in May 1992, leading to Russia terminating the original agreement in October 1993 using the 'Force Majeure' clause. The renegotiation of cryogenic technology contract with GK happened in December 1993, just a few months before Rao laid down his office. The technology transfer clause was rescinded and GK agreed to give 4 fully qualified cryo-engines and 2 mock-ups, as against the original two engines stipulated earlier. Further, three more additional engines were offered at cost, if ISRO desires to procure. Rao's dream of building and qualifying an indigenously developed cryo-engine then had to wait for 20 more years, till K. Radhakrishnan, the current ISRO Chairman fulfilled that dream in January 2014, when GSLV D5 with indigenous cryogenic upper stage went up successfully to deploy *GSAT 14* into designated orbit.

Having been instrumental in the ASLV, PSLV and the GSLV cryo-engines, Rao is justifiably happy that all his efforts towards making a self-reliant operational launch vehicle programme, have at last borne fruits.

Pioneering bold space applications

Any write-up on Rao will not be complete if it does not contain his remarkable

contribution to space technology applications.

When Rao took over as Chairman, ISRO in 1984, the National Natural Resources Management System (NNRMS) had just emerged in 1983 as a unique arrangement under the aegis of the Planning Commission, to ensure optimum utilization of remote sensing at the user end. With the identification of a number of end-to-end experiments by the Preparatory Committee of NNRMS, Rao launched a comprehensive IRS-Utilization Programme (IRS-UP) during mid-80s to prepare the user community to make use of the data from impending launch of *IRS-1A*. IRS-UP paved the way for taking up many fore-runner applications, such as forest mapping, flood mapping, groundwater targeting, regional geological mapping, land degradation studies, drought monitoring, snow melt run-off studies, land-use mapping and soil mapping in a collaborative mode with several user agencies. They served as launch pad for taking up major operational remote sensing applications once the satellites in IRS were available in the 90s.

While recalling some of the bold early initiatives taken by Rao in remote sensing applications, one will always remember the forest vegetation map of India prepared by National Remote Sensing Agency (NRSA) using the US LANDSAT data during 1985–86, and the uproar it created in the country. NRSA had suggested that the forest cover in the country has declined from 16.9% to 14.1% during 10-year period (1972–1982). It triggered major discussions and commotion amongst the user community comprising of Forest of Survey of India (FSI) under the Ministry of Environment & Forests (MoEn&F) and the State forest departments. Questions on methodology, selection of appropriate season for data, etc., were raised in various fora. Though there were some gaps in the quantitative assessment which needed appropriate relook, the utility of satellite remote sensing was firmly established through this pioneering exercise. T. N. Seshan, who was at Department of Space had by then moved to MoEn&F as its Secretary. A joint reconciliation exercise conducted with the user-Department enabled NRSA to evolve an appropriate methodology for periodic biennial assessment of forest wealth of the country to be carried out by FSI itself using satellite remote sensing. This became the first-ever example of effective institutionalization of remote sensing in the user department in the country as envisaged under NNRMS.

Similarly, Rao wanted NRSA to identify and map the large traces of wastelands in the country, which could be judiciously developed for productive purposes. This activity, initiated as Nationwide Wasteland Mapping during mid-1984, was showcased to the then Prime Minister Rajiv Gandhi in August 1985 and it ultimately led to NRSA being asked to periodically update the wastelands information for use by the Ministry of Rural Development. In fact, this led the Ministry to set up a separate Department of Land Resources in mid-90s to speed up the wasteland reclamation efforts.

Rao's most significant initiative was the launching of Integrated Mission for Sustainable Development (IMSD) and carried out in 84 mha in 175 districts in the country around 1992. Rao boldly advocated remote sensing as a key element in preparing resource maps and evolving action plans at watershed level, to provide grass-root solutions, epitomizing the confluence of scientific knowledge, administrative acumen, and local wisdom towards conserving the land and water resources. His advocacy on IMSD went to the extent of roping in some young enthusiastic district collectors and NGOs from across the country to implement the action plan on the ground. Some of the success stories of IMSD are being narrated even today with reported increase in groundwater level, increased cropping intensity along with increased return on investment for the poor farmers in the rainfed agricultural areas. No wonder IMSD became the inspirational role model for all the later projects, including its adaptation in the National Watershed Development Programme for Rainfed Areas (NWDPRA), and also in the much acclaimed World Bank aided Sujala Watershed Development Programme in Karnataka. Incidentally, Radhakrishnan was the then Mission Director of IMSD!

Rao inspecting IMSD action plan implementation.

Considering the vulnerability of our country to recurrent natural disasters, Rao aggressively promoted the use of satellite remote sensing for many disaster management applications, particularly emphasizing its potential role for operational flood management and agricultural drought monitoring. Due to his constant egging, a major national initiative, namely the National Agricultural Drought Assessment and Monitoring System (NADAMS) was launched and NRSA brought out biweekly drought bulletins covering many states. NADAMS underwent constant improvements over time, consistent with advancements made in satellite imaging sensors. Likewise, the flood mapping became operational in Indus, Ganges and Brahmaputra basins with the combination of optical and microwave data.

Yet another ambitious and socially relevant project advocated by Rao was under the Rajiv Gandhi National Drinking Water Mission (RGNDWM), wherein remote sensing data was successfully utilized to map prospective zones for groundwater occurrence, and locations for constructing recharge structures. Funded by the Department of Drinking Water Supply of the Ministry of Rural Development, this application is hailed as a major success story with feedback on the utilization of groundwater prospect maps providing more than 90% success rate.

Thanks to his prodding and constant reviews, there were many other applications launched during his period such as the development of National (Natural) Resources Information System (NRIS) around GIS for facilitating developmental planning and decision-making at national/district levels; monitoring and mapping of mineral resources; biodiversity characterization at landscape level; mapping salt and saline-affected soils; landslide hazard zonation, snow melt run-off studies, coastal wetlands mapping, land cover/land use mapping, to cite only a few. These applications continue to this day, albeit at larger scales, thanks to the availability of satellites with better resolutions.

Thus, Rao is rightly credited by the NNRMS community as the one who initiated many bold experiments using remote sensing for national development,

making India as the leader in carrying out operational remote sensing applications of direct relevance to the country. I would suggest that one should read Rao's masterly book *Space Technology for Sustainable Development* to further understand the breadth and depth of knowledge and the passion he has for making use of space-based inputs in developmental planning. Incidentally, this book bagged the Outstanding Book Award of the International Academy of Astronautics (IAA) in 1997!

Now, let us see what Rao did for satellite communication applications. With hundreds of TV broadcast channels beaming programmes from all over the world directly available at the flip of the remote, and with the availability of instant broadband connectivity for long distance communication, and proliferation of mobiles and social networking, the current generation may not really be fully aware of the situation in the country before the advent of *INSAT* age. Even the computers were yet to enter the country in a big way at that time. It was then that the revolutionary satellite communication era dawned on India, with the successful launch of *INSAT-1B* in 1983 and its follow-on *INSAT-1D*. The multipurpose *INSAT* satellites initiated a major communication revolution in India by substantially contributing to long distance telecommunication, introduction of nationwide TV and radio broadcast services and providing round the clock meteorological observations. Rao as the Chairman of the apex body of INSAT Co-ordination Committee (ICC) had his hands full and was expected to ensure the development of not only the space segment, but also a low cost ground segment and applications to meet the exploding requirements from the user community, and he did all these with great professional aplomb. Some of the special steps taken by him during that initial operational INSAT era have since then become large-scale operational applications in the country.

The most dramatic impact of *INSAT* was the extraordinary expansion of TV broadcast, from the then existing just 8 TV transmitters to over 800, within a year of *INSAT* operation, which has now crossed 1500, providing access to around 90% of India's population to national and regional channels. Use of transportable earth stations and satellite news gathering vehicles, which are so routine now, providing real time coverage of important events anywhere in the country, were innovative introduction by ISRO at that time. ISRO had earlier conducted the much acclaimed Satellite Instructional Television Experiment (SITE) in the mid-70s using the American ATS-6 satellite and the Satellite Telecommunication Experiment Project (STEP) using Franco-German *SYMPHONIE* satellite. So, *INSAT* system provided a major opportunity for ISRO to expand and deploy a number of innovative, inexpensive, indigenous, one-way video and two-way audio systems and transmit specially prepared development educational programmes for target audiences in both urban and rural areas. The resounding success of these innovations on the technology side and the large number of experimental distance education application programmes providing agricultural information, vocational training, quality secondary education and curriculum based teaching, etc., later led ISRO to launch a dedicated operational satellite *EDUSAT* in late 90s under Kasturirangan and the community-based applications like Village Resource Centre (VRC) later under G. Madhavan Nair.

The development of extended C-band and high power Ku-band transponders in the second generation *INSAT-2*, resulted in their extensive use by many closed user groups for educational, cultural and business purposes. This has now led to the establishment of the much appreciated telemedicine application initiatives from ISRO, linking the remote rural populace with super speciality hospitals in large urban areas to enable them to have access to the best medical treatment.

The availability of meteorological imaging since 1983, on a continuous basis from a geostationary orbit, has revolutionized the meteorological services in India. Combining with the communication capability of *INSAT* system, India was the first country to develop a comprehensive cyclone-warning system to provide locale-specific disaster alerts to areas likely to be affected by cyclones and floods. Rao should be credited for the highly innovative *INSAT*-based cyclone warning system developed by ISRO, which has been responsible for saving a large number of lives and livestock over the years. These initial experiments and remote sensing-based operational applications, such as the flood mapping and drought management emboldened ISRO to launch a major operational Disaster Management Support Programme (DMSP), making use of the convergence of technologies of communication, remote sensing and meteorology.

Similarly, it is due to a number of joint exercises conducted between ISRO and the users, viz. India Meteorological Department, National Centre for Medium Range Weather Forecasting (NCMRWF) and the Indian Institute of Tropical Meteorology (IITM) that today, the weather and climate-related information are operationally generated and disseminated at the user end making use of state-of-the-art data from both low earth orbiting IRS and geostationary INSAT systems.

Marketing space – setting up unique model of ANTRIX

Rao is also credited with the setting up of ANTRIX Corporation in 1992, as a wholly owned Government of India company under the Department of Space, to serve as a marketing arm of ISRO, for promotion and commercial exploitation of space products and services, and also to handle the transfer of technologies developed by ISRO to industries. For example, it is through this unique arrangement that ISRO reached its communication transponders to various India users and its IRS satellite data services to many countries in the world. At one time, ANTRIX was able to capture almost 15% of the global remote sensing data market by establishing more than 20 International Ground Stations (IGS) under commercial arrangements to enable the reception of data from IRS. ANTRIX today provides end-to-end solution, ranging from supply of hardware and software systems as well as varied space applications, and has an asset of around Rs 1000 crores. ANTRIX also caters to a prestigious clientele including some of the leading space companies across the globe like EADS Astrium, Intelsat, Inmarsat and EUTELSAT to name a few. This model of ANTRIX set up as an autonomous entity with its own Governing Body and having a strong umbilical connection to ISRO, is considered to be a unique contribution by Rao.

International contributions and accolades

Rao's contribution to space technology and applications at international level is

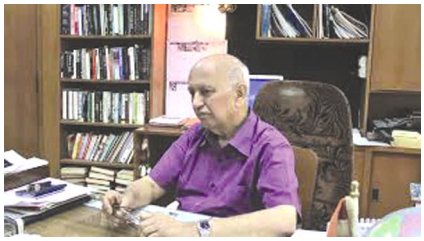
equally enormous. I will cite just a few of them here.

Rao was very actively involved with the activities of the prestigious International Astronautical Federation (IAF) for long and as its Vice President during 1988–1992, and was the Chairman of the IAF Committee on Liaison with International Organizations and Developing Nations (CLIODN) since 1988. As Chairman, IAF CLIODN, Rao initiated many new activities for promoting the use of space technology applications for development in developing countries. He religiously conducted, every year for 16 years, Special Current Event Sessions during the Annual Congress of IAF in different parts of the world on various aspects of space applications with case studies and real life examples, ranging from sustainable agricultural development, disaster management, forest and environmental management, education and communication development, bridging the digital divide and human resources development. Experts from different developing countries were brought together to share their experiences in using space technology applications, and the problems faced by them. These Special Current Event sessions became a major event of attraction in the IAF Congress, and every year, the proceedings of these sessions along with his own contribution, were brought out as IAF CLIODN Publications and widely disseminated amongst the participants. For me, as a person closely associated with Rao in organizing these events and bringing out the publications, it was an unforgettable experience to directly feel the real passion and the true sincerity displayed by him for reaching out to the fellow developing countries in their quest to reap the benefits of space technology, as we have done in India.

In the early-90s, the United Nations Committee on Peaceful Uses of Outer Space (UN COPUOS), Vienna, was in the process of implementing the resolution of the UN General Assembly towards the establishment of UN supported Regional Centres for Space Science Technology Education in existing educational institutions in the developing countries. Rao went on to present India's case as the most suitable in the Asia-Pacific region to host such a UN Centre. There was intense competition from the countries in the region for hosting the Centre, and also associated political pressures and negotiations. To resolve the issue, UN went on to set up an evaluation mission in 1992, with stringent criteria to select a suitable bidder, from among the competing nations. India, as the pioneer of space technology applications, was selected to host the UN affiliated Centre of Space Science Technology Applications in Asia and the Pacific (UN CSSTEAP) at Dehra Dun. UN CSSTEAP came into existence in November 1995 and since then has become the most vibrant centre in the world, bringing laurels to India. Rao's pioneering contribution to bring this Centre to India will always be remembered by all those associated with the Centre.

Further, UN COPUOS set up in 1959 was essentially dominated by USA, USSR (Russia) and Europe and the Chairmanship of UN COPUOS continued to be held by Austria till 1997, when the process was democratized. Rao became the first person from outside this select group to be elected as Chairman of UN COPUOS in 1997. Later, he was unanimously elected as the President of International UNISPACE III Conference, held in Vienna in 1999, an honour and prestige for Rao, as well as for India, signifying India's rise as a global player in space technology applications.

Rao's continued concern and the boldness with which he spearheaded his many innovative ideas to operationalize the space technology applications of direct societal relevance at the user-end made Indian Space programme as one of the most visible and the leading proponent of applications-driven space programmes in the world, and many success stories from India were widely acclaimed in international fora as worth emulating by other developing countries. It is no wonder then that with so many accomplishments to his credit, Rao was the first Indian space scientist to be inducted into the Satellite Hall of Fame in Washington by the Society of Satellite Professionals International (SSPI) in March 2013 for his enormous contribution to the development of Indian space technology and its applications to communications, remote sensing of natural resources, disaster management and weather and climate monitoring. It is a matter of pride for all Indians, as it is a rare honour, bestowed only on the best in the World. In accepting this honour, Rao joined an august select company of just around 50 most famous scientists which includes Arthur C. Clarke, Van Allen, Harold Rosen, Peter Jackson, among others.



Rao at his desk in ISRO Headquarters.

Summary

To summarize, the story of Rao, a humble village boy from a poor Brahmin family from a village near Udupi in Karnataka rising to a lofty position as Chairman of ISRO, a prestigious organization and of international fame should be a motivational force to many young aspirants in our country. For us, who are lucky to be associated with him for long, he is a space scientist, technologist, and a passionate space application protagonist, all rolled into one, with sharp analytical bent of mind and enormous intellectual ability with uncanny knack of grasping the contemporary happenings; and his astounding ability to quickly make back of the envelop computations for complex solutions; a task master with deep insight, abundant enthusiasm and indefatigable tenacity; and an inspirational leader par excellence with forthright views and innovative ideas which continue to inspire and instil enormous confidence in young space scientists and technologists in this country with the mantra 'if others can do, we can do better'.

His ability to connect with subordinates is an attribute often cited as the best quality of Rao. Each one of his subordinates has one story or other to tell about his personal experience with him! I thought I would cite one such instance here that brings out the enormous concern and courage displayed by him at times of crisis. It was during the days preceding the launch of *IRS-1B* from the then USSR in August 1991 and there was turmoil all around with the mighty Soviet Union in the last days of its very existence. There was a coup, famously known as the August Coup, when *IRS-1B* team had landed with the spacecraft at the Baikonur Cosmodrome. Rao, as the

Table 1. Accomplishments of U. R. Rao

Positions held

Post-Doctoral Fellow MIT, USA (1961–1963)
Asst. Professor at S.W. Centre for Advanced Research, Dallas, Texas (1963–1966)
Associate Professor, Physical Research Laboratory, Ahmedabad (1966–1969)
Professor, Physical Research Laboratory, Ahmedabad (1969–1972)
Project Director, Indian Scientific Satellite Project, Bangalore (1972–1975)
Director, ISRO Satellite Centre, Bangalore (1975–1984)
Chairman, Space Commission/Secretary, Department of Space, Government of India & Chairman, Indian Space Research Organisation (ISRO), Bangalore (1984–1994)
Dr Vikram Sarabhai Distinguished Professor of the Department of Space (1994–1999)
Chairman, United Nations–Committee on Peaceful Uses of Outer Space (UN-COPUOS) (1997–2000)
Member, Prasar Bharati Board (1997–2001)
Member, National Security Advisory Board (1998–2001)
Member, Space Commission, Government of India (1981–2001)
Chairman, Prasar Bharati Board (2001–2002)
President, Centre for Space Physics, Kolkata (2007)
Chairman, Governing Council of Indian Institute of Tropical Meteorology, Pune (2007–till date)
Chairman, Karnataka Science & Technology Academy (2005–till date)
Co-Chairman, Governing Council, National Center for Antarctic & Ocean Research, Goa (1997–till date)
Chairman, Advisory Committee for Space Science, ISRO (2005–till date)
Chancellor, Babasaheb Bhimrao Ambedkar University, Lucknow (2006–2011)
Member, Central Board of Directors, Reserve Bank of India (2006–2011)
Additional Director, Bharatiya Reserve Bank Note Mudran Pvt Ltd, Bangalore (2007–till date)
Director, Bank Note Paper Mill India Pvt Ltd, Bangalore (2010–till date)
Chairman, PRL Council, ISRO-DOS (1988–till date)

Professional positions held in International arena

Vice President, International Astronautical Federation (IAF) (1986–1992)
President, Committee for Liaison with Developing Nations (CLODIN) of IAF (1988–2006)
Chairman, UN-COPUOS (United Nations–Committee on Peaceful Uses of Outer Space) (1997–2000)
President, UNISPACE-III Conference (1999)

Selected Honours and Accolades

National

1976 *Padma Bhushan* by the President of India
1975 Karnataka Rajyotsava Award, Bangalore
1975 Hari Om Vikram Sarabhai Award
1975 Shanti Swarup Bhatnagar Award of CSIR for Space Science & Technology
1980 National Design Award
1980 Vasvik Research Award in the Electronic Sciences & Technology
1983 Karnataka Rajyotsava Award, Bangalore
1987 PC Mahalanobis Medal
1993 Om Prakash Bhasin Award in the Energy & Aerospace
1993 Meghnad Saha Medal
1994 P.C. Chandra Puraskar Award
1994 Electronics Man of the Year Award by ELCINA
1995 Zaheer Hussain Memorial Award
1995 Aryabhata Award, Bangalore
1995 Jawaharlal Nehru Award from MP State Government
1996 SK Mitra Birth Centenary Gold Medal
1997 Yudhvir Foundation Award
1997 Rabindranath Tagore Award of Viswa Bharati University
1999 Gujar Mal Modi Award for Science & Technology, New Delhi
2001 Nadoja Award from Kannada University, Hampi
2001 Life Time Contribution Award in Engineering from INAE, New Delhi
2002 Sir M. Visvesvaraya Memorial Award
2003 Press Bureau of India Award
2005 Bharat Ratna Rajiv Gandhi Outstanding Leadership Award
2007 Life Time Achievement Award of Indian Space Research Organisation
2007 Distinguished Scientist Gold Medal of the Karnataka Science & Technology Academy
2008 Jawaharlal Nehru Birth Centenary Award for 2007–2008 from ISCA
2008 A.V. Rama Rao Technology Award – 2007, AVRA Laboratories Pvt Ltd, Hyderabad
2009 Hari Om Ashram Prerit Senior Scientist Award – 2008, PRL, Ahmedabad
2010 Indian Science Congress Association – General President Gold Medal Award
2011 Sivananda Eminent Citizen Award, Sanathana Dharma Charitable Trust, Visakhapatnam

(*Contd*)

Table 1. (*Contd*)

International

1973 Group Achievement Award by NASA, USA
1975 Medal of Honour by Academy of Sciences, USSR
1991 Yuri Gagarin Medal of USSR
1992 Allan D. Emil Award on International Cooperation (International Astronautical Federation)
1994 Frank J. Malina Award (International Astronautical Federation)
1996 Vikram Sarabhai Medal of COSPAR
1997 Outstanding Book Award of the International Academy of Astronautics for book on *Space Technology for Sustainable Development*
2000 Eduard Dolezal Award of International Society of Photogrammetry & Remote Sensing (ISPRS)
2004 *Space News* magazine names him as one of the Top 10 International personalities in Space
2005 Theodore Von Karman Award of the International Academy of Astronautics (IAA)
2013 Inducted into Satellite Hall of Fame in Washington by Society of Satellite Professionals International (SSPI)

Honorary Doctorates

D Litt (Hons Causa) from

2001 Kannada University, Hampi

D Sc (Hons Causa) from

1976 Mysore University, Mysore
1976 Rahuri University, Rahuri
1981 Calcutta University, Calcutta
1984 Mangalore University, Mangalore
1992 University of Bologna, Italy
1992 Banaras Hindu University, Banaras
1992 Udaipur University, Udaipur
1993 SV University, Tirupathi
1994 JN University, Hyderabad
1994 Anna University, Madras
1994 Roorkee University, Roorkee
1995 Punjabi University, Patiala
1997 Shri Shahuji Maharaj University, Kanpur
1999 Indian School of Mines, Dhanbad
2002 Ch. Charan Singh University, Meerut
2005 UP Technical University, Lucknow
2006 Visvesvaraiah Technical University, Belgaum
2007 Indian Institute of Technology, Delhi
2010 Dr D.Y. Patil Vidyapeeth, Pune
2012 National Institute of Technology, Agarthala
2013 Bangalore University, Bangalore
2013 Indian Institute of Technology, Bhubaneswar

Fellowships

Fellow of the Indian Academy of Sciences
Fellow of the Indian National Science Academy
Fellow of National Science Academy
Fellow of The World Academy of Sciences, Trieste
Fellow of the International Academy of Astronautics
Fellow of World Academy of Arts & Sciences, USA
Fellow of Indian National Academy of Engineering
Fellow of the Astronautical Society of India
Honorary Fellow of the Aeronautical Society
Distinguished Fellow, Institution of Electronics and Telecommunication Engineers
Honorary Fellow, Indian National Cartographic Association
Fellow, Broadcasting and Engineering Society of India
Honorary Fellow, Aero Medical Society of India
Distinguished Fellow, Physical Research Laboratory, Ahmedabad

Books

Rao, U. R., Kasturirangan, K., Sridhara Murthi, K. R. and Surendra Pal (eds), *Perspectives in Communications*, World Scientific, 1987.
Rao, U. R., Chandrasekhar, M. G. and Jayaraman, V., *Space and Agenda 21 – Caring for Planet Earth*, Prism Books Pvt Ltd, Bangalore, 1995.
Rao, U. R., S*pace Technology for Sustainable Development*, Tata McGraw-Hill Publishers, New Delhi, 1996.
Rao, U. R., *India's Rise as a Space Power*, Foundation Books, Cambridge University Press India Pvt Ltd, New Delhi, 2014.

then Chairman, ISRO and Secretary, Department of Space, was advised by the Government of India to avoid travelling to USSR at that moment of turmoil. He defied that saying that he would like to be with his team at the moment of crisis, rather than waiting worriedly in India. I was lucky to accompany Rao to Soviet Union during this mission, and fortunately, the coup was aborted by the time the flight landed at Moscow. We could still see the rampage on the ground like the felling of the statue of Lenin, and the cannons and tanks on the road, and the demonstrating crowds in the square. Even as President Gorbachev resigned as general secretary of Communist Party of Soviet Union (CPSU) on 24 August 1991, and the mighty Soviet Union collapsed in the next few days, *IRS-1B* was launched without any hitch on 29 August 1991 from Baikonur. The presence of Rao served as a balm, not only for the ISRO team at the launch pad and helping them to stay focussed and keep a high morale, but also as a great relief for their families back home. For us associated with that historic event, it will remain as an object lesson as to how a leader should behave in times of crisis and to be with his team and work for the goal, whatever be the hurdles. Rao exemplified that attribute with spontaneous geniality.

Above all, Rao is a great Institution builder of global repute, and ranks along with Vikram Sarabhai and Satish Dhawan as the one who brought the vision and mission focus in the Indian space programme with unstinted commitment to align the goals of the organization with national development. In this, Rao took in his stride the brunt of the innumerable initial difficulties, obstacles and the failures of the satellites and launch vehicles in the experimental and its transition to operational era, and steadfastly brought in high levels of professional competence, mutual respect and team spirit with trust that became the organizational norm and continues to be the guiding force in defining what is known today as 'ISRO culture'.

It is no wonder that Rao, for his immense life-long contribution to space science, technology and applications, has been bestowed with many national and international awards and accolades; elected as fellow of many reputed academies and institutions; awarded honorary doctorates by a number of universities; and his multi-faceted skills and services continue to be sought after, by many government and private bodies (see Table 1).

Now, a few words about Yeshoda Rao, the life partner of Rao. She has been the pillar of strength, dedication and support for Rao all along. Ever smiling, Yeshoda Rao, is also well known among other accomplishments, for her dedicated societal services for the differently abled children in Bangalore.

I will close the article with one recent episode. Recently, while attending a wedding reception at Palace Grounds, Rao tripped on the unevenly laid out carpet on the ground and managed to balance himself without any major difficulty. While accompanying to his car after the event, I asked him with concern as to whether he was hurt. He replied with a characteristic twinkle in his eyes, 'Nothing happened. You know I am space qualified!'

That is U. R. Rao!! By the by, is that not the stuff the legendaries are made of?

1. Rao, U. R., *Curr. Sci.*, 2011, **100**(2), 223–225.
2. Collinson, *et al.*, *J. Geophys. Res.*, 2014, **119**, 978.
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4. Rao, U. R., *J. Br. Interplanet. Soc.*, 1981, **34**, 459.

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