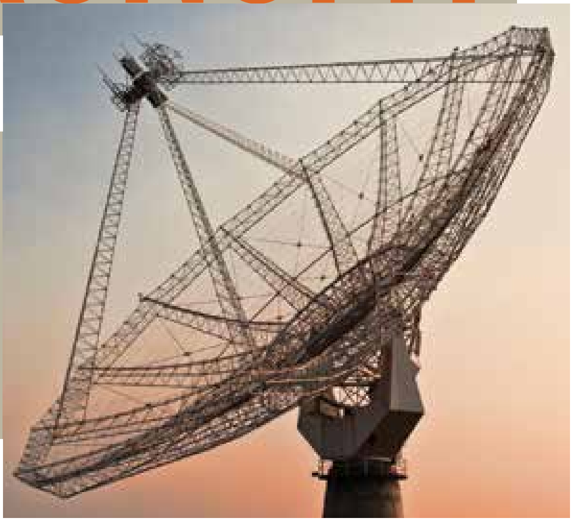
RADIO ASTRONOMY AND THE GIANT METRE-WAVE RADIO TELESCOPE



JAYARAM N CHENGALUR

The cosmos is strange and beautiful, full of unanticipated objects. The only way to understand it is to observe it – in as many different ways as possible. In this article, we take a look at the wonders revealed upon observing radio emissions from celestial objects through the Giant Metrewave Radio Telescope (GMRT), near Pune, India.

More than two decades ago, one of Carl Sagan's science fiction novels, Contact, was made into a major Hollywood motion picture starring Jodie Foster as the protagonist, Dr. Eleanor "Ellie" Arroway. Based on the Search for Extra-terrestrial Intelligence (or SETI, as it is popularly known), Contact is the story of a determined astronomer managing, against heavy odds, to make radio contact with an extra-terrestrial civilisation. An abiding image from the movie is of Jodie Foster with a pair of headphones clamped to her ears, and a massive antenna array in the background, listening intently to this extra-terrestrial signal. For many people of that generation, this is likely to have been their first, and most likely only, exposure to radio astronomy. In some ways, however, what is more surprising is that the general public has some exposure to radio astronomy at all, let alone through a major Hollywood film.

Fig. 1. Jodie Foster as Dr. Eleanor Arroway in the film Contact. The radio telescope in the background is the Very Large Array in the USA. As described in greater detail in the article, radio astronomers don't usually "listen" to extra-terrestrial signals, with headphones or otherwise. Image adapted from a still from the film.

Radio astronomers form a small and esoteric community – the radio astronomy commission of the International Astronomy Union has only a few hundred members. In India, the numbers are smaller still, but there is at least one work of fiction featuring Indian radio astronomers – Manu Joseph's award winning novel, Serious Men. For a small community, radio astronomy has certainly received a disproportionate amount of representation in popular culture! This is caused, at least partly, by the allure of space exploration and the Search for Extra- terrestrial Intelligence. But what does radio astronomy have to do with the SETI? If you go by the small fraction of radio astronomers involved with SETI – very little. But in order to understand radio astronomy, exploring its connections with SETI is as good a place to start as any other.

Radio Astronomy and the Search for Extra-terrestrial Intelligence

Broadly speaking, radio astronomy involves the observation of radio-waves from celestial objects. Radio-waves are one kind of electromagnetic waves; the most familiar kind of electro-magnetic waves being light waves (see Box 1). All of us use radio-waves every day, even if we are not aware of it (see Box 2). But what is the connection between these waves and astronomy?

Astronomy has traditionally used visible light, because that is the only kind of electromagnetic wave that the human eye is sensitive to. Stars and other celestial objects, however, emit all kinds of electro-magnetic radiations – from gamma-rays to radio-waves. In principle, with instrumentation that is sensitive enough, one could study the sky at all of these wavelengths. Which, again, begs the question – why (on earth) would anyone want to do so? It turns out (as we will see below) that studying the universe only in light waves gives us a very limited understanding of all that is out there. Very much as in the story of the blind men and the elephant, one could come away with a completely wrong picture of the universe. To understand the universe in all its richness and variety, one has to observe it in as many different ways as one can. Which brings us to the next question – if it is necessary to observe the universe at all possible wavelengths, what is so special about radio astronomy?

Box 1: Electromagnetic waves are of many different kinds

These range from the metres-long radio-waves to the very short gamma rays. Visible light, the electro-magnetic wave that we are most familiar with, occupies only a small portion of the entire spectrum.

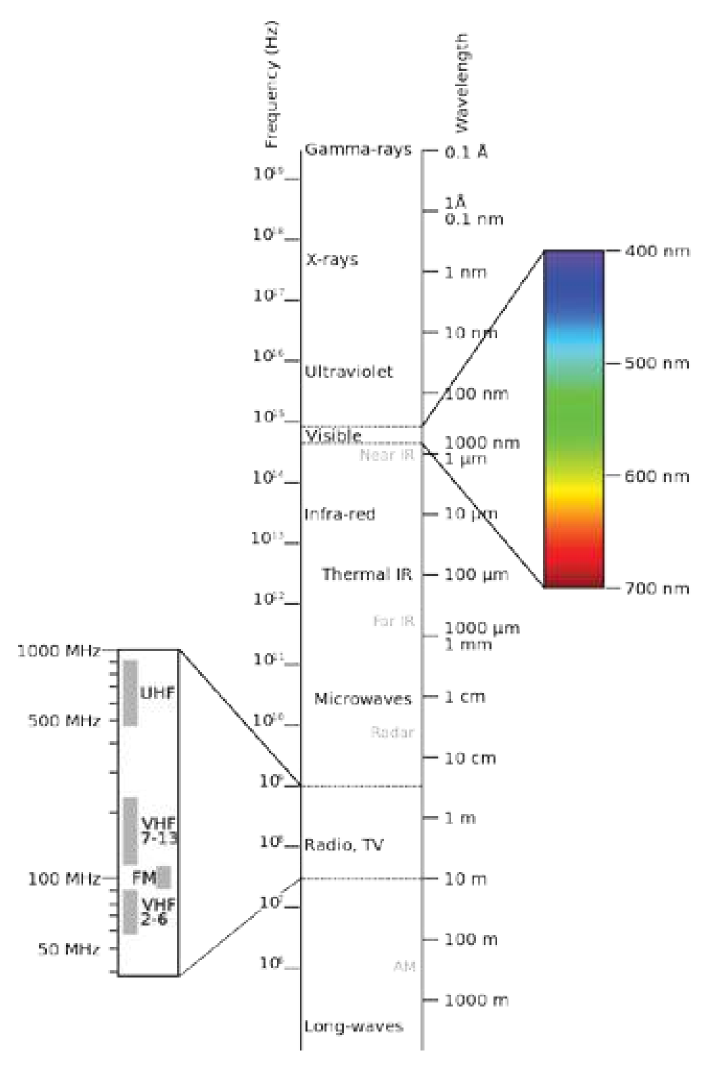


Fig. 2. The electro-magnetic spectrum. All electromagnetic waves travel at the speed of light, but the energy of each type of wave varies inversely with its wavelength. Thus, radio-waves with the longest wavelengths are the least energetic, while gamma-rays with their short wavelengths are the most energetic. X-rays, with relatively short wavelengths, are energetic enough to penetrate through skin and flesh, but not bones. This is why the bones in an X-ray image cast shadows on the photographic plate.

Source: Victor Blacus, Wikimedia Commons. URL: https://commons.wikimedia.org/wiki/File:Electromagnetic-Spectrum.svg. License: CC-BY-SA.

Box 2: We use radio-waves in our daily lives.

Radio-waves are used primarily for communication – from carrying FM radio signals (using waves with a wavelength of about 3m) and mobile phone signals (with waves of a wavelength of about 30cm), to TV signals (typically waves of a wavelength of about 50cm for ground-based TV stations to a few centimetres for satellite TV). Incidentally, microwave ovens also use radio-waves (with a wavelength of a few centimetres) to heat food.

One of the major advantages of using radio-waves to observe the sky stems from the fact that the Earth's atmosphere is transparent to these waves. This means that radio emissions from extra-terrestrial objects can reach telescopes built on the surface of the Earth. In contrast, other electro-magnetic waves, like X-rays, are absorbed before they reach the Earth's surface (see Fig. 3). This is a good thing for us because many of these rays are harmful to life. For astronomers, on the other hand, this is a mixed blessing – the Earth can host astronomers because energetic rays don't reach the Earth's surface; however, these same astronomers need fairly expensive satellites to realize just how lucky they are to have the protection of the atmosphere and ionosphere!

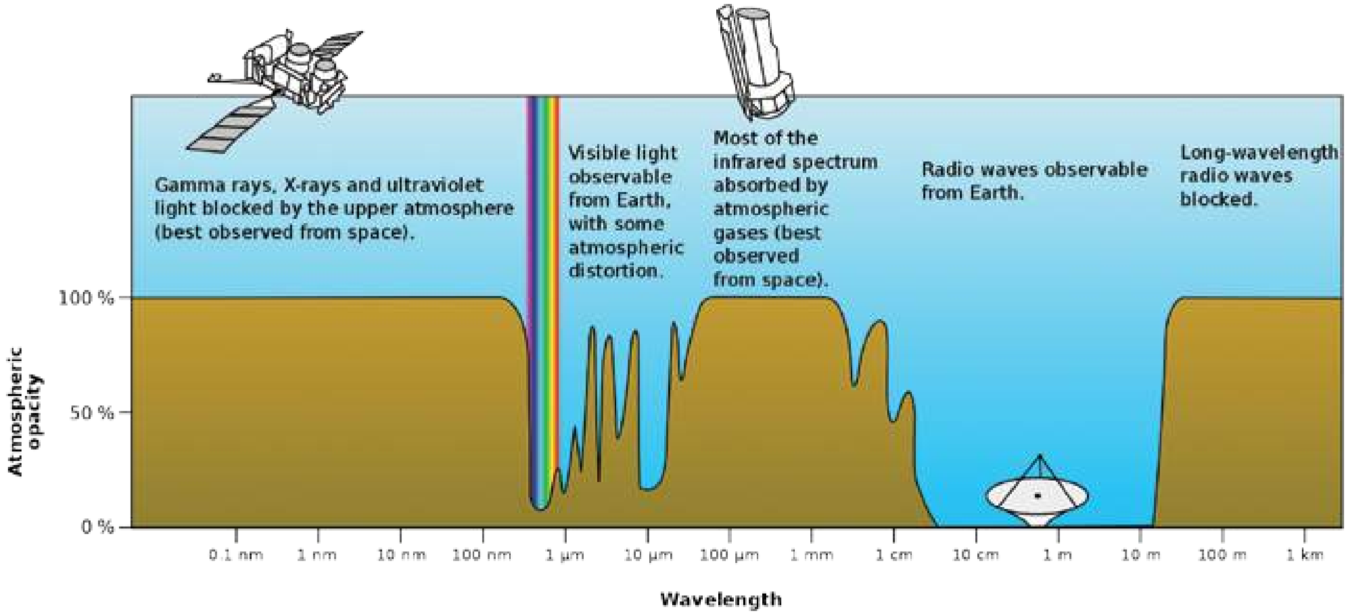


Fig. 3. Atmospheric opacity is a function of wavelength. The atmosphere (and ionosphere) is almost completely opaque in most parts of the electro-magnetic spectrum. It is only in the optical (i.e. ordinary visible light which human eyes are sensitive to) and radio (at which wavelength radio telescopes work) windows where the atmosphere is transparent. Since radiation from distant celestial sources does not reach the surface of the Earth at other wavelengths, they can be observed only by satellites launched into space. This is, in general, much more expensive than building a telescope on Earth.

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It turns out that it's not just the Earth's atmosphere that is transparent to radio-waves; much of the galaxy is also transparent to radio-waves. The same cannot be said of light waves. The space between stars contains fine dust particles, which scatter and absorb light, but don't affect radio-waves. This means that radio-waves allow one to peer into regions of deep space which are completely opaque to star light. This is one of the major reasons why SETI uses radio-waves: they allow one to look for tell-tale signs of a technological civilisation in regions of the sky that no other tracer would allow one to probe. So, for example, if we were to try and eavesdrop on the internal communication in some other civilisations, our best chance of "hearing" something would be at radio wavelengths. Being the least energetic of the electromagnetic waves, radio-waves are also the cheapest forms of communication signals. This is another reason why SETI focuses on radio-waves. Indeed, long-distance communication on Earth really took off only after the discovery of radio-waves. It is not surprising, then, that communications engineering played a central role in establishing radio astronomy.

Radio communication and the birth of radio astronomy

During the 1930s, transatlantic communication using radio-waves was in its infancy. Companies involved in transatlantic communication were looking for ways to identify different sources of noise ("static") picked up by radio receivers and, if possible, eliminate them. The Bell telephone company, a pioneer in this field, assigned the job of characterizing noise in radio communications to one of its engineers, Karl Jansky. Janksy turned out to be an extremely systematic observer, and through careful, painstaking effort, he classified the noise he was receiving into 3 different categories: (i) static generated by nearby thunderstorms; (ii) static generated by distant thunderstorms; and, (iii) static of unknown origin. From a careful follow-up, he discovered that the third class of static had a periodicity of 23 hours and 56 minutes – the time taken for the Earth to complete one rotation. This indicated that its source was far, far away from the solar system (see Box 3). More careful observations, and comparison with what is known from optical observations, allowed Jansky to determine that the radio-waves he was receiving were strongest in the direction towards the centre of the galaxy.

Box 3: The Earth takes a little less than a day to complete one rotation.

We are used to thinking of a day as being 24 hours long, and regarding this as the time taken for the Earth to complete one rotation. But, in addition to rotating around its axis; the Earth is also revolving around the Sun. Thus, strictly speaking, a day (or, more accurately, a solar day) is defined as the time period between one mid-day (i.e. the time at which the Sun is at its maximum height from the horizon) and the next. This takes slightly more time (about 4 minutes) than that required for one rotation (see Fig.4). A periodicity of 23 hours and 56 minutes (called a sidereal day) is, hence, characteristic for stars and other distant celestial objects.

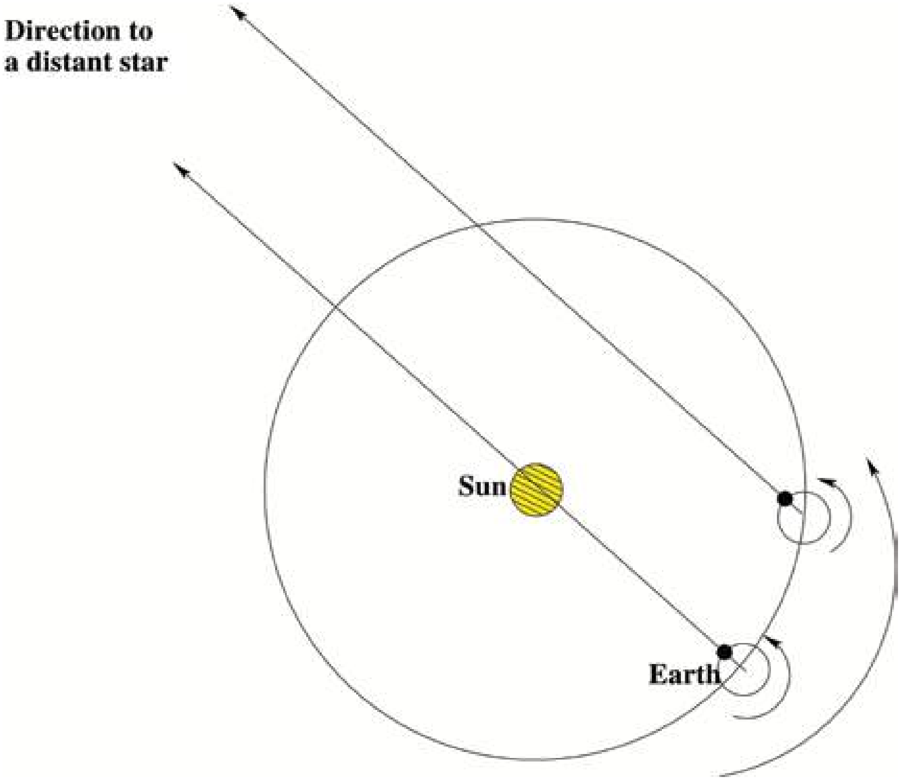

Fig. 4. The Earth is both rotating around its own axis and revolving around the Sun.

One can see that at each of the two instants of time indicated, the Earth has completed one full rotation (since the location marked is pointing, again, to the original direction). While the direction at the first time instant is towards the Sun, this is no longer the case in the second time instant. This difference is because, by the second time instant, the Earth has moved in its orbit around the Sun and would have to rotate a little more to reach a position where the Sun is directly overhead. A solar day is, therefore, slightly longer than the rotation period of the Earth. This phenomenon allows one to distinguish between emissions coming from distant objects (which will have a periodicity equal to that of the rotation of the Earth, viz. 23 hours, 56minutes) to that coming from nearer objects.

Credits: Jayaram N Chengalur.

This was the first detection of radio-waves from an extra-terrestrial object, and received a lot of public attention, including front page coverage in the New York Times and other newspapers. However, it was several years before professional astronomers paid attention to this discovery partly because the technology required for radio astronomy was completely different from that used by optical astronomers. For the optical community to retrain themselves to become radio astronomers would have required a huge effort (in fact, the divide between optical and radio astronomers persists to this day, with radio astronomy remaining a highly specialized sub-field of astronomy). But, this was also partly because Jansky's discovery came during the Great Depression in the US, when funding for new and risky initiatives was difficult to find. During the Second World War, however, there was a sudden explosion in the development of radio technology, driven primarily by the need to have powerful radar defence systems. After the war, some of these radar facilities were used by radio engineers for astronomy. This quickly led to the discovery that the Sun was one of the brightest sources of celestial radio-waves, and that the sky is, in fact, full of radio sources.

Unveiling the cosmos – what do Radio Telescopes "see"?

The most striking thing about the night sky is the tapestry of stars scattered across it. This coupled with the fact that the Sun is a strong source of radio-waves, suggested the possibility that these new observations were detecting some kind of stars, referred to as radio-stars. But, it turns out that radio emissions from stars are very, very faint (see Box 4); and almost none of the sources detected in these early observations correspond to that of stars known to us. If not stars, then what were these objects that radio telescopes were discovering?

Box 4: Stellar radio emissions are much fainter than those from the Sun.

This difference is related to our distance from the Sun versus that from other stars. The nearest star is almost 300,000 times further away from us than the Sun, which means that if it was intrinsically as luminous as the Sun in radio-waves, it would appear to be about a ninety billion times less bright. This was too faint for the early radio telescopes to detect.

The answer to this question remained unclear for a long time. Early radio telescopes had very poor angular resolution (see Box 7), making it very difficult to cross identify radio sources with sources seen in optical images. In 1962, however, the precise location of one of the brightest radio sources, called 3C273, was determined using radio observations from the Parkes radio telescope. The Parkes radio telescope, like all other telescopes of that era, had fairly poor resolution. But, it turns out that 3C273 is occasionally eclipsed (or, occulted) by the moon. Careful observations of the way in which the radio brightness of 3C273 changed during the eclipse allowed astronomers to determine the precise time at which the edge of the moon had just crossed the source. This allowed identification of the source of the mysterious radio-waves from archival optical images. Surprisingly, the source appeared to be a fairly nondescript star-like object. So, were radio-telescopes discovering some kind of stars after all?

To answer this question, an astronomer named Marteen Schmidt observed the spectrum (see Box 5) of the star-like 3C273. The type of spectrum a star produces helps determine its composition. For example, the Sun's spectrum has a characteristic sharp colour (called a spectral line) arising from the element Helium (which gets its name from being first identified from observations of the solar spectrum). The spectrum of 3C273 also had several spectral lines, but of wavelengths that did not match with those expected for any of the elements known to us.

Box 5: Luminous objects can be identified by the kind of spectrum they produce.

White light consists of a blend of different coloured lights, which one can see by breaking it up into its constituent colours (as you may have noticed while handling a CD or DVD) using a prism. This decomposition of light into its constituent colours (or wavelengths, since light of different colours corresponds to light of different wavelengths) is called a spectrum. The spectrum of a luminous object carries information about its composition. For example, the different colours that one sees in fireworks arise from the different elements that are mixed into its powder, with each element emitting light of a different wavelength.

Puzzling over this, Marteen Schmidt suddenly realized that the lines did indeed correspond to those of the known elements, but they had all been shifted to wavelengths that were longer by 15.8%! Such shifts of light from celestial sources towards longer wavelengths (called redshifts) had been observed for several decades by then, and were understood to arise from the expansion of the universe. It was only because the shift in wavelengths in the 3C273 spectrum was so enormous compared to all other redshifts observed before that it took some time for its spectral lines to be recognized as those from a redshifted system. This was, by far, the most distant object discovered till 1962 and, therefore, also one of the most luminous objects known to us. It was, in fact, enormously more luminous than any known star. We now know that 3C273 is not a star; but a black hole – with a mass that is billions of times more than that of the Sun! Matter swirling around a black hole gets heated up to enormous temperatures before it is swallowed, producing bright jets shot out at speeds close to that of light. It is the material in these jets that produce the radio emissions detected by telescopes. So, radio astronomers had found a completely new kind of object, now called by the generic name of radio-galaxies. This is just one example of how observing the universe at a different wavelength can lead to startling new discoveries. This has, indeed, turned out to frequently be the case, with the opening of new observational windows generally leading to the discovery of strange new objects.

Box 6: Shifts in wavelengths from celestial sources arise from the expansion of the universe.

As the universe expands, wavelengths of light emitted by distant sources also expand along with it. So, what you finally receive on Earth is a longer wavelength that what was originally emitted. This is referred to as a redshift, since it involves a shift towards longer wavelengths or reddish colours in the electromagnetic spectrum.

Super massive black holes at the heart of radio galaxies are not the only new objects discovered by radio astronomy. Early discoveries also included pulsars (objects with a density similar to that of atomic nuclei, but with radii of a few kilometres, and masses similar to that of the Sun) and the Cosmic Microwave Background Radiations (relic radiations left over from the time after the Big Bang when the universe cooled sufficiently for electrons and protons to combine together to form neutral atoms). The diffuse gas that is found between stars is also a strong emitter of radio-waves. In general, optical telescopes show us where stars are, while radio telescopes show us the distribution of this gas. These can be quite different (see Fig. 5), once again driving home the point that one needs multiple kinds of observations to fully understand the world around us.

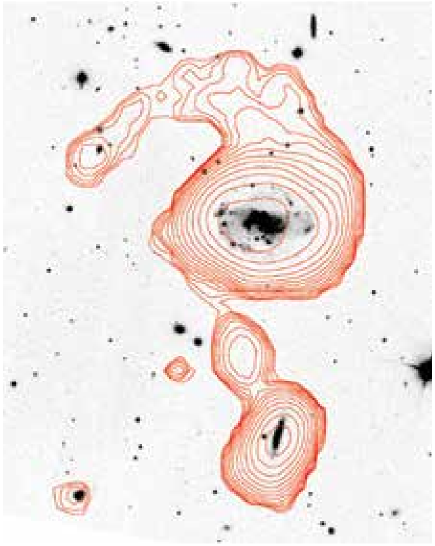

Fig. 5. Optical and radio telescopes show us different aspects of the universe

The black and white image is an optical (i.e. visible light) image. Stars are bright in visible light, so what one sees in this image is the location of stars in two nearby galaxies. The image has been inverted (like a film negative) so darker regions in the image are actually brighter. In visible light, these two galaxies look fairly regular, and don't seem to be interacting with each other. In contrast, the super-imposed red lines are from an image made at radio wavelengths using the GMRT. The red lines, showing the concentration of (Hydrogen) gas arund these galaxies, tell us a very different story. In addition to being concentrated around each galaxy, the gas also forms a bridge joining the two galaxies, and a long tail pulled out of the larger galaxy. This indicates that the two galaxies are clearly interacting, and are likely to merge in the future (see for example, the article "Interactions in Outer Space", by Anand Narayanan, in the June 2016 issue of **i wonder...**.

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The Giant Metre-wave Radio Telescope (GMRT)

The 1960s – India joins the Radio Astronomy Club

Built in the late 1960s, the Ooty Radio Telescope (ORT), located in the hills near Udhgamandalam, is India's first major radio telescope. This cylindrical telescope is 530m long and 30m wide. It was designed and constructed by a group led by Prof. Govind Swarup of the Tata Institute of Fundamental Research (TIFR), Mumbai.

The ORT has been used for a number of influential studies, including determinations of radio source sizes using lunar occultation, observations of spectral line emissions from ionized gas in our galaxy, and measurements of the propagation of energetic plasma emitted by the sun. These last type of observations (generically called studies of "space weather") are growing increasingly important in an era where much of our communications depends on satellites, and can be badly disrupted by energetic solar events. Despite being over 30 years old, the ORT remains one of the most sensitive telescopes in the world at the frequencies at which it operates. The experience of building, maintaining, and using the ORT has also led to the growth of a healthy radio astronomy community in India.

The 1990s and A Seriously Big Telescope

In the mid-1980s, it began to become clear that the ORT, while still a sensitive telescope, was not as versatile as the next generation of radio telescopes, such as the Very Large Array (VLA) in the US, or the Australia Telescope Compact Array (ATCA) in Australia. TIFR's radio astronomy group at Ooty, again headed by Prof. Govind Swarup, began work on the design of a much larger radio telescope, called the Giant Metrewave Radio Telescope (or GMRT).

Large telescopes are quite expensive to build, and as a consequence, very few countries in the world invest in building them. Optical telescopes face the additional problem of requiring a site that has to be dark, at a high altitude, and as free from rain as possible. There are very few locations on Earth which satisfy these criteria, exceptions being Mauna Kea in Hawaii, and the high mountains in Chile. Consequently, many countries end up building optical telescopes at these sites.

Radio telescopes (particularly those working at longer wavelengths), on the other hand, need not be located at such high altitudes, and can thus be constructed at many more parts of the world. The main criterion in choosing a site for a radio-telescope is to ensure that it is protected from man-made interference (such as, mobile phones and towers, TV and radio stations, etc). The TIFR group identified a number of such sites in India, including one near Khodad village, about 80 kilometres from Pune. The site was near enough to a major city (Pune) to have access to a manufacturing base to support the construction of a large telescope. At the same time, the proposed site was far enough (and also protected by encircling hills), to shield it from the interference produced by the industry, TV and radio in Pune and Mumbai. The cost of this facility, however, remained a challenge.

Frugal Engineering and the "SMART" design

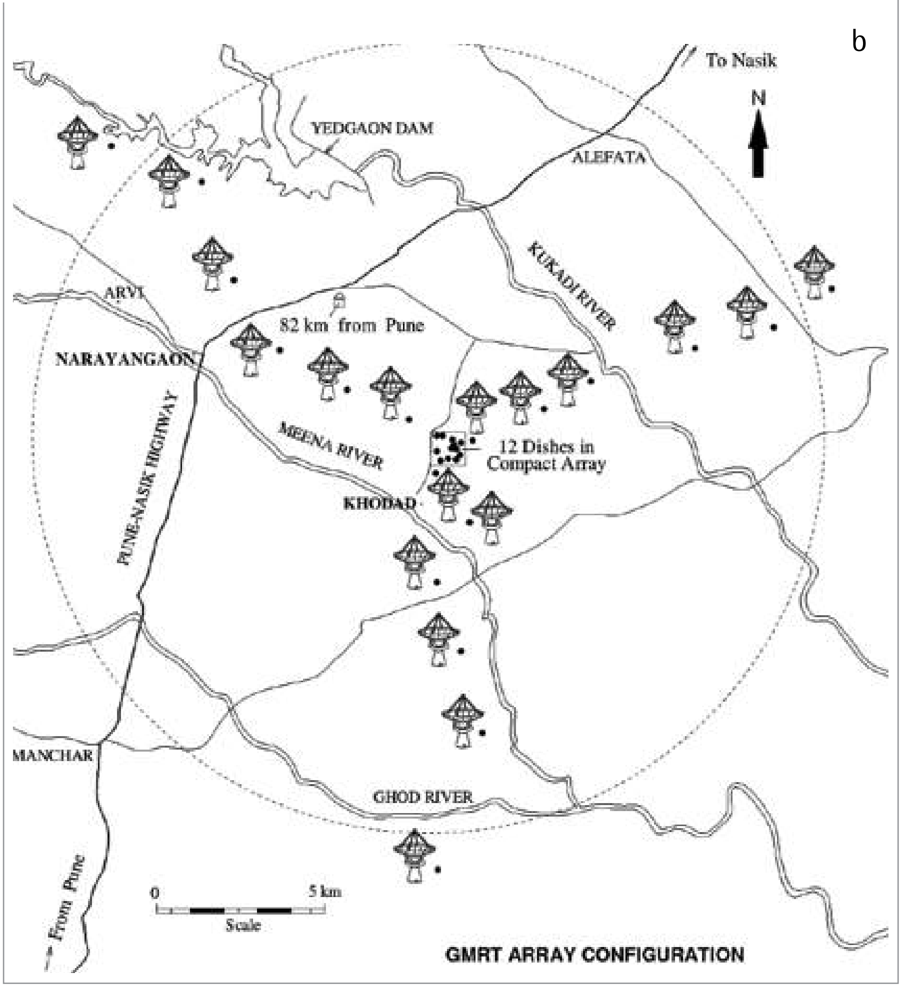
The problem of cost was finally resolved by an innovative design proposal from Prof. Govind Swarup to build a much cheaper type of antenna than has traditionally been used for radio astronomy.

Most radio-telescopes, even newer ones like the VLA and ATCA mentioned before, work at short radio wavelengths that require expensive solid reflecting surfaces. However, since the Indian radio-astronomy group has been working largely at long radio frequencies, it made sense to build a large long-wavelength radio telescope that would also occupy a unique global niche. Prof. Swarup's design proposal took advantage of precisely this difference. It was based on the fact that imperfections in a mirror that are smaller than its wavelength of operation have a negligible effect on its performance. For example, rough rock cliffs echo sound (which has a long wavelength) very well, but do not reflect light (which has a shorter wavelength) at all. So, long-wavelength radio telescopes did not need the finely polished reflecting surfaces that would be needed at short wavelengths.

The quality of the reflecting surface in a radio telescope has a multiplicative effect on its cost. Smooth surfaces require material that can be finely shaped and polished, which means that they are generally solid. These are preferred in cold countries, where these surfaces would need to be able to withstand the significant load of snow in winters. This translates into a need to have strong back-up structures to support the reflecting telescope, and hence a huge cost. At low frequencies, and at a sub-tropical location like Pune, all of these considerations become irrelevant. Prof. Swarup conceived a design where the reflecting surface was a simple wire mesh, worked into a parabolic shape by connecting thousands of wires to a light back-up structure, with each wire tensed by just the right amount so that the entire mesh takes the shape that one wants. He dubbed this new design SMART, for Stretched Mesh Attached to Rope Trusses. The SMART design led to a dramatic decrease in cost, allowing one to think of building a large telescope for a relatively modest amount of money.

The GMRT was a bold step forward for TIFR's radio astronomy group, and promised to place India at the forefront of radio astronomy research. Constructed through the nineties, the GMRT was dedicated to the nation in 2001, by Shri Ratan Tata. The design and construction of the telescope is entirely indigenous, with most of its systems being designed in-house at TIFR's National Centre for Radio Astrophysics (which was established specifically in the context of the GMRT), and some of the sub-systems being designed and

LOCATIONS OF GMRT ANTENNAS (30 dishes)



built by the Raman Research Institute (RRI), Bangalore.

The telescope consists of 30 separate antennas – each of which is a parabolic dish, 45m in diameter. The 30 dishes of the GMRT are spread over an area 25km in diameter. The antennas are all connected together by optical fibre, and operate in unison, to produce images with a resolution of a telescope 25km across (see Fig.6). The signals from these antennas are combined by a technique that is generally called interferometry or aperture synthesis (see Box 7). The GMRT is one of the largest operational interferometric arrays in the world, and India is one of a handful of countries operating such a facility. Like other such facilities, like the VLA and ATCA (operated by the USA and Australia respectively), allocation of observing time at the GMRT is independent of the nationality of the proposer. All proposals go through a process of international peer review, and the highest ranked ones are allocated time. The GMRT runs about a hundred different projects every year, observing a variety of objects, ranging from planets in our solar system to emissions from diffuse gas in very distant parts of the universe. Over the last several years, about half of all of the observing time at the GMRT has ended up being allocated to astronomers from India, while the other half goes to astronomers from across the world.

Fig. 6. Antennae of the Giant Metrewave Radio Telescope (GMRT) located at Khodad Village, near Pune. The GMRT is one of the largest radio interferometers in the world, and also one of the most sensitive telescopes at its wavelengths of operation. Spread across an area of 25km, its antennae operate synchronously to produce images with an angular resolution comparable to a mirror that is 25km in size. (a) A view of some of its antennae. The GMRT has 30 such antennae, each of which is 45m in diameter. (b) The location of the GMRT antennae. 12 dishes, arranged in a compact array, are located at Khodad village near Pune. The remaining antennae are spread along 3 roughly Y-shaped arms, each about 14km long. The antennae that are most far apart from each other are separated by a distance of about 25km.

Credits: B. Premkumar, NCRA-TIFR.

Box 7. Signals from the 30 antennae of the GMRT are combined through a process called Aperture Synthesis.

It may seem natural to think that a bigger telescope would be better than a smaller one. But in what specific ways is a bigger telescope better?

There are two different criteria by which we judge the performance of a telescope. The first is the ability to see fine details in a distant object (for example, can one distinguish between two nearby stars, or is the image so blurred that you can only see what looks like one?). This is called the resolution of the telescope. The second is the ability to detect faint objects. The further a source is, the fainter it appears, so this also translates into the ability to observe a radio source as it moves further and further away. This parameter is generally called the sensitivity of the telescope.

In parabolic telescopes, all the light that falls on the aperture is concentrated at the focus (see Fig. 7). Clearly, the larger the telescope, the more light it will gather, with the telescopes acting like a giant light bucket. It is easy to see that the larger the telescope, the more light it will gather, and the more sensitive it will be. What is less obvious is that larger telescopes also have better resolution. This happens through diffraction (observed for all kinds of waves), which causes the resolution of a telescope at a fixed wavelength to improve as its mirror size increases. Similarly, for a fixed size of reflector, the resolution improves as the wavelength decreases (a related phenomenon, which may be more familiar to readers is that blu-ray DVDs which work with shorter wavelength blue light can pack more information into the same geometric area as compared to normal DVDs).

The wavelength of optical light is about a million times smaller than that of the radio-waves to which the GMRT is sensitive to. To have a radio telescope with a resolution that matches that of an optical telescope a few centimetres in size, one would need to build a telescope that is tens of kilometres across – a formidable challenge! How do we build a telescope which has the resolution of a mirror that is tens of kilometres in size?

Let us step back and see what it is that a mirror does to the light that falls on it. As can be seen in Fig. 7, all the reflected light is concentrated at the focus. We could achieve the same effect by building a collection of small mirrors, collecting the radiation that is concentrated at each of their foci, and adding all of these signals together. This combined signal would be like one from a giant mirror (i.e. a mirror with a size equal to that of the largest separation between the small mirrors); except that this mirror is not complete, it has large holes in it. This is because light is collected only from the regions covered by the small mirrors, and the light falling on the regions in between (or the 'holes') is lost. So, a telescope formed by properly putting together the signals from a collection of small mirrors would have the resolution of a mirror with a size corresponding to the largest separation between the mirrors, but with a sensitivity corresponding to that of a mirror with an area equal to the sum of the areas of the smaller mirrors.

If we went one step further, we could look at what happens when we track a radio source from rise to set. From the point of view of this distant source, what is happening is that because of the Earth's rotation, these small mirrors are being carried around in space. Equivalently, these small mirrors sweep out large areas of the hypothetical large mirror as one observes a source from rise to set. The resultant mirror (i.e. the aperture that one has synthesized) is significantly closer to a perfect mirror than that obtained by a snapshot produced by individual small mirrors (see Fig. 8). This is what is called Earth rotation aperture synthesis, and is the technique that the GMRT and other such telescopes employ to take high resolution images of the sky.

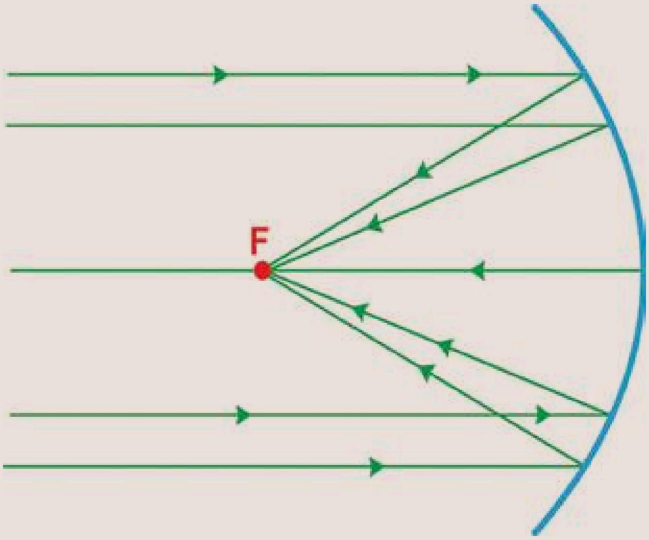


Fig. 7. Light rays falling on a parabolic mirror get concentrated at the focus. Parabolic mirrors act like light buckets, collecting all the energy falling on their surface, and concentrating it at their focal point. Clearly, larger telescopes will collect more light, or are more sensitive, capable of detecting fainter objects. It turns out that larger telescopes also have better resolution, or are better able to distinguish finer details in the source.

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Fig. 8. The tracks traced out by the GMRT antennae in the central part of its array when following a source from rise to set. As can be seen from this image, even with a small number of antennae, the rotation of the Earth results in a fairly good coverage of the 'mirror' that one is trying to synthesize.

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One issue that has been brushed under the carpet in this description is how exactly one 'combines' the signals of the small mirrors together to get the signal of a large mirror scanning the sky. This, unfortunately, is a highly detailed technical issue, and discussion of this would take us too far afield. However, one thing that is probably worth making clear is that it involves very sophisticated digital electronics and software algorithms – radio astronomers do not listen to the signals coming out of their telescopes using headphones!

Conclusion

Since the first instruments that came into service after World War II, radio telescopes have taken giant leaps. The most sensitive telescopes today, amongst which is the GMRT, have much greater sensitivities than those of the first generation of telescopes. Modern telescopes are extremely versatile. The GMRT, for example, has been used to search for a variety of emissions – from those of hydrogen that filled the universe 12 billion years ago (i.e. just before the first stars and black holes converted all of the intergalactic gas into a hot plasma) to those from other planets in the solar system. Three Nobel prizes have so far been awarded for discoveries made by radio astronomers. Although the radio astronomy community is small, it has clearly had a disproportionate impact on society, and not just via films and novels. Being a small community, it has also been relatively collaborative and forward-looking. Radio astronomers are one of the few research communities, for example, that allow free use of their telescopes. As described before, the GMRT can be used by anyone in the world whose proposal is judged to be good enough (by an international panel of experts). Similarly, Indian astronomers can use radio-telescopes built by other countries. In an environment of growing insularity and isolationism, radio astronomers provide not just a broader perspective with which to view our place in the universe, but also a practical example of the advantages of working together.

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Note: Credits for the image used in the background of the article title: One of the antennae of GMRT telescope, Pune, India. Photographer: Rohit Gowaika. URL: https://www.flickr.com/photos/18419987@N00/3119728744. License: CC-BY-SA.

Further Reading and useful links:

1. A brief introduction to radio astronomy and SETI can be found at: http://www.bigear.org/guide.htm.
2. The Australia Telescope National Facility has some interesting material on radio astronomy and radio telescopes: http://www.atnf.csiro.au/outreach/education/everyone/radio-astronomy/index.html.
3. More about the GMRT at Pune can be found at: http://www.ncra.tifr.res.in/ncra/.
4. A very readable account of the discovery of pulsars can be found at: http://www-outreach.phy.cam.ac.uk/camphy/pulsars/pulsars_index.htm.
5. More about galactic interactions and mergers can be found in the article titled – Interactions in Outer Space, by Anand Narayan, **i wonder...**, Issue 2, June 2016, Page 4.
6. A popular account of radio astronomy can be found in the book, The Invisible Universe, by Gerrit Verschuur, Springer Publishing.

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