Properties and Observations of Black Bole Jets Based on the State-of-art Facilities

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Abstract. The research on black hole jets started way back in the 1970s. From the first hypotheses that question the center of a galaxy, to nowadays' detailed structure of active galactic nuclei, the research on black hole jets has progressed immensely. This study is dedicated to summarizing all aspects of black hole jet research. This includes its research history, background information, theorems, properties, simulations, possible future research, and limitations on current research. Various papers are cited, including ones published as early as the 1980s, and current ones, to give a full view of black hole jet research. Original work has been done in order to create a timeline for the evolution of black hole jet research. Black hole jet research is crucial in understanding mechanisms behind black holes, which embody the active galactic nuclei. Speculations on galactic formation and evolution processes could be done by fully understanding the active galactic nuclei.

Keywords: Black hole jet, galactic formation, active galactic nuclei.

1. Introduction

The road of black hole jets research was paved back in 1969. At that time, the idea that supermassive black holes generate the energies quasars emit was promoted by Donald Lynden-Bell [1]. Lynden-Bell theorized that, as objects fall into the black hole's immense gravitational well, huge amounts of gravitational energy is released to provide the quasar's luminosity [1]. Although not quite matching to current studies of black hole jets, Donald Lynden-Bell's research started the research on black holes. One of the early successors to Lynden-Bell's quasar emissions work is John Archibald Wheeler on "Mechanisms for Jets", published in 1971. This paper analyzes the known and hypothesized facts of black hole jets with respect to hydrodynamics, Newtonian mechanics, and relativistic physics [2]. The paper also considers other factors in the universe that might influence black hole jets, such as cosmic rays. By analyzing Sagittarius A, the active galactic nuclei of the Milky Way Galaxy, this paper is one of the first to observe the phenomenon of twin ionized jets directed oppositely out of it [3].

Another successor to Lynden-Bell's theories is proposed by bramowicz and Tsvi Piran. Instead of researching directly on the two physical jets of ionized particles, the paper was one of the first to find relationships of luminosity, accretion rate and black hole life time with the thick accretion disk. It is also one of the first to point out that the process happens in relativistic velocities [4]. In the paper, Abramowicz and Piran ultimately shows that thick accretion disks provide a way to produce visible and infrared radiation that thin accretion disks cannot. However, the calculations ignore redshifts, radiation absorption of black holes and the change of photon paths [4].

In modern time, the large theoretical model of black hole jets has been safely and soundly built. It is only the matter of tinkering with the details. This includes further research on specific parts of the black hole, finding relationships between some quantities, and making simulations [5,6,7]. In this part, three current papers will be discussed ad summarized, in order to show the present research progress on black hole jets. The first paper models and describes the results of tidal disruption events on the accretion disks, and how it affects accretion flows and jet activities [5]. Tidal disruption events happen when a start gets “disrupted”, or torn apart, by a supermassive black hole. About half of the star debris falls in towards the black hole due to gravitation, while the other half continues its path. It is the half that falls towards the black hole that causes a relatively short emission of electromagnetic radiation, called tidal disruption event [8]. Observations on tidal disruption events and its interaction with the accretion disk is key in understanding black hole jets and examining general relativity near black holes [5]. Another paper focuses more on radiation processes in black hole jets. It starts with radio-luminosity observations on active galactic nuclei [6]. Then, it dives deep into a minority of active galactic nuclei, the blazars [6]. In the research of blazars, it draws interesting conclusions, such as the super luminal speeds of propagating jets in the observer’s frame of reference [6]. Evaluating radiation later on in this paper also includes well-known processes such as Compton scattering [6].

The third paper includes a simulation done that models the jets formed by a collapse of massive stars [7]. This simulation made is a 3D model of magnetohydrodynamic and general-relativistic creation that has dimensions of over six orders of magnitude. Results in this simulation include the finding that there is magnetic energy dissipation caused by the instability of magnetized jet [7]. Another result is finding a tilt in the jets shown in Fig. 1. The significant tilt of the jets is said to be a result of the deflection of jets when it was launched by the blue-gray material shown in the results.

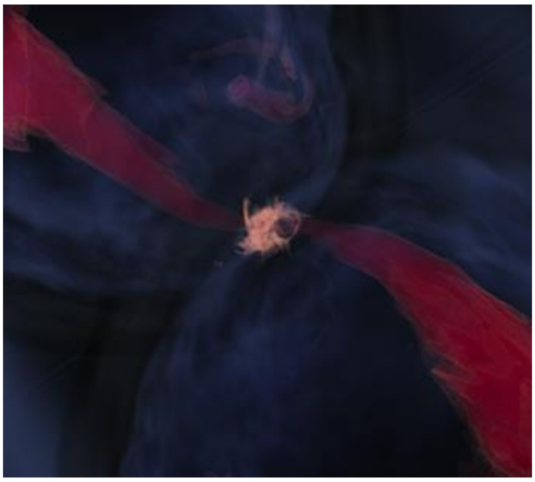

Figure 1. Simulation shows a tilt of the jets.

The purpose of this paper is to give readers an as all-inclusive as possible description of the properties, observations and future outlooks of black hole jets. The main body of this paper is split into six parts, each dedicated to thoroughly describe one detail of black hole jets. The first part of this paper is dedicated for the basic definition, description and mechanisms of the black hole jets. In this part, questions such as what is a black hole jet and how does it work will be answered. The second part of this paper is used to describe its theorems and properties, where the three different types of black holes and its features will be explained. The third part of this paper will discuss the principles. The fourth part of this paper explores the experimental observations of black hole jets. It displays the detectors used to observe black hole jets, and some experimental results based on information collected by detectors. The fifth part of this paper states the research limitations on the field of black hole jets. This part briefly describes the current black hole jet studies, and how experimental and observational constraints hinder discoveries.

2. Basic Description of Black Hole Jets

Black holes, as people all know, has a tendency to devour and suck in everything, including light, that comes in its path. However, some special black holes, namely the supermassive black holes acting as active galactic nucleus (AGN) in the center of galaxies, are known to exhibit properties of shooting out ionized gases [8]. In fact, near the event horizon of these “special” black holes, the ionized gases are found to be accelerated to near light speeds. The most widely accepted theory for this phenomenon has to do with the accretion disk. The accretion disk is a disk consisting of ionized gases that is circulating the black hole. The charged particles inside the spinning disk creates a strong magnetic field. And, if the black hole also spins around its axis, it would interact with the magnetic field, twisting it into the shape of a cone relative to the rotational poles of the spinning black hole. Scientists hypothesized that the twist of the magnetic field accelerates ionized particles to near-light speeds, and out of the black hole [9].

Additionally, recent observations on the black hole jets also reveal some proves to the hypothesis. Information gathered by NASA's Fermi Gamma-Ray Space Telescope displays that there is a clear linear relationship between the luminosity of the accretion disk and the power of the jets [9]. This suggests that the power of the jets depend on the charged particles in the disk, which relates to the magnetic field. A furthermore research on blazars done by a research group also gives evidence to the magnetic field hypothesis. Blazars are essentially a type of quasar, a supermassive black hole, with its black hole jets pointing directly at the observer. By using the hypothesis as a basis, the research group conducts a multiple linear regression to explore relationships encompassing the black hole's mass, spin, accretion, and kinetic power [10]. As a result, the research group finds that the contribution of black hole accretion and spin added together goes up to 95 percent of the total value. Thus, the results suggest that the spin plays an important role on powering black hole jets [10]. This goes back to the hypothesis, as the acceleration supposedly relies on the twist of the magnetic field created surrounding it by the black hole's spin.

3. Theorems and Properties

Currently there's three type of black hole jet model based on MHD. The Blanford-Znajek model [11], Blanford-Payne model [12] and magnetic tower model [13]. The Blanford-Znajek model consider that the rotational energy can release from interaction between blackhole and magnetic field line and form the black hole jet. The Blanford-Payne model consider that interaction between blackhole and magnetic field line can heat the surrounding matters. Difference between the two models is that the former one extracts rotation energy of black hole and dominated by Poynting flux of energy while the latter one extracts the rotation energy of accretion disc and dominated by matter [14]. This model considers that there's poloidal magnetic crossing the horizon. rotating drags the time and space, so the magnetic field line rotates with time space, while the magnetic field line far away from blackhole is affected little by the black hole, so there produce axial component of Magnetic field line, and forms Poynting flux of energy. The core of this theorem is that in the view of an observer at infinity, a negative energy flux goes in to the black hole, reducing energy and angular momentum of black hole, so there forms a pointing flux with positive energy and angular momentum. The power of this energy flux:

$$P_{BZ} = \frac{\kappa}{4\pi c}\Phi^2\Omega_H^2 \tag{1}$$

Here, Φ is the magnetic flux through the black hole horizon, Ω_H^2=$a_* c/2R_H$ models the angular velocity of horizon.$a_* \equiv a/M$ is the dimensionless spin parameter. a is the angular momentum of black hole, R_H is radius of horizon [14]. This model also relies on the axial component of magnetic field, but it considers that the magnetic field line is in accretion disc, and extracts the rotation energy from the accretion disc (seen from Fig. 2).

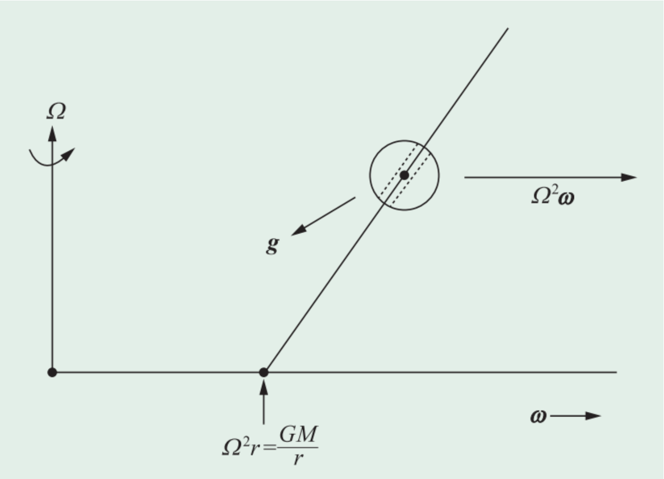

Figure 2. A sketch of Blandford-Payne Model diagram.

Assuming the disk corona is strongly magnetized, the magnetic pressure is bigger than the gas pressure. Assume there is a big scale polar axial magnetic field, that the magnetic field line is fixed on the accretion disc, so the whole magnetic field line has the same angular velocity. The angular velocity is Ω ,so the fluid element at the radius R has a linear velocity ΩR. So, as the radius increases, the centrifugal force increases. Aside from the centrifugal force, the fluid element also experiences a gravitational force of black hole. Because the disk corona area is strongly magnetized, it has a magnetic frozen effect, so the fluid element can only move along the magnetic field line. If the angle between the magnetic field line is smaller than 60°,then the fluid element will accelerate outward along the magnetic field line. In the inner region of accretion disc,there exists a large magnetic field. The field lines are fixed on the disc .so the rotation of disc produces an axial component of the magnetic field line. The intensity of axial component of magnetic field increase when approaching the accretion disk, so the magnetic field line has a gradient vertical to the disk. The gradient can accelerate gas and form jets. The shape looks like a tower.

4. GRMHD Simulation

Simulation is the most common way to help understand the properties of cosmologic objects. General Relativistic Magnetohydrodynamics (GRMHD) simulation is a highly complex numerical simulation method used to solve problems involving strong gravitational fields (such as black holes or neutron stars) and the interaction of complex fluid dynamics with magnetic fields. These simulations are important in multiple subfields of astronomy and physics, especially when simulating accretion disks around black holes, jets, and other phenomena associated with these extreme environments [17]. When using GRMHD to simulate black holes, there are many factors to consider. So, there is a need to establish the basic equations in the simulation. The Einstein field equations (EFE) is needed to describe the geometry and curvature of spacetime. EFE may be written in the form:

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \kappa T_{\mu\nu} \tag{2}$$

where $G_{\mu\nu}$ is the Einstein tensor, $g_{\mu\nu}$ is the metric tensor, $T_{\mu\nu}$ is the stressenergy tensor, Λ is the cosmological constant and κ is the Einstein gravitational constant.

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} \tag{3}$$

The Navier-Stokes equation is used to describe the motion of fluid. For a three-dimensional, incompressible, Newtonian fluid, the Navier-Stokes equations can be represented as:

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} = -\frac{1}{\rho}\nabla p + \nu \nabla^2 \mathbf{u} + \mathbf{f} \tag{4}$$

Here, u is the velocity field of the fluid; t is time; ρ is the fluid density; p is pressure; ν is the dynamic viscosity of the fluid; f is the body force (such as gravity). The Maxwell equation is needed to describe the interaction of electromagnetic fields. The equations are usually written in both integral and differential forms. The differential forms of Maxwell's equations are:

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0} \tag{5}$$

$$\nabla \cdot \mathbf{B} = 0 \tag{6}$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \tag{7}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} \tag{8}$$

Here, E and B are the electric and magnetic field vectors respectively. ρ is the electric charge density. ϵ_0 is the vacuum permittivity. μ_0 is the vacuum permeability. J is the current density. t is time. Three-dimensional simulations were conducted on the accretion disks that remain after neutron star mergers. The results indicate that when binary neutron stars or a neutron star and a black hole merge, it can lead to the formation of a large rotating torus around a spinning black hole. Additionally, these simulations demonstrate that mass ejection and rapid neutron capture nucleosynthesis are caused by unbound outflows from these disks. The simulations provide a detailed look at the complex interplay between magnetic fields, turbulence, and neutrino cooling in these disks, and show that the magneto-rotational instability (MRI) drives vigorous turbulence in the disk. This turbulence is responsible for the generation of outflows and the r-process nucleosynthesis that produces heavy elements [18]. Fig. 3 provides information on the type and total amount of outflow, as well as other relevant parameters.

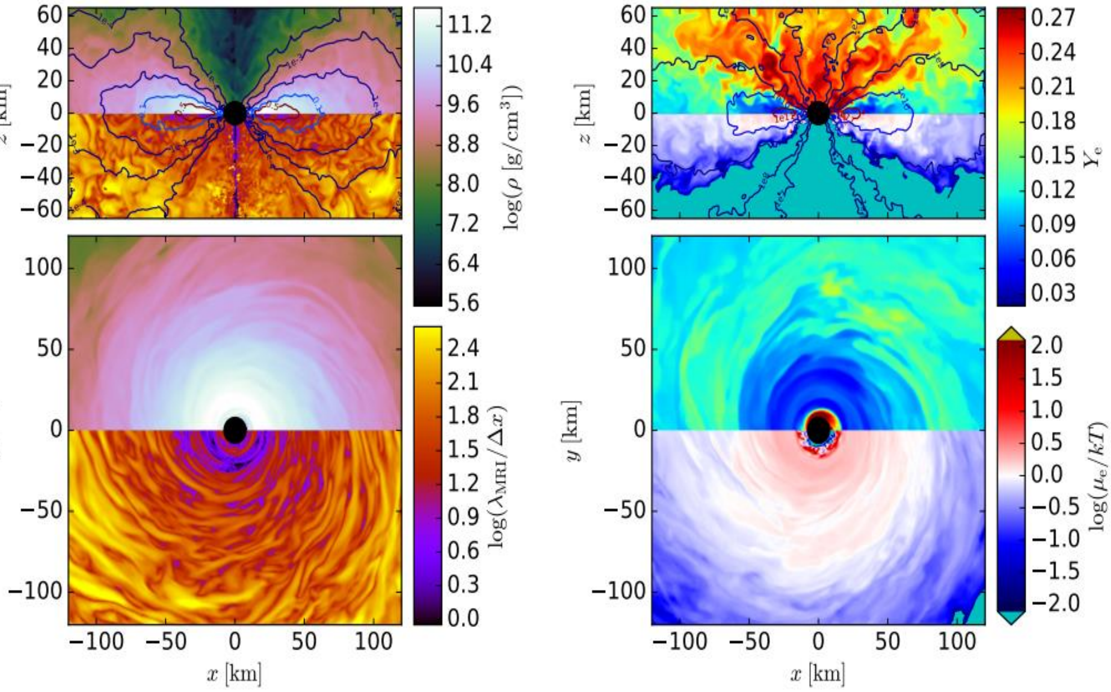

Figure 3. Snapshots capture the moment when the disk has achieved a state of mild electron degeneracy while concealing any information about the interior of the black hole

5. Experimental observation

This section will introduce some advanced telescopes for detecting black holes and black hole jets, whilst explaining the detection principles of these detectors, and show their detection and scientific research results through pictures.

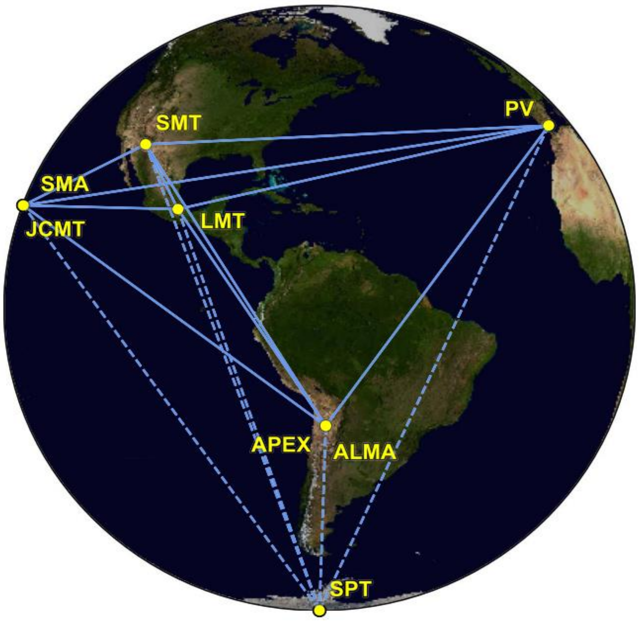

Figure 4. A sketch of EHT.

The Event Horizon Telescope is a cutting-edge telescope that links radio telescopes worldwide to create a telescope with the same diameter as Earth [19]. By utilizing Very Long Baseline Interferometry (VLBI) at shorter wavelengths, radio dishes across the globe are interconnected to form an interferometer equivalent in size to our planet(seen from Fig. 4) [20]. This technique has been employed to measure the dimensions of the emission regions surrounding two supermassive black holes known for their prominent apparent event horizons: Sagittarius A located in the center of our Milky Way galaxy and M87 situated at the core of Virgo A galaxy. VLBI plays a crucial role in enhancing resolution capabilities, especially considering that even the black hole positioned at the heart of our closest neighboring galaxy is approximately 27,000 light-years away.Below this scale, X-rays, radio waves, visible and ultraviolet light, or gamma rays emitted by the black hole are transmitted to Earth in the form of approximately flat waves [21]. At this distance, it is difficult for a single radio telescope to provide high-resolution and effective information. VLBI is a technique that combines multiple telescopes to improve the angular resolution of the image. Radio telescopes in different places observe radio waves with phase differences, and the phase difference itself is different when the electromagnetic waves travel from different points. By accurately measuring the phase difference, the accurate angular resolution is obtainable. The baseline's angular precision is defined by λ/D, with D representing the projected distance between the antennas. To achieve sharper angular precision, one can observe at a more abbreviated wavelength and expand the spacing between the telescopes. Hence, there is a continual strive for optimal resolution, capitalizing on the capability to discern tiny objects with the utmost clarity possible [19]. The use of atomic clocks to accurately synchronize the time of telescopes around the world is the key to VLBI technology. This ensures that the data observed by the telescope can be precisely aligned and combined as shown in Fig. 5 [19].

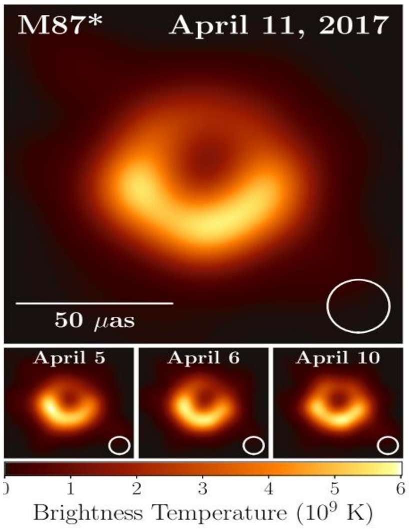

Figure 5. The first image of the supermassive black hole at the center of the galaxy M87.

When an object is captured by a black hole, it spirals inward toward the central body. The closer it gets, the higher the temperature and speed it achieves. Under extreme temperatures and the immense mass of the central body, photons and other plasma materials accumulate around the black hole, generating magnetic fields. The particles are ejected near light speeds, as explained in part 2. Among the electromagnetic waves emitted during black hole observation, X-rays have the highest radiation intensity. Although X-rays possess strong penetrating power, protons in Earth's atmosphere absorb their energy [21-23]. Thus, launching space-based X-ray telescopes is crucial for observing the jets emanating from black holes. High-Energy X-ray Telescope (HE): The energy range of HE is 20-250 keV. The High Energy X-ray Telescope uses 18 identical detector modules. Each module contains a sodium iodide crystal detector to detect high-energy X-rays. HE is used to study high-energy radiation from black holes, neutron stars, and other compact bodies [24]. Medium Energy X-ray Telescope (ME): The energy range of ME is 5-30 keV. The Medium Energy X-ray Telescope consists of a two-layer detector consisting of a sodium iodide crystal and a zinc-germanium (ZnGe) crystal. This design provides good energy resolution and reduces background radiation. ME is mainly used in the study of medium energy X-ray objects, including the afterglow of gamma-ray bursts, X-ray binaries, and active galactic nuclei [24]. Low Energy X-ray Telescope (LE): The energy range of LE is 1-15 keV. The low-energy X-ray telescope uses X-ray focusing technology, which has an array of multilayer thin film mirrors capable of focusing low-energy X-rays onto a silicon drift detector. This design provides high spatial resolution for low-energy X-rays. LE is specifically used for the study of celestial bodies with low-energy X-rays, such as supernovae, supernova remnants, X-ray binaries, and the inner regions of star clusters [24]. A sketch is shown in Fig. 6.

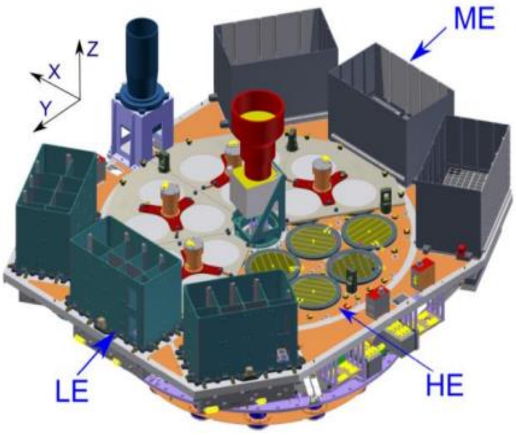

Figure 6. China's first X-ray astronomical satellite.

6. Limitations and Prospects

Currently, there are still many limitations on the study of black hole jets. For example, the intensity of radiation is proportional to the work of jet rate. In this relationship, there is no consideration of the spin of a black hole. Apparently, this may be due to the lack of data on the spin of black holes, so this physical quantity is not considered in statistics. However, another method can be used to verify the observation, as the Blandford-Znajek model predicts that the jets are driven by the spin of a black hole [11, 17]. Therefore, if the model is right, estimation shows that the jet power has a strong correlation with the angular momentum of the black hole. But unfortunately, the Blandford-Znajek model is only Suitable for Intermittent jets, so for continuous jets, it does not necessarily apply [17].

The second constraint is that the composition of matter in the jet of a black hole is unknown [24]. Theoretically, it is expected that most of the material in the jet comes from the formation of positive and negative electron pairs caused by the destruction of the vacuum gap. However, in the actual study, due to technical limitations, the density of matter in the simulation area cannot be too low. So, the numerical simulation in the future is necessary to add some material components to the area close to the axis of the black hole. This makes the simulated Lorentz factor values unreliable. There are currently two schools of opinion about the composition of black hole jet matter. First, the jet flow is dominated by the pointing flow, and the material components in it are only positive and negative electron equivalent leptons matter. The jets produced by the Blandford-Znajek model fall into this category [11, 17]. Another school of opinion is that the material composition of the jet is the same as positive, often the accretion disk plasma is completely phased. Similarly, it is composed of baryonic matter. Except the Blandford-Znajek model [11, 17], several remaining models include Blandford-Payne model [12], magnetic tower models [13], as well as models for intermittent jets type, all prophesied that the jet should be made of composed of normal baryonic matter. The next step is to integrate the observational data more closely with numerical simulation studies, is a breakthrough to address these issues.

7. Conclusion

To sum up, the reviewing of achievements in black hole jet studies from the step of building the MHD models in the 1980s to the step of observation and simulation, which is still ongoing today, is done. The jet is closely linked with accretion disk and there's three kinds of model about the jet and accretion disk. We introduce two advanced telescopes that detects black hole and black hole jets. The event horizon telescope (connect the radio telescope to utilize Very Long Baseline Interferometry (VLBI) at short wavelengths) and Hard X-ray Modulation Telescope. We discussed applications from the Einstein field equations, The Navier-Stokes equation and Maxwell's equations. We summarized the limitations of current studies: the simulation models have inapplicable scope, and the composition of black hole jet are unable to be determined. It is hoped that in the future someone can do a more detailed and description of models. This paper provides a route to know the achievements of black hole jet studies in simple words.

Author Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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