A project report on

RADIO OBSERVATIONS AND THEIR PHYSICAL INTERPRETATIONS

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Abstract

The analysis of radio galaxy CGCG 049-033 in Abell Cluster of galaxies is done from GMRT data. The new image of this galaxy is showing a faint counter-jet which was not detected previously. It seems that the gigantic jet $(\sim 440kpc)$ precesses, so that its projected image is like a sinusoidal waveform structure which is observed. This is the largest radio jet ever detected in context of its projected length in the sky plane. This jet emanates from an extremely massive black hole (>$10^9 M_\odot$) and forms a strikingly compact lobe. The counterjet and main jet are similar in brightness up to a scale of tens of kiloparsecs. With several unusual properties, this magajet is an exceptionally useful laboratory for testing the role of magnetic field in jet stabilization and radio lobe formation.

1. RADIO ASTRONOMY

1.1 Radio Astronomy:-

Radio astronomy is the study of distant objects in the universe by collecting and analyzing the radio waves emitted by those objects. The initial detection of radio waves from an astronomical object was made in the 1930s, when Karl Jansky observed radiation in radio wavelength coming from the Milky Way. Subsequent observations have identified a number of different sources of radio emission. These include stars and galaxies, as well as entirely new classes of objects, such as radio galaxies, quasars, pulsars, etc. The radio noise discovered by Jansky belongs to an entirely different physical regime; it comes from charged particles, usually electrons, with very high energies, moving at relativistic velocities in the magnetic fields of Interstellar Medium (ISM). This regime of *synchrotron radiation*, although it can generate radiation upto X-ray and beyond, is a particularly prominent long-wavelength phenomenon, giving radio astronomy a unique role in the investigation of some of the most energetic objects in the universe. With radio astronomy, we can study astronomical phenomena that are often invisible in other portions of the electromagnetic spectrum. Since radio waves penetrate dust, one can use radio astronomy techniques to study regions that cannot be seen in visible light, such as the dust-shrouded environments where stars and planets are born, and the center of our Galaxy, the Milky Way.

1.2 Importance of radio observations

Discovery of radio emission from the interstellar medium gives birth to new technique to study astronomy which is known today as radio astronomy. It sets new levels in study of astronomy. It generate enormous amount of data which will give large amount of information to us for understanding the universe.

Electromagnetic radiations are an important source of getting information about the universe. Electromagnetic spectrum is spread over long range. The electromagnetic spectrum mainly consists of different parts viz. gamma ray, X-ray, U.V., visible, infrared, microwave, radio region. Their wavelengths and frequencies are listed in the Table 1.1. Though many sources emit through all these regions, but only some of these radiations can enter through the earth's atmosphere. If we plot energy flux of electromagnetic radiation coming on earth's surface from cosmos, atmospheric windows are indicated in Figure 1.1. We can easily see that higher frequency regions like gamma ray, X-ray, U.V. are blocked by the ozone, nitrogen and oxygen absorption. While optical region have a narrow window and infrared are blocked by the principle absorbing agents viz. water vapour and carbon dioxide. It is remarkable that there is very broad window at the radio end that suggesting it is very easy for radiations in radio region to enter through the atmosphere. This is the reason why radio astronomy has gained importance in overall study of astronomy.

Table 1.1 Regions of electromagnetic spectrum with wavelength range

Spectral region	Wavelength range	Objects detectable
Gamma ray	0.1nm and below	Gamma ray bursts

X-ray	0.1nm-10nm	X-ray Binaries, Active galactic Nuclei, cluster of galaxies
Optical	400nm-700nm	Stars, Star clusters, Galaxies, planets, comets
Infrared	700nm-10µm	Interstellar and Intergalactic dust, Molecular clouds, Nebulae
Radio	1cm-30m	Radio galaxies, Pulsars, HI regions, stars, star clusters, interstellar and intergalactic dust, molecular clouds, nebulae, etc.

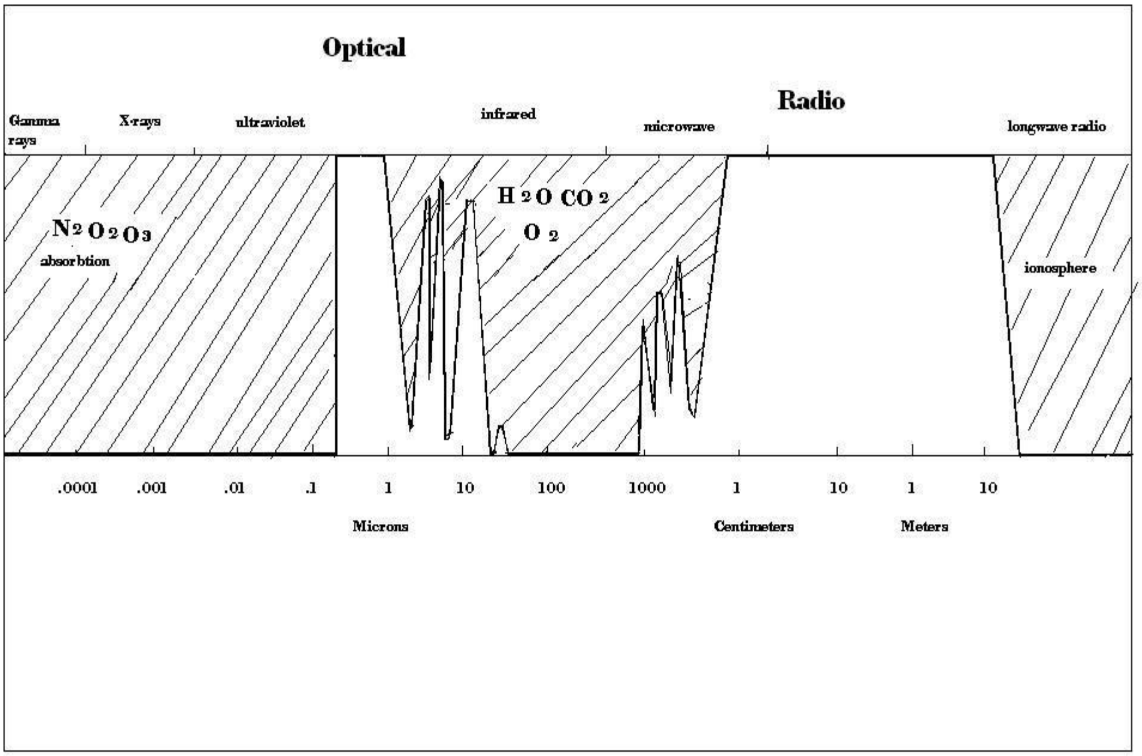


Figure-1.1: Electromagnetic spectrum showing windows in different wavelength range.

2. OBSERVATIONAL TECHNIQUES

2.1 Resolving power of a Radio Telescope:-

We observe the radio universe through radio telescopes whose angular resolution depends on the wavelength and the diameter of the aperture of the telescope. Its limit of resolution ‘θ’ is

$$\theta = \frac{\lambda}{D}$$

where ‘λ’ and ‘D’ are wavelength of electromagnetic radiation observed and diameter of the aperture of the telescope respectively.

‘θ’ is the least possible angle a telescope can resolve. As the wavelength of radio waves are much higher than those of optical wavelengths, the resolution of optical telescopes are very much higher than those of radio telescopes with same aperture diameter. Therefore, to obtain a higher angular resolution we need very large apertures which are severely restricted by cost and technological complexities. So radio interferomerty is proper alternative to the use of a single gigantic aperture to get better resolution. In fact, with the use of many telescopes at a time and using the interferometry techniques, we get extremely high resolution which can not be obtained with even a gigantic single dish telescope.

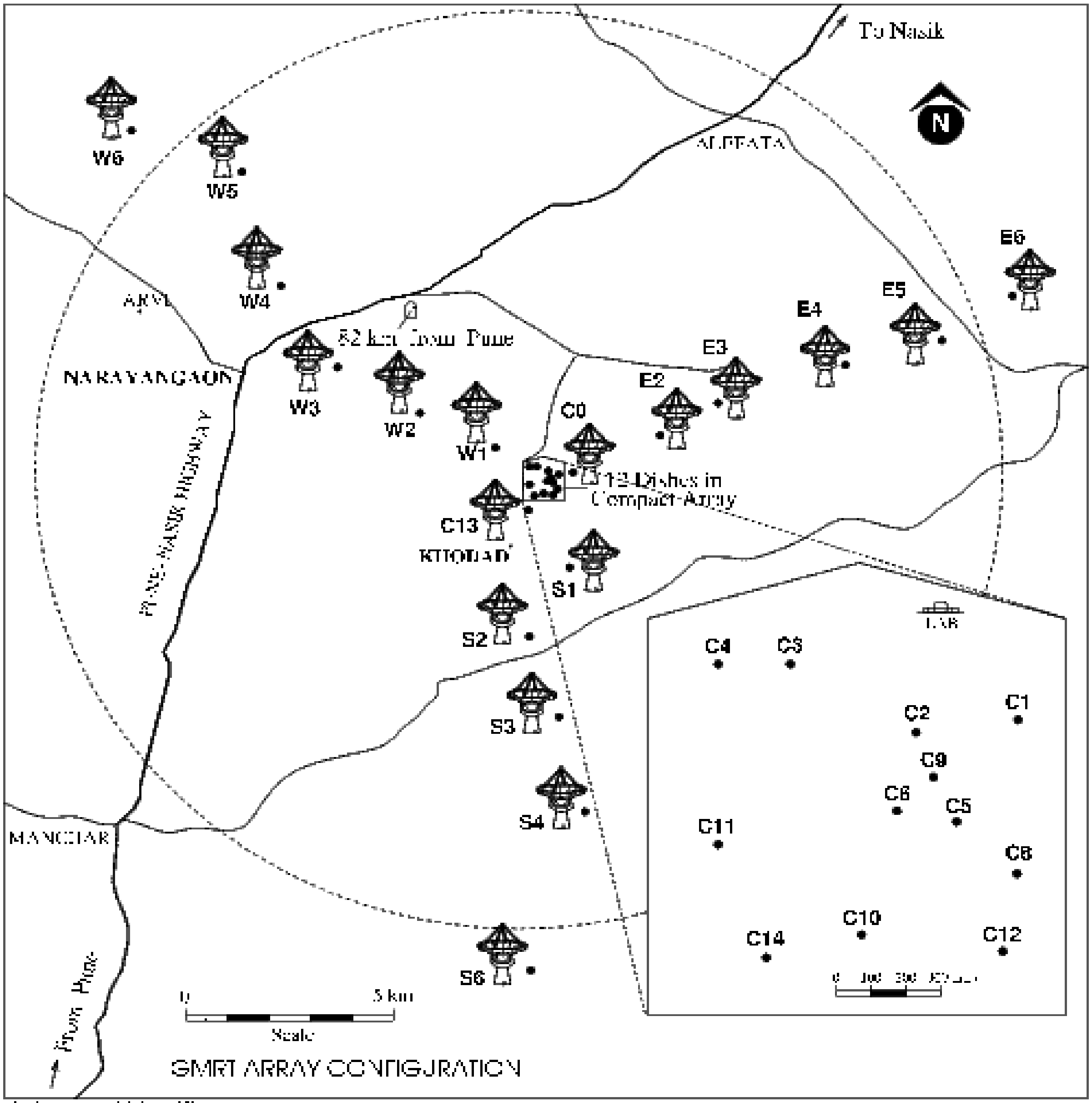
2.2 Aperture Synthesis / Radio Interferometry and their Advantages:-

Aperture synthesis or synthesis imaging is a type of interferometry that mixes signals from a collection of telescopes to produce images having the same angular resolution as an instrument the size of the entire collection. At each separation and orientation, the lobe-pattern of the interferometer produces an output which is one component of the Fourier transform of the spatial distribution of the brightness of the observed object. The image (or "map") of the source is produced from these measurements.

Astronomical interferometers are commonly used for high-resolution optical, infrared, submillimetre and radio astronomy observations.

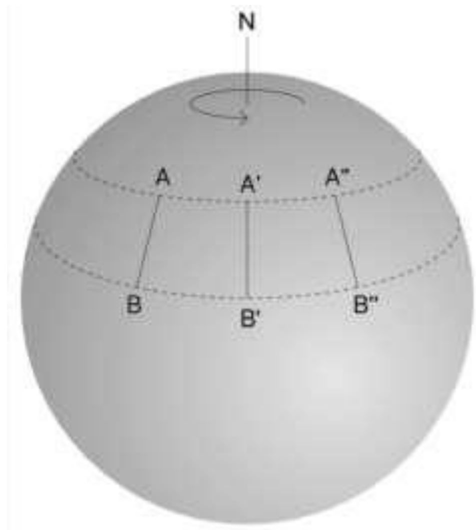
Aperture synthesis is possible only if both the amplitude and the phase of the incoming signal is measured by each telescope. For radio frequencies, this is possible by electronics, while for optical lights, the elecromagnetic field cannot be measured directly and correlated in software, but must be propagated by sensitive optics and interfered optically. Accurate optical delay and atmospheric wavefront aberration correction is required, a very demanding technology which became possible only in the 1990s. This is why imaging with aperture synthesis has been used successfully in radio astronomy since the 1950s and in optical/infrared astronomy only since the 2000 decade.

In order to produce a high quality image, a large number of different separations between different telescopes are required (the projected separation between any two telescopes as seen from the radio source is called a baseline) - as many different baselines as possible are required in order to get a good quality image. The number of baselines (n_b) for an array of 'n' telescopes is given by $n_b = (n^2 - n)/2$. For example the Very Large Array has 27 telescopes giving 351 independent baselines and Giant Meterwave Radio Telescope (GMRT) has 30 telescopes (each is 45m in diameter) giving 435 independent baselines at once, and can give high quality images.



Caption: Positions of telescopes of GMRT. C-series corresponds to telescopes ate the centre of the Y-shape array while E, W and S-series corresponds to eastern, western and southern arms of Y-shape array respectively.

Most aperture synthesis interferometers use the rotation of the Earth to increase the number of different baselines included in an observation (see diagram on below).



Caption: A base line AB moving along the earth's rotation

Taking data at different times provides measurements with different telescope separations and angles without the need for buying additional telescopes or moving the telescopes manually, as the rotation of the Earth moves the telescopes to new baseline.

3. ACTIVE GALACTIC NUCLEI (AGN)

3.1 Active Galactic Nuclei And Active Galaxies:-

An **active galactic nucleus (AGN)** is a compact region at the centre of a galaxy which has a much higher than normal luminosity over some or all of the electromagnetic spectrum (in the radio, infrared, optical, ultra-violet, X-ray and/or gamma ray wavebands). A galaxy hosting an AGN is called an **active galaxy**. The radiation from AGN is believed to be a result of accretion of mass by the supermassive black hole at the centre of the host galaxy.

Active galaxies exhibit evidences of activity in a variety of ways. Their total luminosities may be around $10^{44} erg\, s^{-1}$ (compared with luminosity of Sun, which is $4 \times 10^{33}\ erg\, s^{-1}$) and can go upto $10^{48-49}\ erg\, s^{-1}$ for quasars. This tremendous energy release is possible only if these objects swallow a few stars per year and convert their mass into energy. The AGN must be powered by accretion onto massive black holes (with masses between 10^6 and 10^{10} times that of the Sun). These galaxies emit non-thermal emission in all the wavelengths, i.e., radio to γ-rays. Compared to a normal galaxy, where the nuclear brightness never masks the spiral arms or the rest of the galaxy, in extremely active galaxies, the nucleus is so bright that the rest of the structure is not visible. Active galaxies also produce (generally) jet-like outflows of very high energy particles on both sides, normal to galactic plane. These jets are highly collimated and continuously ejected. Normal galaxies do not produce these jets.

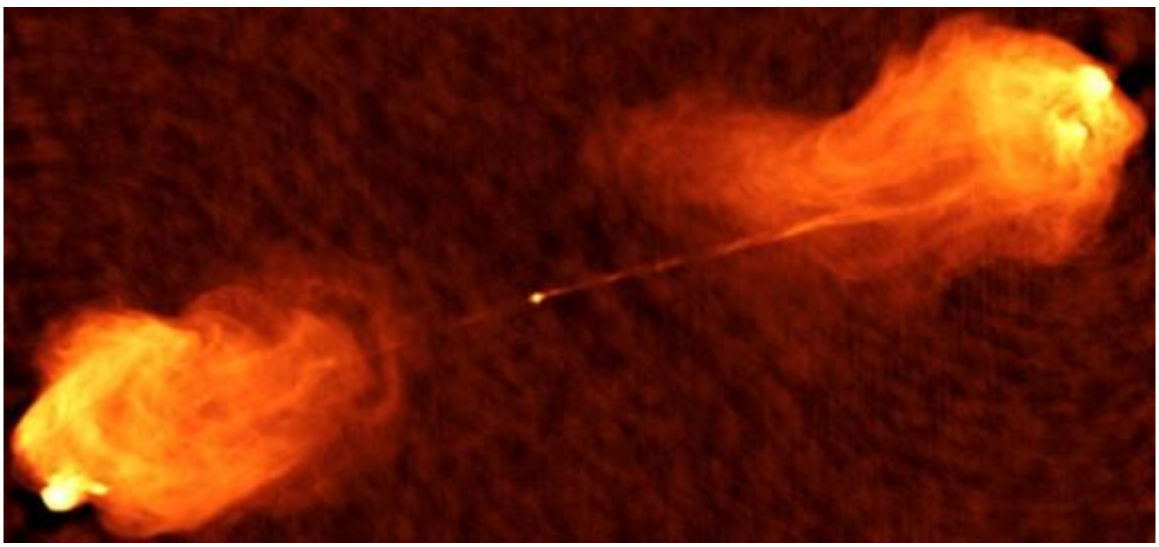
Since the tremendous amount of energy is released continuously (rather than a one-time event as in supernovae), it is natural to assume that the main reason of this is the gravitational energy released by the accretion of matter. What is the source of this matter? How would the radiation be emitted and at what frequency? Why do the jets form? How are the jets collimated? All these important questions still puzzle astrophysicists today and only some of these questions have been answered satisfactorily.

3.2 Radio Galaxies:-

Radio galaxies and their relatives, radio-loud quasars and blazars, are types of active galaxy that are very luminous at radio wavelengths (up to 10^{39} W between 10 MHz and 100 GHz). The radio emission is due to the synchrotron process. The observed structure in radio emission is determined by the interaction between twin jets and the external medium, modified by the effects of relativistic beaming. The host galaxies are almost exclusively large elliptical galaxies.

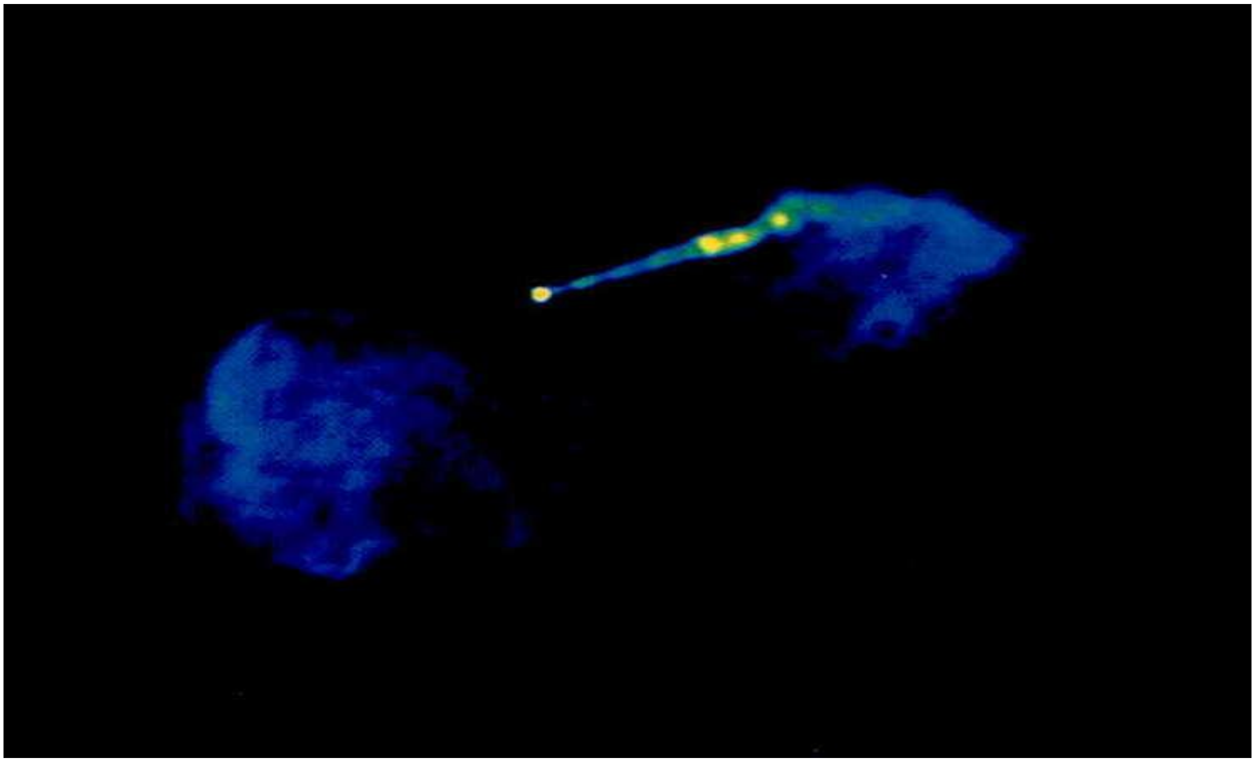
Some images of radio galaxies are shown below:-

1. **Cygnus A**



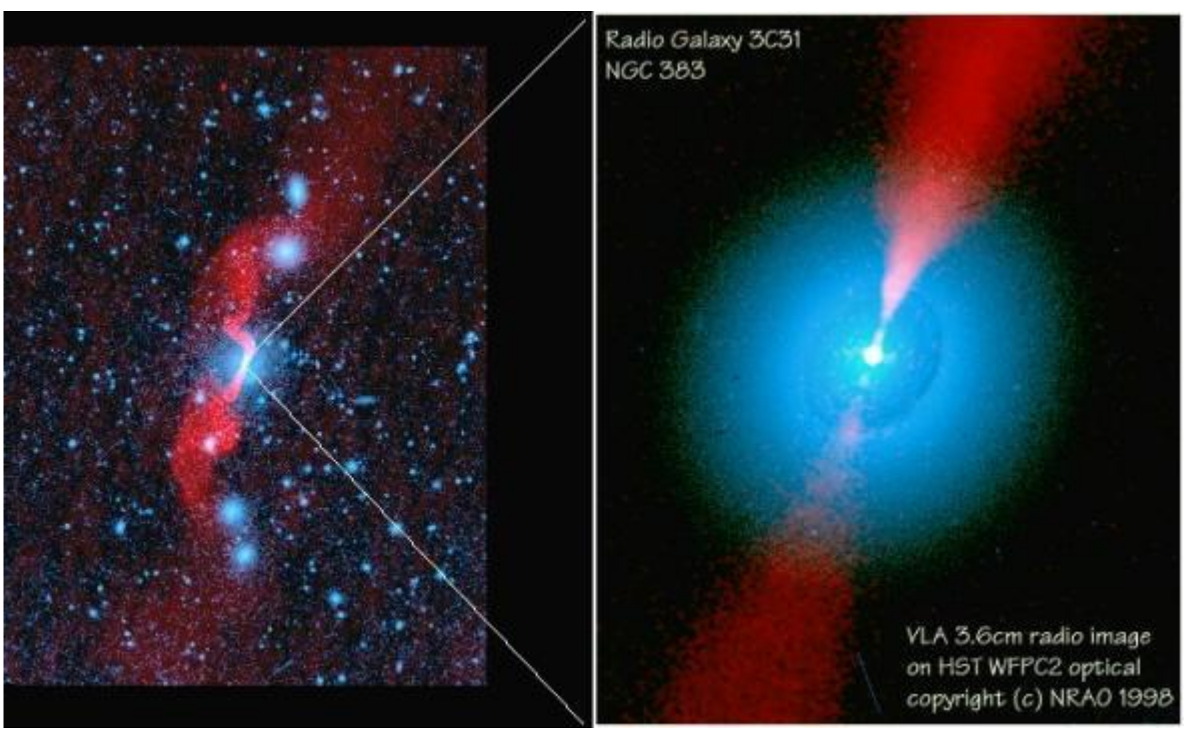
Caption: The radio source Cygnus A is produced in a galaxy some 600 million light-years away. The radio waves are coming from electrons propelled at nearly the speed of light through a long, thin "jet" at the core of the galaxy and deposited in giant "radio lobes." It is here where the speeding electrons are trapped by the magnetic field around the galaxy to produce radio waves. The electrons come from the bright, small radio component in the center of the galaxy -- the location of a black hole.

2. **M 87**



Caption: M87 is an elliptical galaxy containing Active galactic nucleus.

3. **Radio Galaxy 3C31 / NGC 383**

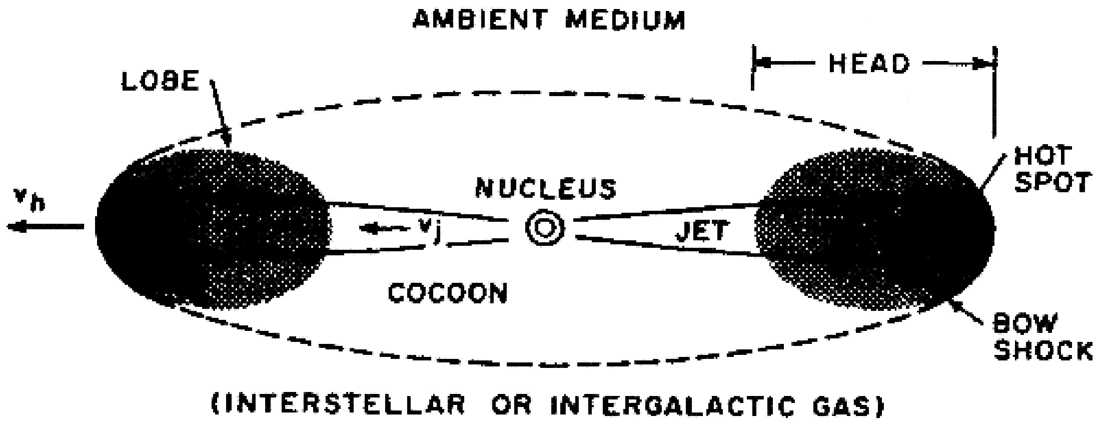


Caption: This image shows the optical and radio morphology of the radio galaxy 3C31 (NGC 383). In this image, red colors depict radio emission, and blue colors depict the optical emission from starlight. This system is a powerful radio source, with conical inner jets developing into wiggling jets and irregularly shaped plumes, which stretch to a distance of 300 kpc from the center of the galaxy. The left-hand image shows the large-scale morphology of the radio jet and the surrounding optical field, while the right-hand image shows the center of the galaxy with its conical radio jets. The optical image shows prominent dust features in the host galaxy. The high energy particles are shot into extragalactic space at speeds approaching the speed of light, where they eventually balloon into massive radio plumes.

3.3 A Simple Model of an AGN:-

In a simple model, an Active Galactic Nucleus (AGN) has a central massive object, perhaps a black hole, or at least a mass concentration with total mass around 10^6 to 10^9 solar masses within 0.01 pc or even less, that is about the size of the solar system. The energy of the AGN derives from the gravitational potential energy of the surrounding material, which is released as it falls into the central object, which we will hence forth refer to as black hole. A large part of the rest mass of this material is released in process. Stars are disrupted as they pass within the Roche limit of the black hole, and the angular momentum of the infalling material concentrates the material of the disrupted star to an accretion disk, which is heated by frictional dissipation of the differentially rotating disk, and by turbulent dissipation. This hot disk is called Accretion Disk. So the radiation from the disk is thermal radiation.

Along the axis of the rotating accretion disk are the pair of jets of energetic material ejected from the nucleus along the polar directions; these are astonishingly narrowly collimated, and may travel very large distances. These jets feed energetic particles and magnetic field energy into the lobes of radio galaxies. The energetic radio jet is stopped by dense intergalactic medium and produces a hot spot at the point of interaction and forms a lobe around it.



Caption: Schematic diagram of strong double radio source, illustrating the nomenclature of parts.

3.3.1 <u>The Core and The Jet</u>:-

At the centre of the AGN, occupying a space similar to our solar system, is the intensely bright core, emitting synchrotron radiation over the whole spectrum from radio to gamma-rays. The core is the origin of the jets emitted along the polar directions; where these jets exist, the core and the jets may be regarded as continuous. In radio observations at high angular resolution the core and the jet completely dominate the centre of the galaxy. In common situations only one jet is dominant which demands explanation in terms of either of an intrinsic asymmetry in the core, or of Doppler brightening.

In bright quasars only the core can be observed optically. According to the model, the AGN is seen very nearly pole on, so that any jet is close to the line of sight. The jet material is streaming out with high relativistic velocity, so that radiation from any source within it will be beamed in the direction of the jet, with an increase in intensity because of 'Doppler boosting'. A jet pointing away from observer would be faint, or unobservable

3.3.2 <u>The Radio Jets and Lobes</u>:-

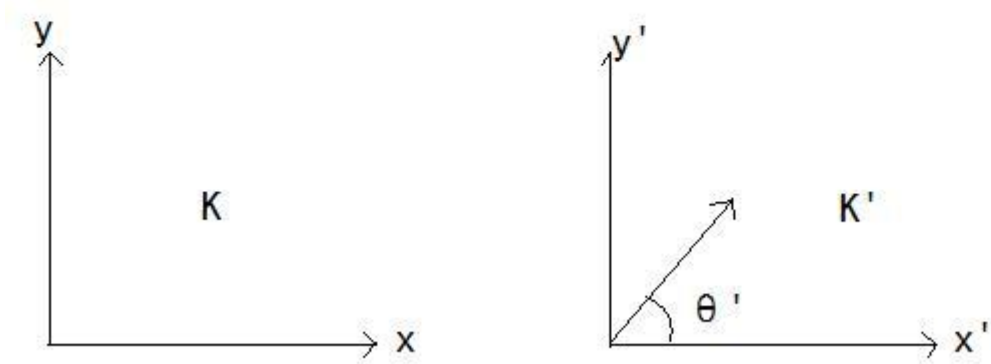
The radio luminosity of powerful radio galaxies is dominated by the extensive double lobe structure. This structure extends to over a magaparsec from the active nucleus, deriving energy from the very narrow elongated jets. The jets are continuous from core out to over 100s of kiloparsec, expanding only slowly from diameter ranges from 1pc to few kpc. The energy of radiating particles is evidently maintained by a flow of particles down to jet. Along the jet, jet turbulently interacts with the surrounding interstellar and intergalactic medium, culminating in the major interactions at the 'Hot Spots' in the radio lobe. A high degree of polarization of the radio emission, reaching 50% in some cases, indicates that a well organized magnetic field is involved in the stabilization of the jet; the field is directly along the jet for most of its length, and becomes transverse in the hot spots where the jet comes to a halt. Jets are generally straight.

The 'hot spots', where the jets break up, are the outer boundary of a cavity through which the jet bore sits narrow tunnel. This cavity contains hot plasma flowing back from the hot spot; it still have energy to radiate synchrotron radiation, although it has fewer high-energy electrons and consequently a steeper radio spectrum. The cavity is therefore seen best at lower frequencies. The radiation from the jets, hot spots and radio lobes is synchrotron, as shown by the high brightness temperature, spectrum and the polarization. The total energy in the lobes (total of particle energy and magnetic energy) reaches 10^{60} erg in most of the galaxies. Typically, the radio emission is from electrons with relativistic energy $\gamma = 1000$, accelerated in a magnetic field of about 10 microgauss.

4. THEORY

4.1 Transformation of Velocities:-

Suppose that a frame K’ is moving with constant velocity $\boldsymbol{v}$ with respect to a frame K and the x-axis of both the frames coincide. If a point has a velocity **u**´ in K’-frame, what is its velocity **u** in K-frame?



Caption: Lorentz transformation of velocities

The Lorentz transformations for differentials are

$$dx = \gamma(dx' + v\, dt')$$

$$dy = dy'$$

$$dz = dz'$$

$$dt = \gamma\left(dt' + \frac{v}{c^2}\, dx'\right)$$

Then we will get the three components of velocities in K-frame as

$$u_x = \frac{dx}{dt} = \frac{\gamma(dx' + v dt')}{\gamma\left(dt' + \frac{v}{c^2} dx'\right)} = \frac{u'_x + v}{1 + \frac{v}{c^2} u'_x}$$

$$u_y = \frac{u'_y}{\gamma\left(1 + \frac{v}{c^2}u'_x\right)}$$

$$u_z = \frac{u'_z}{\gamma\left(1 + \frac{v}{c^2}u'_x\right)}$$

The generalization of these equations to an arbitrary velocity $\boldsymbol{v}$, not necessarily along the x-axis, can be stated in terms of the components of **u** perpendicular to and parallel to and parallel to $\boldsymbol{v}$:

$$u_{\parallel} = \frac{u'_{\parallel} + v}{\Upsilon\left(1 + \frac{v}{c^2}u'_{\parallel}\right)} \quad and \quad u_{\perp} = \frac{u'_{\perp}}{\Upsilon\left(1 + \frac{v}{c^2}u'_{\parallel}\right)}$$

The directions of the velocities in the two frames are related by the aberration formula,

$$\tan\theta = \frac{u_{\perp}}{u_{\parallel}} = \frac{u'\sin\theta}{\Upsilon(u'\cos\theta' + v)}$$

An interesting application is for the case $u' = c$, i.e., for the case of light, where

$$\tan\theta = \frac{\sin\theta'}{\Upsilon\left(\cos\theta' + \frac{v}{c}\right)}$$

and

$$\cos\theta = \frac{\cos\theta' + \frac{v}{c}}{1 + \left(\frac{v}{c}\right)\cos\theta'}$$

Either of the above two equations represent ***Aberration of Light***.

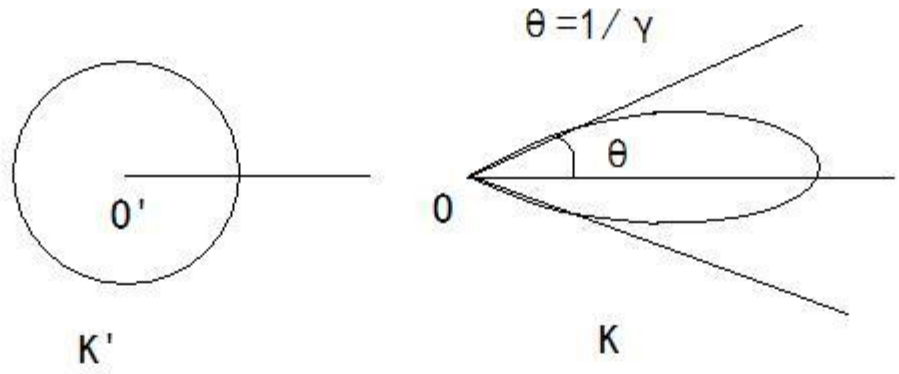
Now consider the case for $\theta' = \frac{\pi}{2}$, i.e. for a photon emitting at right angles to $\boldsymbol{v}$ in K'-frame. Then we have

$$\tan\theta = \frac{c}{\gamma v}$$

$$\sin\theta = \frac{1}{\gamma}$$

Now for highly relativistic speeds, $\gamma \gg 1$, and therefore θ becomes very small, so

$$\theta \sim \frac{1}{\gamma}$$



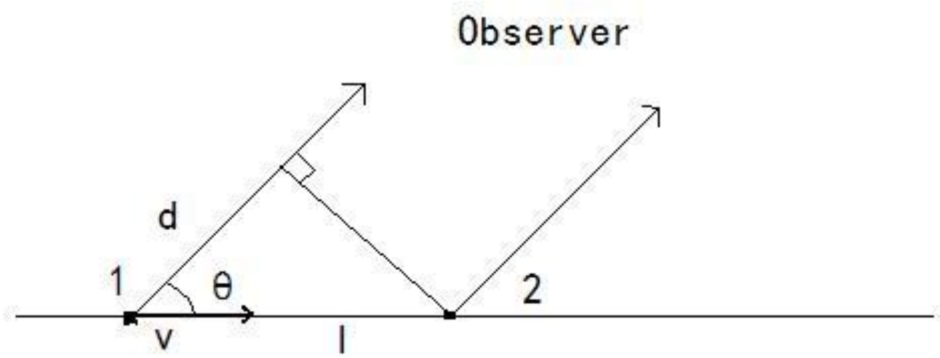
Caption: Relativistic beaming of radiation emitted isotropically in the rest frame K'

Therefore if photons are emitted isotropically in K'-frame, then in K-frame, photons are concentrated in the forward direction lying within a cone of half angle $\left(\frac{1}{\gamma}\right)$. This is called ***Relativistic Beaming effect***.

4.2 Relativistic Doppler Effect:-

We know that any periodic phenomenon in the moving frame K' will appear to have a longer period by a factor γ when viewed by local observer in K-frame due to time dilation effect. This means that if we measure the arrival times of pulses or other indications of the periodic phenomenon that propagate with the velocity of light, then there will be an additional effect on the observed period due to delay times for light propagation. The joint effect is called the ***Doppler Effect***.

In the rest frame of the observer K, imagine that the moving source emits one period of radiation as it moves from point 1 to point 2 at velocity $\boldsymbol{v}$.



Caption: Geometry for the Doppler effect

If the frequency of the radiation in the rest frame of the source is ω' then the time taken to move from point 1 to point 2 in the observer's frame is given by the time dilation effect :

$$\Delta t = \frac{2\pi\gamma}{\omega'}$$

Now considering the figure and note

$$l = v.\Delta t$$

$$d = v(\Delta t)\cos\theta$$

The difference in arrival time Δt_A of the radiation to propagate a distance 'd'. Thus we have

$$\Delta t_A = \Delta t - \frac{d}{c} = \Delta t - \frac{v(\Delta t)\cos\theta}{c}$$

$$\Delta t_A = \Delta t\left(1 - \frac{v}{c}\cos\theta\right)$$

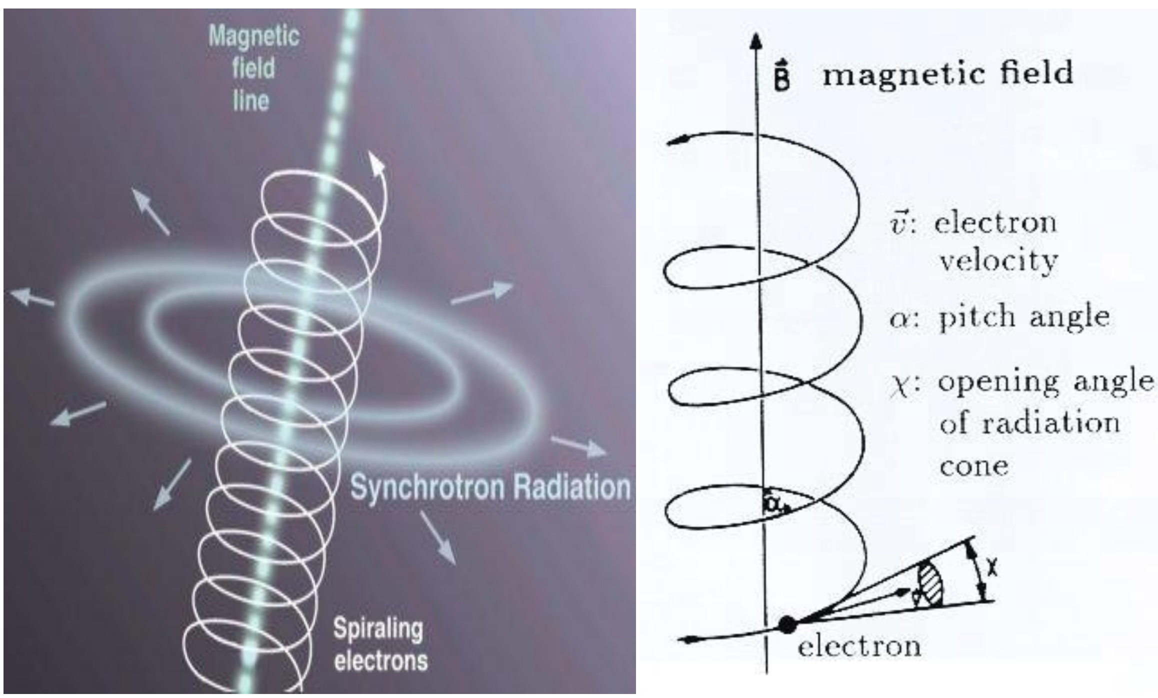
Therefore, the observed frequency ω will be

$$\omega = \frac{2\pi}{\Delta t_A} = \frac{\omega'}{\gamma\left(1 - \frac{v}{c}\cos\theta\right)}$$

This is the ***<u>Relativistic Doppler Formula</u>***. The factor (γ^{-1}) is purely relativistic effect, whereas the $\left(1-\frac{v}{c}\cos\theta\right)$ factor appears even classically.

4.3 <u>Synchrotron Radiation</u>:-

The synchrotron radiation, the emission of very relativistic and ultra relativistic electrons gyrating in a magnetic field, is the process which dominates much of high energy astrophysics. This process is responsible for the radio emission from the galaxy, from supernova remnants and extragalactic radio sources. It is also responsible for the non-thermal optical and X-ray emission observed in the Crab Nebula and possibly for the optical and X-ray continuum emission of quasars.



Caption: *Left*- Spiraling relativistic electrons in a constant magnetic field. *Right*- Relativistic electrons showing relativistic beaming of radiation.

The equation of motion for a charged particle of rest mass 'm_o', charge 'ze' and Lorentz factor γ in a uniform magnetic field $\boldsymbol{B}$ is

$$\frac{d}{dt}(\gamma m_o \boldsymbol{v}) = ze(\boldsymbol{v} \times \boldsymbol{B}) \tag{1}$$

Left hand side of this equation can be expanded as follows :-

$$m_o \frac{d}{dt}(\gamma \boldsymbol{v}) = m_o \gamma \frac{d\boldsymbol{v}}{dt} + m_o \gamma^3 \boldsymbol{v}(\boldsymbol{v}.\boldsymbol{a})$$

Because the Lorentz factor γ should be written as

$$\gamma = \left(1 - \frac{\boldsymbol{v}.\boldsymbol{v}}{c^2}\right)^{-\frac{1}{2}}$$

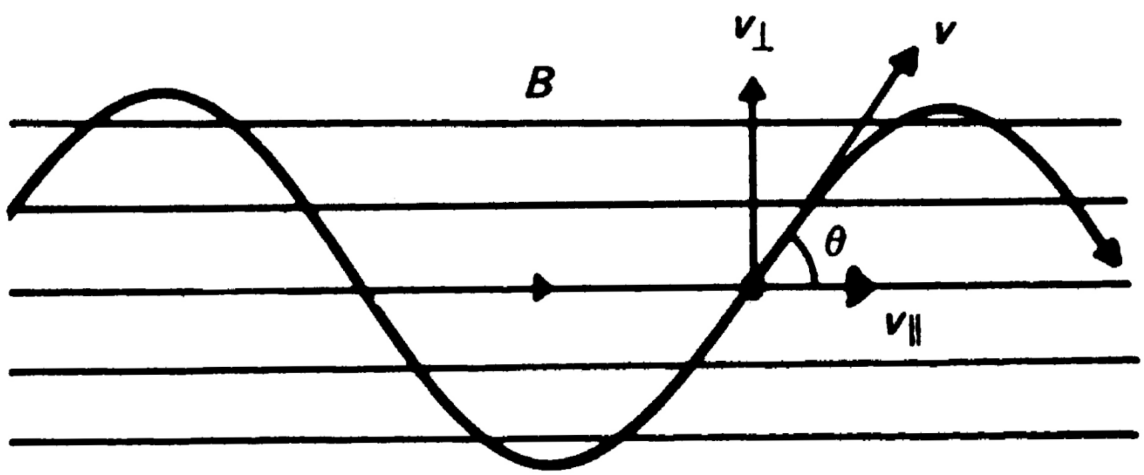
In a magnetic field, the three acceleration, $\boldsymbol{a} = d\boldsymbol{v}/dt$, is always perpendicular to $\boldsymbol{v}$ and consequently

$$\boldsymbol{v}.\boldsymbol{a} = 0$$

As a result

$$\gamma m_o \frac{d\boldsymbol{v}}{dt} = ze(\boldsymbol{v} \times \boldsymbol{B}) \quad (2)$$

We now split $\boldsymbol{v}$ into components parallel and perpendicular to uniform magnetic field, $v_{\|}$ and $v_{\perp}$ respectively.



Caption: The directions of $v_{\|}$, $v_{\perp}$ and B. Also showing the pitch angle θ.

The pitch angle 'θ' of the particle's orbit is given by

$$\tan\theta = \frac{v_{\perp}}{v_{\|}}$$

i.e. the angle between the vectors $\boldsymbol{v}$ and $\boldsymbol{B}$. Since $v_{\|}$ is parallel to magnetic field, eqn (2) tells us that there is no change in $v_{\|}$. The acceleration is perpendicular to the magnetic field direction and to $v_{\perp}$.

$$\gamma m_o \frac{d\boldsymbol{v}}{dt} = zev_{\perp}B(\boldsymbol{i_v} \times \boldsymbol{i_B}) = zevB\sin\theta\,(\boldsymbol{i_v} \times \boldsymbol{i_B})$$

where $\boldsymbol{i_v}$ and $\boldsymbol{i_B}$ are unit vectors in the direction of $\boldsymbol{v}$ and $\boldsymbol{B}$ respectively.

Thus, the particle's acceleration vector is perpendicular to the plane containing both the instantaneous velocity vector $\boldsymbol{v}$ and the direction of the magnetic field $\boldsymbol{B}$. Because the magnetic field is uniform, this constant acceleration to the instantaneous velocity vector results in circular motion about the magnetic field. Equating this acceleration to the centrifugal acceleration, we find

$$\frac{{v_{\perp}}^2}{r} = \frac{zevB\sin\theta}{\gamma m_o}$$

$$r = \frac{\gamma m_o v\sin\theta}{zeB}$$

This means that the particle moves in a spiral path with constant pitch angle 'θ'.

The angular frequency of the particle in its orbit ω_g is known as angular gyrofrequency and is given by

$$\omega_g = \frac{v_{\perp}}{r} = \frac{zeB}{\gamma m_o}$$

The corresponding gyrofrequency ϑ_g i.e. the number of times per second the particle rotates about the magnetic field direction, is

$$\vartheta_g = \frac{\omega_g}{2\pi} = \frac{zeB}{2\pi\gamma m_o}$$

The acceleration is perpendicular to the velocity, with magnitude $a_{\perp} = \omega_g v_{\perp}$, so that the total emitted radiation for the case of electron is,

$$P = \frac{\gamma^4 e^4}{6\pi\varepsilon_o c^3} a_{\perp}^2 = \frac{e^4 B^2}{6\pi\varepsilon_o c m_o^2}\frac{v^2}{c^2}\gamma^2(\sin\theta)^2$$

For an isotropic distribution of velocities it is necessary to average this formula over all angles for a given speed. Thus, we get total emitted power as

$$P = \frac{4}{3}\sigma_T c U_B \left(\frac{v}{c}\right)^2 \gamma^2$$

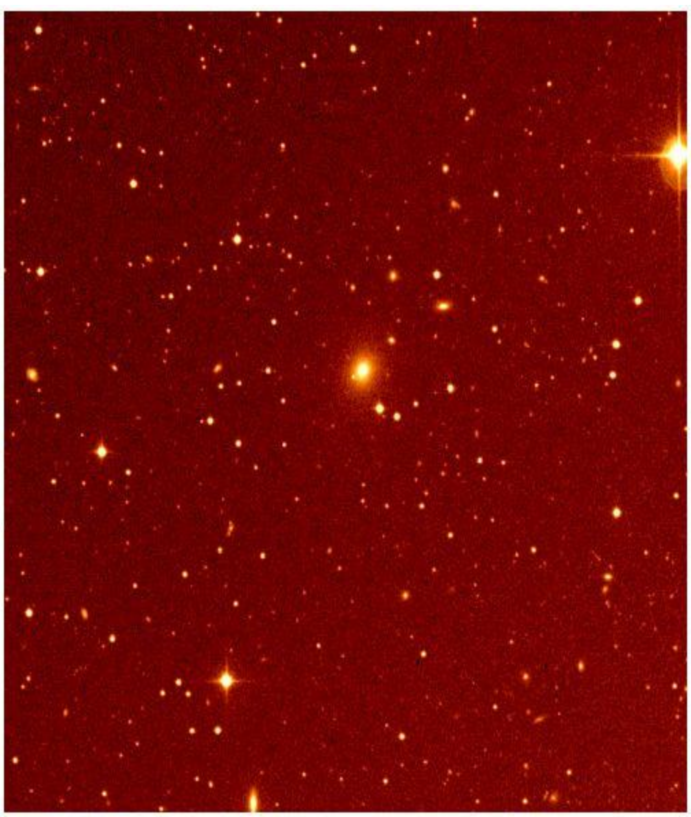
where $\sigma_T = \left(\frac{e^4}{6\pi\varepsilon_o^2 c^4 m_o}\right)$, is the Thomson cross-section and $U_B = \frac{B^2}{2\mu_o}$, is the energy density of magnetic field.

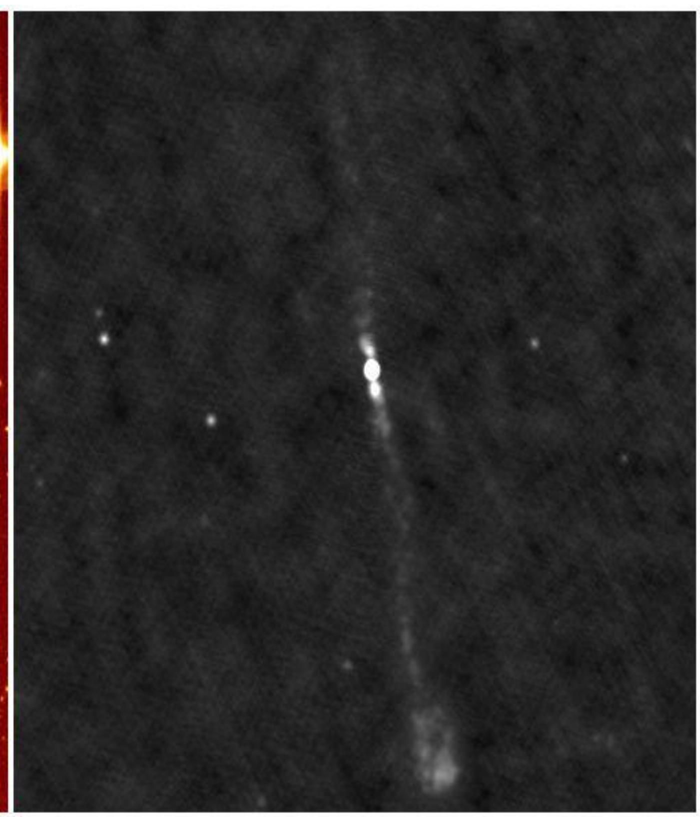
5. OUR SOURCE GALAXY

5.1 Elliptical Galaxy CGCG 049-033:-

Our source CGCG 049-033 is an elliptical galaxy in Abell cluster known as A-2040. This is an active galaxy offset from the cluster centre by $\sim$22’ (1.1 Mpc) having a redshift, $z = 0.04464$. From the optical spectrum of the galaxy, the mass of the Black Hole at the centre of this galaxy is estimated to be of the order of $\sim 10^9 M_{\odot}$. The polar coordinates of this galaxy are, $R.A. = 15^h\ 11^m\ 31.006^s$ and $Dec. = +07^{\circ}\ 15^{'}\ 5.973"$. The radial velocity of this galaxy, $v = 0.132628\, c$ and radial distance, $d_{rad} = 186.6\, Mpc$ with Hubble constant $H_o = 71\ kms^{-1}Mpc^{-1}$.

5.2 Optical and Radio Images of CGCG 049-033:-





The above image shows the optical image (from SDSS website) and radio image (obtained by us from GMRT data) on the same scale and showing exactly the same field of view for both images. The left image is the optical image having CGCG 049-033 as very bright galaxy near the centre of the image (slightly above the centre of the image). This image is filled with many other bright galaxies also.

The right image is our radio image of CGCG 049-033 clearly showing the bright core, the long main jet with main lobe (coming downward from core), bright main innerjet and counter innerjet. There is also a faint counterjet visible in this image which if we change the contrast of the image will be visible in a much better way. There are also other galaxies visible in this radio image. The radio image can still be further improved. Clearly we can see the jet and the lobe structures only in radio image whereas these features are absent in optical image.

6. Observations and Results

6.1 Observations:-

The radio observations of CGCG049-033 at frequency 1.28 GHz were taken from Giant Meterwave Radio Telescope (GMRT). The processed image is giving the following parameters of the core, jets and lobes.

Galaxy's feature	Flux Density(mJy)
Core	101.61
Main Lobe	45.985
Main Inner Jet	17.071
Counter Inner Jet	14.919
Counter Lobe	10

The values of flux densities observed along the main jets vary from 4.637mJy to 8.06mJy while the detected values of the flux densities along the counterjet vary from 2.334mJy to 7.25mJy. The total flux density of the radio galaxy measured is 245mJy.

6.2 Results:-

1. The projected length of the main jet is ∼440kpc which is the largest ever known.
2. The shape of the jet is like a sinusoidal wave showing one cycle upto ∼375kpc. The main lobe is highly compact and come into existence at a projected distance of ∼350kpc from the core. The shape of the faintly visible counterjet seems to have the same shape as of the main jet. There are radio knots observed on the main jet at regular spacing of ∼40kpc over most of its length.
3. The observed core-to-lobe flux density ratio, $f_c = 2.21$, at 1.28MHz is, $F = 22.1$, times higher than FR-II radio galaxies with matching radio lobe power to CGCG 049-033 (for these galaxies $f_c = 0.1$ only). With these values, the corresponding viewing angle, θ, of the main nuclear jet with respect to the our line of sight will be (Giovannini et al. 1994)

$$\cos\theta = \frac{\left[0.5 + \frac{\left(\sqrt{F} - 1\right)}{\beta_j}\right]}{\sqrt{F}}$$

This gives the value of $\theta \rightarrow (26.66)^{\circ}$ as $\beta_j \rightarrow 1$ where β_j is the speed of the jet in units of speed of light. With this value, the actual length of the jet will become $\sim$980kpc which is not possible and also disfavoured by the apparent symmetry of the innerjets.

4. It seems that there is a counter jet visible which is very faint because we are getting some flux density on the counterside and along the direction opposite to the main jet which has high flux density value than the noise. The ratio of main lobe to counter lobe flux density R is found out to be

$$R = \frac{S_h(\nu)}{S_{ch}(\nu)} = \frac{45}{10} = 4.5$$

The velocity of the jet, cosine of viewing angle, spectral index α (α: $S_{\vartheta} \propto \vartheta^{-\alpha}$) and main lobe to counter lobe flux ratio are related to each other by the following relation (Stawarz 2004)

$$R = \left[\frac{1 + \beta_h \cos\theta}{1 - \beta_h \cos\theta}\right]^{3+\alpha}$$

The spectral index values are 0.23, 0.50, 0.58 and 0.37 for core, jet, lobe and integral emission respectively. By taking $\beta_h \sim 1$, we will get the viewing angle of the lobe $\sim 81^{\circ}$. By assigning different values to β_h we see that the values of $\beta_h < 0.2$ are not possible.

Similarly calculated value of θ for the inner jets is $\sim 88^{\circ}$. By measuring flux density of the visible parts of the counterjet and the corresponding parts of the jet and using the above formula we are getting the values of θ varying from $\sim 80^{\circ}$ to $\sim 87^{\circ}$. This implies that the jet is nearly in the plane of sky.

5. The apparent speed $\beta_{app.}$ of the jet i.e. the projected speed of the jet is given by (Stawarz, L. 2004)

$$\beta_{app.} = \frac{\beta_h \sin\theta}{1 - \beta_h \cos\theta}$$

So for $\theta = 81^{\circ}$ (for the case of lobe) , we get $\beta_{app.} \rightarrow 1.17$ as $\beta_h \rightarrow 1$ (but in real situations $\beta_h < 1$. Thus time period of the jet t_{jet} (which is the lower limit, it can go greater than this value) in which it emanates from AGN and terminates at the hot spot is given by (Stawarz 2004)

$$t_{jet} = \frac{d_{proj}}{\beta_{app.} . c}$$

The projected distance d_{proj} of the main jet is ~440kpc which gives the value of t_{jet} ~1.23 million years.

6. The total radiating power P_{rad} from the AGN is given by

$$P_{rad} = \dot{M}c^2 \times \epsilon$$

where $\dot{M}$ is the rate of accreting mass on the accretion disk around the black hole, ϵ is a factor equal to 0.1 and c is the speed of light. The total flux density we are getting from radio wavelength from the galaxy, $S = 245$mJy is not the i flux density (considering all the wavelengths) and therefore S is less than the net value of S. The total power in radio wavelengths emitted by CGCG 049-033 corresponding to 1.28MHz is

$$P = 4\pi D_L^2 \times S$$

where D_L is the luminosity distance of the galaxy, gives us $P = 8.82 \times 10^{23} watt/Hz$. Therefore,

$$\dot{M} = \frac{P}{c^2.\epsilon}$$

gives us $\dot{M} \sim 1.5 \times 10^{-15} M_{\odot}/year$. If we take into account for the difference in S due to absence of other wavelengths' flux densities, then $\dot{M} \sim 1.5 \times 10^{-14} M_{\odot}/year$ which is very low. The Eddington Luminosity limit L_{Edd} (the luminosity lequired to stop accretion) is given by

$$L_{Edd} = 1.31 \times 10^{31} \left(\frac{M_{BH}}{M_{\odot}}\right)$$

where M_{BH} and $M_{\odot}$ are the masses of black hole and sun respectively. As $M_{BH} \sim 2 \times 10^9 M_{\odot}$, we will get

$$L_{Edd} \sim 2.6 \times 10^{40}\ watt$$

The accretion rate corresponding to this luminosity is

$$\dot{M_{Edd}} \sim 4.5\ M_{\odot}/yr.$$

This implies that this galaxy is not a quasar whose accretion rate is much higher than the present case value. So CGCG 049-033 is accreting at sub Eddington accretion rate.

7. About the Observed Characteristics of CGCG 049-033

1. The sinusoidal shape of the jet and the variation in viewing angle values varying from $\sim 80°$ to $\sim 88°$ along the jet may suggest the precession of the jet in a half conic angle of $\sim 4°$ to $8°$. The lobe viewing angle $\sim 81°$ suggests that when that part was emanated from the core it was closer to the line of sight but the inner jet viewing angle $\sim 88°$ suggests that it is now at different position and also the variation in angles suggesting that while precessing it is coming towards the sky plane.
2. If the sinusoidal shape (which is projected image of helical precessing jet) of the jet is due to precession then from core, one sine cycle (one sine cycle correspond to one precession cycle of the jet) has length of $\sim 375kpc$ giving the precession period of the jet as ~1.08 million years (which is the lower limit for the time of precession). But the reason of this precession is unknown and this value of precession is not matching with $\dot{M}$, the rate of accreting mass on the accretion disk.
3. The counterlobe and counterjet was not detected (accept the innerjet) before and therefore giving us the value of very small viewing angle resulting in beaming effect which is still valid for our values of core to jet flux density ratio.
4. To solve this contradiction and to tell if the counterlobe and counter jet structure is real or not, we need to take deeper and more sensitive radio obseservation are required.

8. Future Scope

Due to many strange properties exhibit by CGCG 049-033, it's deep and more sensitive radio observation in future is required. This can be done by Very Large Baseline Interferometry (VLBI), which has much higher resolution than GMRT. The analysis of that data can reveal the source of many unusual properties shown by CGCG 049-033. And the observed detection of the counter jet can be verified in those observations, which will be helpful in understanding the physical processes going in this galaxy which are extremely energetic.

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