

Applications of Radio Telescopes in Deep Space Research

Vishalakshi Singh¹, Atul Kumar Pandey*², Rajesh Kumar Verma³

Assistant Professor, Department of Physics^{1,2,3}

D. D. U. Government P. G. College Saidabad Prayagraj, Uttar Pradesh, India¹

Government Degree College, Sehmo Basti, Uttar Pradesh, India²

K. S. Saket PG College Ayodhya, Uttar Pradesh, India³

singhvishalakshi15@gmail.com,

*Correspondence: atulkumarpandey78@gmail.com

iitr.rajesh@gmail.com

Abstract: *Radio telescopes have been among the strongest tools for astronomers trying to figure out the universe's fine structure and how it all fits together for quite a while. The radio telescope has made substantial progress in recent years by producing an image of a black hole. This review examines how radio telescopes have been used to study deep space across a range of methods. Highlights include the Event Horizon Telescope teamwork; advances made in pulsar timing arrays; further progress made on very long baseline interferometry (VLBI); current contributions made by FAST and the VLA; and how radio astronomy has been used to study the cosmic microwave background. Overall, these advancements emphasise both the importance of and the continuing growth of radio astronomy to contemporary astrophysics as a tool for astronomers.*

Keywords: *Radio telescopes*

I. INTRODUCTION

Radio astronomy provides a unique means of exploring the universe. In contrast to optical telescopes, radio instruments detect radio waves, which are electromagnetic radiation that has wavelengths between one millimetre and many tens of meters. Because of their long wavelength, radio instruments can see past clouds of gas and dust and penetrate through the vastness of space for distances beyond the limits of optical telescopes. Since Karl Jansky discovered cosmic radio waves by chance in the early 1930s, the field has become one of the most productive branches of observational astronomy (Kellermann & Moran 2001).

The release of the first resolved image of a supermassive black hole in the centre of M87 represented a major milestone in radio astronomy, drawing worldwide attention and providing direct support for theoretical predictions that up until now were based solely on indirect evidence (Event Horizon Telescope Collaboration 2019a). Meanwhile, there has been substantial progress in pulsar timing, centimetre wave cosmology and survey science, which are equally important yet less visible than the image of the supermassive black hole. This paper examines each of these research areas as they relate to the evolution of radio telescopes and points to where their trajectories suggest future work.

II. THE EVENT HORIZON TELESCOPE AND BLACK HOLE IMAGING

Without a doubt, the Event Horizon Telescope (EHT) collaboration's announcement had the greatest public and scientific impact of any scientific image to date. Rather than one telescope, the EHT is made up of eight radio observatories distributed over an entire planet and producing data through very long baseline interferometry techniques. The result is like a huge telescope with an angular resolution corresponding to Earth's diameter; therefore, it can produce images with the greatest possible detail.

To ensure all observations were in sync and to have a high-quality record of the data, the EHT collaboration set up an observing system between sites, culminating in the use of hydrogen maser atomic clocks to synchronize the telescopes from Hawaii to Antarctica, allowing them to use high-density hard drives as their data collection medium. The final

result of this work was the EHT collaboration producing observational data that resulted in an angular resolution of approximately 20 microarcseconds. This resolution is sufficient to provide an image of the structure of M87*'s event horizon.

The first image consisted of a bright asymmetrical ring of emission surrounding a dark centre (shadow of SM BH). The southern portion of the emission ring appears much brighter due to the relativistic beaming of the material orbiting the black hole (Event Horizon Telescope Collaboration, 2019b). The mass of the SMBH estimated from the size of the shadow (about 6.5 billion solar masses) agrees with previous stellar-dynamical estimates and also serves as a precise test of general relativity within the strong-field limit. The accomplishment demonstrated that the use of global coordinated Very Long Baseline Interferometry (VLBI) at 1.3 mm was not only a feasible technical achievement, but also a scientific paradigm shift.

The advancement of methodological radio imaging was greatly advanced by the work done on the Event Horizon Telescope (EHT). The reconstruction algorithms developed for this project (particularly clean and regularised maximum likelihood families of algorithms) required significant refinement to operate with the sparse/non-uniform baseline coverage associated with a ground-based VLBI array (Akiyama et al., 2019) and will also have a broader impact on radio interferometric imaging.

III. VERY LONG BASELINE INTERFEROMETRY AND DEEP SPACE ASTROMETRY

VLBI techniques extend well beyond black hole imaging. In the domain of astrometry, networks such as the Very Long Baseline Array (VLBA) and the European VLBI Network (EVN) continued to provide some of the most precise positional measurements available in astronomy. The method works by recording the signal from a distant compact radio source — typically a quasar — simultaneously at widely separated stations, then cross-correlating the recordings to extract the difference in signal arrival times with sub-nanosecond precision (Reid & Honma, 2014). The resulting position measurements reach microarcsecond accuracy, making VLBI indispensable for studies of proper motion and parallax out to kiloparsec distances.

A notable application of VLBI astrometry involved the measurement of parallax distances to masers associated with star-forming regions in the Milky Way, as part of the ongoing BeSSeL (Bar and Spiral Structure Legacy) survey. These measurements constrain the distance to the Galactic Centre and the size of the Galaxy's spiral arms with a level of precision that optical surveys struggle to match in obscured regions (Reid et al., 2019). The survey reported that the Sun orbits the centre of the Milky Way at a slightly larger radius than previous estimates had suggested, with implications for Galactic mass models.

IV. PULSAR TIMING ARRAYS AND GRAVITATIONAL WAVE DETECTION

To detect gravitational waves at nanohertz frequency (10^{-9} Hz) using millisecond pulsars (individual neutron stars), one of radio astronomy's most ambitious long-term goals is to develop an array of pulsed signal sources to help locate gravitational waves. Pulsar Timing Array (PTA) is a way to measure PAARs that are produced by gravitational waves, with individual pulsars behaving like atomic clocks. The detection of a gravitational wave will produce an observable difference in the arrival time of pulses from each pulsar on the array for at least two of those sources (Hellings & Downs, 1983). It has been established that, by monitoring several long-term stable millisecond pulsars over long periods of time (years to decades), the potential exists to recreate and identify the statistical signature from the PAAR.

As of the writing of this article, the primary PTA collaborative institutions (i.e., NANOGrav, EPTA, and PPTA) continue to grow both their catalogues and improve their noise modelling. A 12.5-year PTA dataset published by NANOGrav provided improved upper limits on expected stochastic gravitational wave backgrounds caused by supermassive black hole binaries (Arzoumanian et al., 2018). These data will provide an increasing scientific impact over time, even if no definite discovery occurs at the present time.

V. FAST AND THE NEW GENERATION OF LARGE APERTURE TELESCOPES

The Five-hundred-meter Aperture Spherical Telescope (FAST) of China, completed in 2016 as it was beginning its full commissioning operational phase, was the world's largest single-dish radio telescope (Nan et al., 2011). With an area for collecting data that was approximately twice that of its predecessor, Arecibo Observatory (Puerto Rico), FAST

provided new insight into numerous fields of deep space. With respect to pulsar searches, for example, dozens of new pulsars were discovered in FAST's initial survey, an outcome that subsequently illustrated how exceptional FAST was at detecting faint and faraway objects.

Because FAST's L-band receiver provides the capability to survey vast areas of sky simultaneously through 19 separate beams, FAST completed its surveys more quickly than a telescope with a single operating beam could. Additionally, FAST has a flexible active surface made of 4450 triangular panels that can be repositioned through a range of zenith angles, which gives FAST the capability of more versatility than several competing fixed-dish radio telescopes (Li et al., 2019). In addition to pulsar research, the commissioning phase of FAST is being dedicated to preparing the telescope to map cosmic-scale structures by observing neutral hydrogen in very distant galaxies. During this stage of FAST'S commissioning, early attempts were made to search for fast radio bursts (FRBs), which are short (on the order of milliseconds), unexplained transitory signals that originate outside the Milky Way and whose mechanisms remain the subject of active research.

VI. FAST RADIO BURSTS: A NEW WINDOW ON THE UNIVERSE

Radio astronomers have become increasingly interested in fast radio bursts (FRBs). They were first identified in Parkes radio telescope data from 2007 by Lorimer and colleagues, who highlighted their very short durations, high dispersion measures indicating they have travelled through large amounts of ionised gas, and mostly non-repeating sources (Lorimer et al., 2007). There were only very few repeating sources until Canada's CHIME (Canadian Hydrogen Intensity Mapping Experiment) telescope was launched with the capacity to automatically detect a large number of FRBs in real-time, allowing astronomers to broadly expand their research.

The CHIME/FRB collaboration published a catalogue of their first thirteen new bursts, of which one was a second repeating source (CHIME/FRB Collaboration 2019). The discovery of the repeating behaviour of FRB 180814.J0422+73 confirmed that at least some FRBs are ongoing recurring events and may allow researchers to study in detail their host environments. Additionally, the presence of high dispersion measures for the detected FRBs may demonstrate that they can be used as probes of the intergalactic medium: by comparing measured dispersion values to expected cosmological values researchers can constrain the baryon content of the universe, which has been a long-standing cosmological mystery sometimes referred to as the "Missing Baryon Problem" (Shull et al., 2012).

VII. RADIO TELESCOPES AND COSMIC MICROWAVE BACKGROUND SCIENCE

The CMB spectrum is in the microwave region, but it is not defined precisely between radio- and microwave-based astronomy. Since the CMB is of cosmological importance, there have been many different radio-frequency instruments contributing to cosmology over time. For example, the South Pole Telescope (SPT) and the Atacama Cosmology Telescope (ACT) have mapped the temperature and polarization anisotropies of the CMB on arcminute scales, allowing for more accurate investigations of physics during recombination and the early universe (Henning et al., 2018). These measurements are more sensitive to secondary anisotropies ascribed to large-scale structure, including the Sunyaev-Zel'dovich (SZ) effect in massive clusters of galaxies.

The SZ effect (the distortion of the CMB due to hot electron scattering of CMB photons via inverse Compton scattering) provides a mass estimation that is very nearly independent of redshift, making it particularly important to use when combined with measurements from cosmological surveys (Sunyaev & Zel'dovich, 1972). Using the cluster catalogue constructed from SPT-SZ data combined with optical lensing measurements provided complementary measurements to determine the matter power spectrum and the dark energy equation of state (Bocquet et al., 2019). Red, microwave and optical astronomy provide complementary methods of measurement that enable triangulation of cosmological parameters with greater confidence than using a single method.

VIII. CHALLENGES AND ONGOING LIMITATIONS

Despite these amazing technological developments, there have been many continuing issues for radio astronomy. In particular, increased levels of radio frequency interference (RFI) from telecommunications companies' satellite constellations and terrestrial electronics are increasingly threatening to affect the sensitive observations of radio astronomy, particularly as commercial operators plan for the creation of massive low Earth orbit satellite constellations

which will downlink at frequencies that overlap with protected radio astronomy bands (Offringa et al 2015). Although frequency allocations for passive scientific use are nominally protected by the regulatory framework of the International Telecommunications Union (ITU), enforcement will be difficult at the levels necessary to properly protect modern instruments.

In addition to RFI, there are also massive amounts of data being produced in the next few years. The current state-of-the-art correlators used for processing VLBI data from large arrays of radio telescopes produce datasets that are measured in many petabytes. The computing capability of the observatory is limited, as is its ability to transport all of the data generated (Whitney et al 2013). As the array grows and the amount of bandwidth increases — this trend has begun with new facilities such as FAST, MeerKAT and the new expanded VLA — the computational burden required to perform the processes of processing, archiving and transmitting the resultant data will require sustained commitments in hardware and algorithmic developments.

IX. CONCLUSION

The black hole image from the EHT represents an incredibly iconic achievement, but it is also part of a much larger body of steady advancement: the expansion of pulsar timing array datasets inching toward gravitational wave detection, FAST living up to its immense sensitivity, CHIME changing our fast radio burst census and microwave arrays tightening cosmological parameters each season of new data. All these can be attributed to the maturation of interferometric and multi-telescope techniques that allow instruments in different geographic regions to operate together as one, larger virtual observatory.

From this standpoint, radio telescope development is headed toward even greater ambitions. Facilities under construction or well along in planning, such as the Square Kilometre Array and next-generation Very Large Array, will enable radio astronomy to make measurements ever further out in the universe, both farther and in more frequency ranges. However, even with the current set of instruments operating, this report shows that there is still much work to be done and that radio telescopes will continue to play a vital role as humans explore the deep universe.

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