Prof. Govind Swarup's connection to the archetypal radio galaxy Cygnus A*

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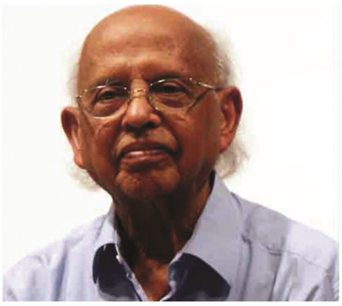
Cygnus A has been the prime enabler for investigating the physics of radio galaxies, because it is anomalously close to our galaxy (about 10 times), as compared to typical radio galaxies of the same luminosity class. Consequently, it has been studied with the highest spatial resolution of all the powerful radio galaxies which either appear much fainter or their structures have been delineated with ten times poorer spatial resolution. In 1953, radio interferometric observations of Cygnus A at Jodrell Bank, UK, led to the epoch-making discovery that radio emission of Cygnus A arises from two separate 'lobes' located far apart on opposite sides of the parent stellar galaxy. The direct Indian connection (M. K. Das Gupta) of this discovery which revolutionized the theoretical perspective of radio galaxies, has been well documented. However, another fundamental, albeit much less known discovery, again with a strong Indian link, came a decade later in 1963 when a team led by Govind Swarup at Stanford clearly demonstrated that the two distinct radio lobes of Cygnus A are in fact connected by a long continuous 'bridge' of radio emission and that the bridge becomes more prominent at longer radio wavelengths. It took yet another decade for the emergence of an enduring theoretical framework for radio galaxies, which established radio bridges as its key element, as well as a powerful tool which has been extensively used for estimating ages of radio galaxies. The discovery of radio bridge in Cygnus A is also likely to have been a key motivator for the large Ooty radio telescope (Muthorai, India), which was indigenously conceived, designed and built during 1966–1969, under the leadership of Govind Swarup, and which ushered India into the select world of radio astronomy at an early stage.



Prof. Govind Swarup

Although by 1950, radio galaxies had already made their entry into the arena of astrophysics, a breakthrough in unravelling their mystery came from radio interferometric observations of Cygnus A, an outstandingly bright radio galaxy in the nearby universe. This unexpected, startling discovery was reported[1] in 1953 by two young researchers named Roger Jennison and Mrinal Kumar Das Gupta, both working for their Ph.D. at the Jodrell Bank Observatory in UK. Their landmark observations revealed that the radio emission of Cygnus A actually arose from not one, but two distinct regions (lobes) well separated and apparently disconnected from each other[1]. Soon thereafter, the (optical) galaxy responsible for the two radio lobes was found, situated roughly in the middle of the two radio lobes well separated from the galaxy[2]. Although such a morphology took everyone by much surprise, it was subsequently found to be a generic feature of powerful radio galaxies, and this led to the paradigm of *double radio sources*. This fascinating story about Cygnus A radio galaxy has been recounted in several publications (e.g. ref. 3) and, very recently, by Rai Choudhuri and Chatterjee[4]. In particular, the latter article traces in detail the background of the crucial contribution of Mrinal Das Gupta to this foundational discovery of double radio sources.

The purpose of this note is to point out that the saga of Cygnus A radio galaxy would remain wanting without highlighting another fundamental discovery related to this classical, archetypal radio galaxy. That discovery was reported a decade later, in 1963 and, interestingly, the key player in this was yet another Indian radio astronomer, Govind Swarup. The landmark finding by the team led by Swarup was that the wide gap between the two radio lobes of Cygnus A, as reported by Jennison and Das Gupta[1], was, in fact, filled by a continuous bridge of radio emission which, moreover, was seen to become an increasingly prominent feature of the radio structure of Cygnus A at longer wavelengths[5] (Figure 1). Their finding too was based on radio interferometry (at 3.3 GHz), but performed at Stanford (USA), and supplemented with their improved analysis of published interferometric observations of Cygnus A made at Nancay radio observatory (1.4 GHz)[6] and at Jodrell Bank (127 MHz)[7]. It also happened to be the last scientific result reported by Swarup from Stanford, before his joining the

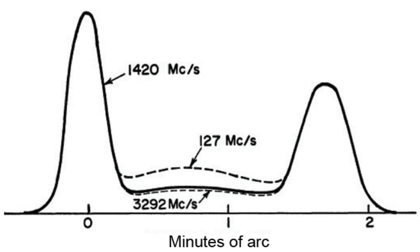


Figure 1. Model of Cygnus A involving a wide central component. Based on a frequency-independent spacing of 101″ and interferometry of Lequeux and Jennison and Latham. This illustration is a reproduction of figure 2 in the article 'The Structure of Cygnus A', by Swarup, G., Thompson, A. R. and Bracewell, R. N., *Astrophys. J.*, 1963, **138**, 305–309 and is reproduced by permission of AAS.

*A tribute to late Prof. Govind Swarup whose 92nd birth anniversary falls on 23 March 2021.

Tata Institute of Fundamental Research (TIFR), Mumbai, India. Here it may be mentioned that a hint of radio bridge in Cygnus A had indeed emerged in 1962 from the Nancay observations mentioned above[6]. However, in the published radio brightness profile of Cygnus A, the bridge did not appear clearly resolved from the two radio lobes.

Radio bridges are now known to be a fairly common morphological feature of double radio sources[8] and their prime role in the energetics and age estimation of radio galaxies has been underscored in several publications[9–16]. Some currently popular theories of double radio sources envision bridges to be the main repository of magnetized relativistic plasma, earning the epithet of *waste energy basket*[10,11].

Probably, their original finding that the radio bridge in Cygnus A becomes more prominent at longer wavelength, was a key motivating factor when Swarup undertook in mid-1960s, the daunting task of building a large radio telescope capable of providing arc-second resolution at metre wavelengths, so that many double radio sources could be adequately resolved not only for measuring the overall angular size, but also delineating the radio bridge emission between the two lobes. This extremely ambitious vision (for that era) fructified in the form of Ooty radio telescope[17], innovatively designed and built on a hill slope in the Nilgiri mountains, by an unusually young team led by Govind Swarup. Dr Vikram Sarabhai visiting the giant antenna on the hill slope, had asked Swarup if he did not feel scared that one day the whole structure may come tumbling down, as in the movie Zorba the Greek!. That day has not yet arrived.

The primary goal of the telescope was to record lunar occultations (eclipses) of hundreds of distant radio galaxies and determine their structures with arc-second resolution at a wavelength of 92 cm. The Ooty radio telescope established India as an international player in radio astronomy, during its Golden Era.

The lunar occultation observations carried out at Ooty during 1970–71 revealed radio bridges in many bright double radio sources[18–21], thanks to their sensitivity and angular resolution matching with those attained at an order-of-magnitude shorter wavelength, using the contemporarily commissioned 5-km aperture-synthesis radio telescope at Cambridge (UK). It thus became possible, for the first time, to accurately measure the variation of spectral index along the bridges in double radio sources[20,22] using radio images spanning a wavelength range of >10 : 1. Soon, such information for double radio sources began to be used routinely for estimating their ages[23], and has since become the most popular and standard method for their age estimation. For weaker radio sources, numbering almost 1000, the Ooty lunar occultation survey provided the most detailed radio information (positional and structural), until the commissioning of Very Large Array in USA in 1980 and the MERLIN Array in UK in 1981.

One impetus for highlighting Swarup's brief but original dalliance with a radio galaxy (i.e. Cygnus A) in early 1960s came from the need to set right the widespread impression that his studies prior to 1970 were confined to solar research alone. It is true that even the first radio telescope, the Kalyan radio telescope, set up by Swarup's group after his joining TIFR in 1963, had been designed for radio imaging of the sun. It did produce results significant enough to appear in Nature[24]. However, by 1970, radio galaxies and their application to cosmological studies had become his staple.

Govind Swarup is widely acknowledged as the Father of Indian radio astronomy, although the honour of being the first Indian radio astronomer to achieve international acclaim goes to Mrinal Das Gupta[4]. Some possible reasons behind the latter's inability to set up major radio-astronomical facilities in India, on returning from abroad after completing Ph.D., have been hinted by Rai Choudhuri and Chatterjee[4]. A fact remains that both these pioneers have inspired generations of radio astronomers in India. Lest we forget, their own induction into radio astronomy owes a great deal to the foresight of their academic mentors, S. K. Mitra of Calcutta University[4] in case of Mrinal Das Gupta, and K. S. Krishnan of National Physical Laboratory in case of Govind Swarup. Not only did these two veterans of Physics recognized the burgeoning potential of radio astronomy while the field was still nascent, but they also worked proactively in sending their bright young wards to two of the world's leading centres in radio astronomy, namely, Jodrell Bank (UK) for Das Gupta, and CSIRO (Australia) for Swarup. The rest, as they say, is history.

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